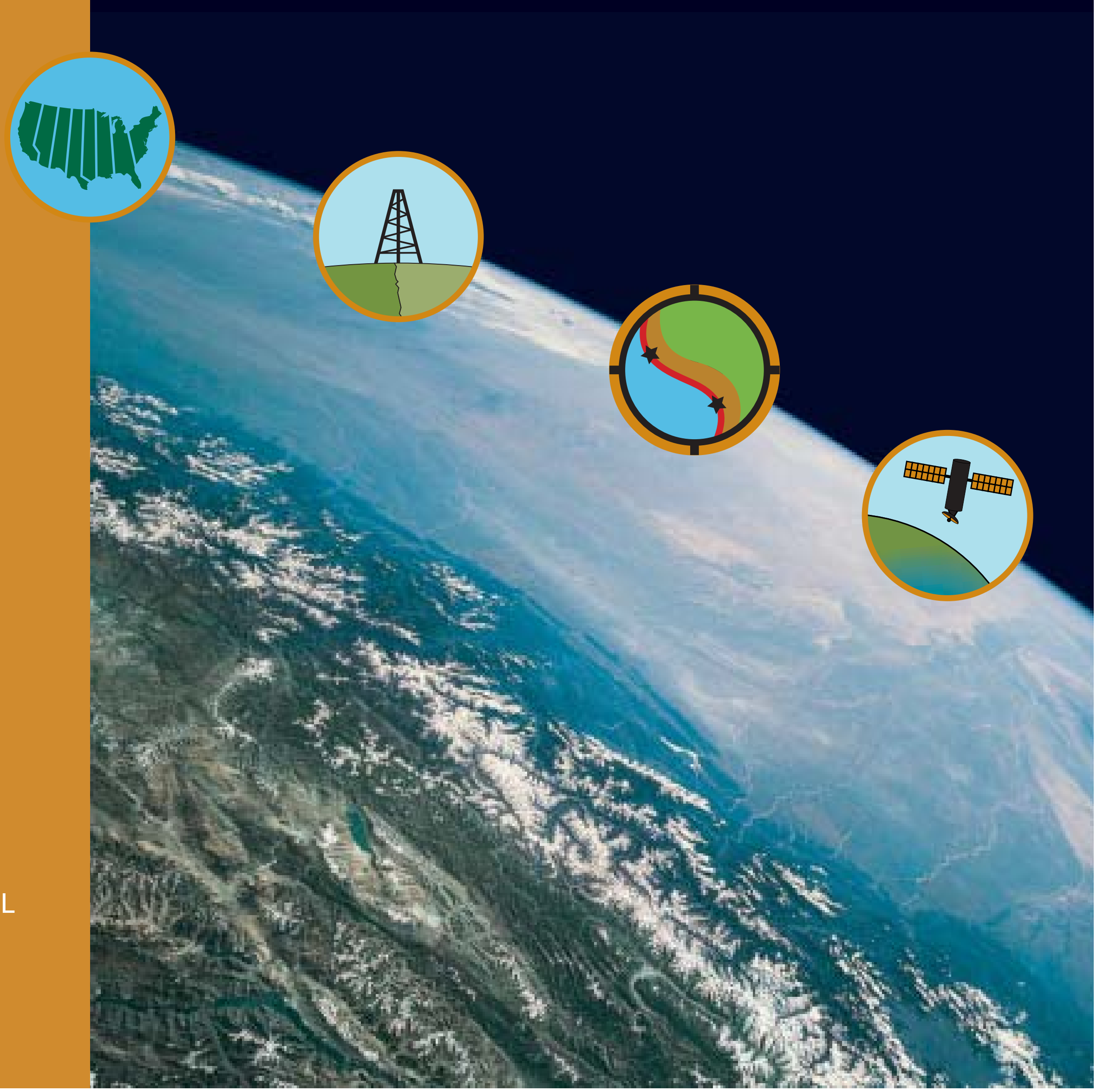
# earthscope

ACQUISITION,
CONSTRUCTION
INTEGRATION AND
FACILITY MANAGEMENT



MREFC
PROPOSAL

# COVER SHEET FOR PROPOSAL TO THE NATIONAL SCIENCE FOUNDATION

| | |
|---|---|
| PROGRAM ANNOUNCEMENT/SOLICITATION NO./CLOSING DATE/if not in response to a program announcement/solicitation enter NSF 03-2<br>**NSF 03-2** | **FOR NSF USE ONLY**<br>**NSF PROPOSAL NUMBER** |
| FOR CONSIDERATION BY NSF ORGANIZATION UNIT(S) (Indicate the most specific unit known, i.e. program, division, etc.)<br>**EAR - INSTRUMENTATION & FACILITIES** | |

| DATE RECEIVED | NUMBER OF COPIES | DIVISION ASSIGNED | FUND CODE | DUNS# (Data Universal Numbering System) | FILE LOCATION |
|---|---|---|---|---|---|
| | | | | **183277938** | |

| EMPLOYER IDENTIFICATION NUMBER (EIN) OR TAXPAYER IDENTIFICATION NUMBER (TIN) | SHOW PREVIOUS AWARD NO. IF THIS IS | IS THIS PROPOSAL BEING SUBMITTED TO ANOTHER FEDERAL AGENCY? YES ☐ NO ☒ IF YES, LIST ACRONYM(S) |
|---|---|---|
| **521362650** | ☐ A RENEWAL<br>☐ AN ACCOMPLISHMENT-BASED RENEWAL | |

| | |
|---|---|
| NAME OF ORGANIZATION TO WHICH AWARD SHOULD BE MADE<br>**Incorporated Research Institutions for Seismology** | ADDRESS OF AWARDEE ORGANIZATION, INCLUDING 9 DIGIT ZIP CODE<br>**Incorporated Research Institutions for Seismology**<br>**1200 New York Avenue, NW**<br>**Washington, DC. 20005** |
| AWARDEE ORGANIZATION CODE (IF KNOWN)<br>**4076212000** | |
| NAME OF PERFORMING ORGANIZATION, IF DIFFERENT FROM ABOVE | ADDRESS OF PERFORMING ORGANIZATION, IF DIFFERENT, INCLUDING 9 DIGIT ZIP CODE |
| PERFORMING ORGANIZATION CODE (IF KNOWN) | |

IS AWARDEE ORGANIZATION (Check All That Apply) (See GPG II.C For Definitions)
☐ SMALL BUSINESS ☐ MINORITY BUSINESS
☐ FOR-PROFIT ORGANIZATION ☐ WOMAN-OWNED BUSINESS
☐ IF THIS IS A PRELIMINARY PROPOSAL THEN CHECK HERE

TITLE OF PROPOSED PROJECT **Collaborative Research: Earthscope-Acquisition, Construction, and Facility Management \(USArray\)**

| REQUESTED AMOUNT | PROPOSED DURATION (1-60 MONTHS) | REQUESTED STARTING DATE | SHOW RELATED PRELIMINARY PROPOSAL NO. IF APPLICABLE |
|---|---|---|---|
| $ **69,848,258** | **60** months | **07/01/03** | |

CHECK APPROPRIATE BOX(ES) IF THIS PROPOSAL INCLUDES ANY OF THE ITEMS LISTED BELOW

☐ BEGINNING INVESTIGATOR (GPG I.A)
☒ DISCLOSURE OF LOBBYING ACTIVITIES (GPG II.C)
☐ PROPRIETARY & PRIVILEGED INFORMATION (GPG I.B, II.C.6)
☐ HISTORIC PLACES (GPG II.C.9)
☐ SMALL GRANT FOR EXPLOR. RESEARCH (SGER) (GPG II.C.11)
☐ VERTEBRATE ANIMALS (GPG II.C.11) IACUC App. Date ________
☐ HUMAN SUBJECTS (GPG II.C.11)
Exemption Subsection ________ or IRB App. Date ________
☐ INTERNATIONAL COOPERATIVE ACTIVITIES: COUNTRY/COUNTRIES INVOLVED (GPG II.C.9)
________
☒ HIGH RESOLUTION GRAPHICS/OTHER GRAPHICS WHERE EXACT COLOR REPRESENTATION IS REQUIRED FOR PROPER INTERPRETATION (GPG I.E.1)

| | |
|---|---|
| PI/PD DEPARTMENT | PI/PD POSTAL ADDRESS<br>**1200 New York Avenue, NW**<br>**Suite 800**<br>**Washington, DC 20005**<br>**United States** |
| PI/PD FAX NUMBER<br>**202-682-2444** | |

| NAMES (TYPED) | High Degree | Yr of Degree | Telephone Number | Electronic Mail Address |
|---|---|---|---|---|
| PI/PD NAME<br>**David W Simpson** | **PhD** | **1973** | **202-682-2220** | **simpson@iris.edu** |
| CO-PI/PD | | | | |
| CO-PI/PD | | | | |
| CO-PI/PD | | | | |
| CO-PI/PD | | | | |



TPI 6213930

# CERTIFICATION PAGE

## Certification for Authorized Organizational Representative or Individual Applicant:

By signing and submitting this proposal, the individual applicant or the authorized official of the applicant institution is: (1) certifying that statements made herein are true and complete to the best of his/her knowledge; and (2) agreeing to accept the obligation to comply with NSF award terms and conditions if an award is made as a result of this application. Further, the applicant is hereby providing certifications regarding debarment and suspension, drug-free workplace, and lobbying activities (see below), as set forth in Grant Proposal Guide (GPG), NSF 03-2. Willful provision of false information in this application and its supporting documents or in reports required under an ensuing award is a criminal offense (U. S. Code, Title 18, Section 1001).

In addition, if the applicant institution employs more than fifty persons, the authorized official of the applicant institution is certifying that the institution has implemented a written and enforced conflict of interest policy that is consistent with the provisions of Grant Policy Manual Section 510; that to the best of his/her knowledge, all financial disclosures required by that conflict of interest policy have been made; and that all identified conflicts of interest will have been satisfactorily managed, reduced or eliminated prior to the institution's expenditure of any funds under the award, in accordance with the institution's conflict of interest policy. Conflicts which cannot be satisfactorily managed, reduced or eliminated must be disclosed to NSF.

### Drug Free Work Place Certification

By electronically signing the NSF Proposal Cover Sheet, the Authorized Organizational Representative or Individual Applicant is providing the Drug Free Work Place Certification contained in Appendix A of the Grant Proposal Guide.

### Debarment and Suspension Certification

(If answer "yes", please provide explanation.)

Is the organization or its principals presently debarred, suspended, proposed for debarment, declared ineligible, or voluntarily excluded from covered transactions by any Federal department or agency? Yes ☐ No ☒

By electronically signing the NSF Proposal Cover Sheet, the Authorized Organizational Representative or Individual Applicant is providing the Debarment and Suspension Certification contained in Appendix B of the Grant Proposal Guide.

### Certification Regarding Lobbying

This certification is required for an award of a Federal contract, grant, or cooperative agreement exceeding $100,000 and for an award of a Federal loan or a commitment providing for the United States to insure or guarantee a loan exceeding $150,000.

### Certification for Contracts, Grants, Loans and Cooperative Agreements

The undersigned certifies, to the best of his or her knowledge and belief, that:

(1) No federal appropriated funds have been paid or will be paid, by or on behalf of the undersigned, to any person for influencing or attempting to influence an officer or employee of any agency, a Member of Congress, an officer or employee of Congress, or an employee of a Member of Congress in connection with the awarding of any federal contract, the making of any Federal grant, the making of any Federal loan, the entering into of any cooperative agreement, and the extension, continuation, renewal, amendment, or modification of any Federal contract, grant, loan, or cooperative agreement.

(2) If any funds other than Federal appropriated funds have been paid or will be paid to any person for influencing or attempting to influence an officer or employee of any agency, a Member of Congress, an officer or employee of Congress, or an employee of a Member of Congress in connection with this Federal contract, grant, loan, or cooperative agreement, the undersigned shall complete and submit Standard Form-LLL, ''Disclosure of Lobbying Activities,'' in accordance with its instructions.

(3) The undersigned shall require that the language of this certification be included in the award documents for all subawards at all tiers including subcontracts, subgrants, and contracts under grants, loans, and cooperative agreements and that all subrecipients shall certify and disclose accordingly.

This certification is a material representation of fact upon which reliance was placed when this transaction was made or entered into. Submission of this certification is a prerequisite for making or entering into this transaction imposed by section 1352, Title 31, U.S. Code. Any person who fails to file the required certification shall be subject to a civil penalty of not less than $10,000 and not more than $100,000 for each such failure.

| AUTHORIZED ORGANIZATIONAL REPRESENTATIVE | SIGNATURE | DATE |
|---|---|---|
| NAME | | |

| TELEPHONE NUMBER | ELECTRONIC MAIL ADDRESS | FAX NUMBER |
|---|---|---|
| | | |

*SUBMISSION OF SOCIAL SECURITY NUMBERS IS VOLUNTARY AND WILL NOT AFFECT THE ORGANIZATION'S ELIGIBILITY FOR AN AWARD. HOWEVER, THEY ARE AN INTEGRAL PART OF THE INFORMATION SYSTEM AND ASSIST IN PROCESSING THE PROPOSAL. SSN SOLICITED UNDER NSF ACT OF 1950, AS AMENDED.

# COVER SHEET FOR PROPOSAL TO THE NATIONAL SCIENCE FOUNDATION

PROGRAM ANNOUNCEMENT/SOLICITATION NO./CLOSING DATE/if not in response to a program announcement/solicitation enter NSF 03-2

**NSF 03-2**

FOR NSF USE ONLY

NSF PROPOSAL NUMBER

FOR CONSIDERATION BY NSF ORGANIZATION UNIT(S) (Indicate the most specific unit known, i.e. program, division, etc.)

**EAR - INSTRUMENTATION & FACILITIES**

| DATE RECEIVED | NUMBER OF COPIES | DIVISION ASSIGNED | FUND CODE | DUNS# (Data Universal Numbering System) | FILE LOCATION |
|---|---|---|---|---|---|
| | | | | 046857483 | |

| EMPLOYER IDENTIFICATION NUMBER (EIN) OR TAXPAYER IDENTIFICATION NUMBER (TIN) | SHOW PREVIOUS AWARD NO. IF THIS IS | IS THIS PROPOSAL BEING SUBMITTED TO ANOTHER FEDERAL AGENCY? YES ☐ NO ☒ IF YES, LIST ACRONYM(S) |
|---|---|---|
| 841588357 | ☐ A RENEWAL<br>☐ AN ACCOMPLISHMENT-BASED RENEWAL | |

NAME OF ORGANIZATION TO WHICH AWARD SHOULD BE MADE

UNAVCO, Inc.

ADDRESS OF AWARDEE ORGANIZATION, INCLUDING 9 DIGIT ZIP CODE

**UNAVCO, Inc.**
**3360 Mitchell Lane**
**Boulder, CO. 803012260**

AWARDEE ORGANIZATION CODE (IF KNOWN)

**6250001876**

NAME OF PERFORMING ORGANIZATION, IF DIFFERENT FROM ABOVE

ADDRESS OF PERFORMING ORGANIZATION, IF DIFFERENT, INCLUDING 9 DIGIT ZIP CODE

PERFORMING ORGANIZATION CODE (IF KNOWN)

IS AWARDEE ORGANIZATION (Check All That Apply) (See GPG II.C For Definitions)
☐ SMALL BUSINESS ☐ MINORITY BUSINESS
☐ FOR-PROFIT ORGANIZATION ☐ WOMAN-OWNED BUSINESS
☐ IF THIS IS A PRELIMINARY PROPOSAL THEN CHECK HERE

TITLE OF PROPOSED PROJECT **Collaborative Research: Earthscope-Acquisition, Construction, and Facility Management \(PBO\)**

| REQUESTED AMOUNT | PROPOSED DURATION (1-60 MONTHS) | REQUESTED STARTING DATE | SHOW RELATED PRELIMINARY PROPOSAL NO. IF APPLICABLE |
|---|---|---|---|
| $ 100,000,000 | 60 months | 07/01/03 | |

CHECK APPROPRIATE BOX(ES) IF THIS PROPOSAL INCLUDES ANY OF THE ITEMS LISTED BELOW
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☐ DISCLOSURE OF LOBBYING ACTIVITIES (GPG II.C)
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☐ HUMAN SUBJECTS (GPG II.C.11)
Exemption Subsection ________ or IRB App. Date ________
☐ INTERNATIONAL COOPERATIVE ACTIVITIES: COUNTRY/COUNTRIES INVOLVED (GPG II.C.9)
________
☐ HIGH RESOLUTION GRAPHICS/OTHER GRAPHICS WHERE EXACT COLOR REPRESENTATION IS REQUIRED FOR PROPER INTERPRETATION (GPG I.E.1)

PI/PD DEPARTMENT

PI/PD POSTAL ADDRESS
**3360 Mitchell Lane**
**Suite C**
**Boulder, CO 803012260**
**United States**

PI/PD FAX NUMBER
**720-565-5992**

| NAMES (TYPED) | High Degree | Yr of Degree | Telephone Number | Electronic Mail Address |
|---|---|---|---|---|
| PI/PD NAME<br>William H Prescott | PhD | 1980 | 720-565-5973 | prescott@unavco.org |
| CO-PI/PD<br>Michael Jackson | PhD | 1994 | 303-497-8008 | mikej@unavco.ucar.edu |
| CO-PI/PD | | | | |
| CO-PI/PD | | | | |
| CO-PI/PD | | | | |



TPI 6215721

# CERTIFICATION PAGE

## Certification for Authorized Organizational Representative or Individual Applicant:

By signing and submitting this proposal, the individual applicant or the authorized official of the applicant institution is: (1) certifying that statements made herein are true and complete to the best of his/her knowledge; and (2) agreeing to accept the obligation to comply with NSF award terms and conditions if an award is made as a result of this application. Further, the applicant is hereby providing certifications regarding debarment and suspension, drug-free workplace, and lobbying activities (see below), as set forth in Grant Proposal Guide (GPG), NSF 03-2. Willful provision of false information in this application and its supporting documents or in reports required under an ensuing award is a criminal offense (U. S. Code, Title 18, Section 1001).

In addition, if the applicant institution employs more than fifty persons, the authorized official of the applicant institution is certifying that the institution has implemented a written and enforced conflict of interest policy that is consistent with the provisions of Grant Policy Manual Section 510; that to the best of his/her knowledge, all financial disclosures required by that conflict of interest policy have been made; and that all identified conflicts of interest will have been satisfactorily managed, reduced or eliminated prior to the institution's expenditure of any funds under the award, in accordance with the institution's conflict of interest policy. Conflicts which cannot be satisfactorily managed, reduced or eliminated must be disclosed to NSF.

### Drug Free Work Place Certification

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### Debarment and Suspension Certification

(If answer "yes", please provide explanation.)

Is the organization or its principals presently debarred, suspended, proposed for debarment, declared ineligible, or voluntarily excluded from covered transactions by any Federal department or agency? Yes ☐ No ☒

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### Certification for Contracts, Grants, Loans and Cooperative Agreements

The undersigned certifies, to the best of his or her knowledge and belief, that:

(1) No federal appropriated funds have been paid or will be paid, by or on behalf of the undersigned, to any person for influencing or attempting to influence an officer or employee of any agency, a Member of Congress, an officer or employee of Congress, or an employee of a Member of Congress in connection with the awarding of any federal contract, the making of any Federal grant, the making of any Federal loan, the entering into of any cooperative agreement, and the extension, continuation, renewal, amendment, or modification of any Federal contract, grant, loan, or cooperative agreement.

(2) If any funds other than Federal appropriated funds have been paid or will be paid to any person for influencing or attempting to influence an officer or employee of any agency, a Member of Congress, an officer or employee of Congress, or an employee of a Member of Congress in connection with this Federal contract, grant, loan, or cooperative agreement, the undersigned shall complete and submit Standard Form-LLL, ''Disclosure of Lobbying Activities,'' in accordance with its instructions.

(3) The undersigned shall require that the language of this certification be included in the award documents for all subawards at all tiers including subcontracts, subgrants, and contracts under grants, loans, and cooperative agreements and that all subrecipients shall certify and disclose accordingly.

This certification is a material representation of fact upon which reliance was placed when this transaction was made or entered into. Submission of this certification is a prerequisite for making or entering into this transaction imposed by section 1352, Title 31, U.S. Code. Any person who fails to file the required certification shall be subject to a civil penalty of not less than $10,000 and not more than $100,000 for each such failure.

| AUTHORIZED ORGANIZATIONAL REPRESENTATIVE | SIGNATURE | DATE |
|---|---|---|
| NAME | | |

| TELEPHONE NUMBER | ELECTRONIC MAIL ADDRESS | FAX NUMBER |
|---|---|---|
| | | |

*SUBMISSION OF SOCIAL SECURITY NUMBERS IS VOLUNTARY AND WILL NOT AFFECT THE ORGANIZATION'S ELIGIBILITY FOR AN AWARD. HOWEVER, THEY ARE AN INTEGRAL PART OF THE INFORMATION SYSTEM AND ASSIST IN PROCESSING THE PROPOSAL. SSN SOLICITED UNDER NSF ACT OF 1950, AS AMENDED.

# COVER SHEET FOR PROPOSAL TO THE NATIONAL SCIENCE FOUNDATION

| PROGRAM ANNOUNCEMENT/SOLICITATION NO./CLOSING DATE/if not in response to a program announcement/solicitation enter NSF 03-2 | FOR NSF USE ONLY |
|---|---|
| NSF 03-2 | NSF PROPOSAL NUMBER |
| FOR CONSIDERATION BY NSF ORGANIZATION UNIT(S) (Indicate the most specific unit known, i.e. program, division, etc.) | |
| EAR - INSTRUMENTATION & FACILITIES | |

| DATE RECEIVED | NUMBER OF COPIES | DIVISION ASSIGNED | FUND CODE | DUNS# (Data Universal Numbering System) | FILE LOCATION |
|---|---|---|---|---|---|
| | | | | 009214214 | |

| EMPLOYER IDENTIFICATION NUMBER (EIN) OR TAXPAYER IDENTIFICATION NUMBER (TIN) | SHOW PREVIOUS AWARD NO. IF THIS IS | IS THIS PROPOSAL BEING SUBMITTED TO ANOTHER FEDERAL AGENCY? YES ☐ NO ☒ IF YES, LIST ACRONYM(S) |
|---|---|---|
| 941156365 | ☐ A RENEWAL<br>☐ AN ACCOMPLISHMENT-BASED RENEWAL | |

| NAME OF ORGANIZATION TO WHICH AWARD SHOULD BE MADE | ADDRESS OF AWARDEE ORGANIZATION, INCLUDING 9 DIGIT ZIP CODE |
|---|---|
| Stanford University | Stanford University<br>651 Serra Street<br>Stanford, CA. 94305 |
| AWARDEE ORGANIZATION CODE (IF KNOWN): 0013052000 | |
| NAME OF PERFORMING ORGANIZATION, IF DIFFERENT FROM ABOVE | ADDRESS OF PERFORMING ORGANIZATION, IF DIFFERENT, INCLUDING 9 DIGIT ZIP CODE |
| PERFORMING ORGANIZATION CODE (IF KNOWN) | |

IS AWARDEE ORGANIZATION (Check All That Apply) (See GPG II.C For Definitions)
☐ SMALL BUSINESS ☐ MINORITY BUSINESS
☐ FOR-PROFIT ORGANIZATION ☐ WOMAN-OWNED BUSINESS
☐ IF THIS IS A PRELIMINARY PROPOSAL THEN CHECK HERE

TITLE OF PROPOSED PROJECT **Collaborative Research: Earthscope-Acquisition, Construction and Facility Management \(SAFOD\)**

| REQUESTED AMOUNT | PROPOSED DURATION (1-60 MONTHS) | REQUESTED STARTING DATE | SHOW RELATED PRELIMINARY PROPOSAL NO. IF APPLICABLE |
|---|---|---|---|
| $ 20,476,449 | 60 months | 07/01/03 | |

CHECK APPROPRIATE BOX(ES) IF THIS PROPOSAL INCLUDES ANY OF THE ITEMS LISTED BELOW
- ☐ BEGINNING INVESTIGATOR (GPG I.A)
- ☐ DISCLOSURE OF LOBBYING ACTIVITIES (GPG II.C)
- ☐ PROPRIETARY & PRIVILEGED INFORMATION (GPG I.B, II.C.6)
- ☐ HISTORIC PLACES (GPG II.C.9)
- ☐ SMALL GRANT FOR EXPLOR. RESEARCH (SGER) (GPG II.C.11)
- ☐ VERTEBRATE ANIMALS (GPG II.C.11) IACUC App. Date ________
- ☐ HUMAN SUBJECTS (GPG II.C.11) Exemption Subsection ________ or IRB App. Date ________
- ☐ INTERNATIONAL COOPERATIVE ACTIVITIES: COUNTRY/COUNTRIES INVOLVED (GPG II.C.9) ________
- ☐ HIGH RESOLUTION GRAPHICS/OTHER GRAPHICS WHERE EXACT COLOR REPRESENTATION IS REQUIRED FOR PROPER INTERPRETATION (GPG I.E.1)


| PI/PD DEPARTMENT | PI/PD POSTAL ADDRESS |
|---|---|
| Department of Geophysics | Mitchell Building, Room 360<br><br>Stanford, CA 943052215<br>United States |
| PI/PD FAX NUMBER: 650-725-7344 | |

| NAMES (TYPED) | High Degree | Yr of Degree | Telephone Number | Electronic Mail Address |
|---|---|---|---|---|
| PI/PD NAME: Mark D Zoback | PH.D. | 1975 | 650-725-9295 | zoback@pangea.stanford.edu |
| CO-PI/PD: William L Ellsworth | Ph.D | 1978 | 650-329-5020 | ellsworth@usgs.gov |
| CO-PI/PD: Stephen Hickman | PhD | 1989 | 650-329-4807 | hickman@usgs.gov |
| CO-PI/PD | | | | |
| CO-PI/PD | | | | |




TPI 6214457

# CERTIFICATION PAGE

## Certification for Authorized Organizational Representative or Individual Applicant:

By signing and submitting this proposal, the individual applicant or the authorized official of the applicant institution is: (1) certifying that statements made herein are true and complete to the best of his/her knowledge; and (2) agreeing to accept the obligation to comply with NSF award terms and conditions if an award is made as a result of this application. Further, the applicant is hereby providing certifications regarding debarment and suspension, drug-free workplace, and lobbying activities (see below), as set forth in Grant Proposal Guide (GPG), NSF 03-2. Willful provision of false information in this application and its supporting documents or in reports required under an ensuing award is a criminal offense (U. S. Code, Title 18, Section 1001).

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| AUTHORIZED ORGANIZATIONAL REPRESENTATIVE | SIGNATURE | DATE |
|---|---|---|
| NAME | | |

| TELEPHONE NUMBER | ELECTRONIC MAIL ADDRESS | FAX NUMBER |
|---|---|---|
| | | |

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# COVER SHEET FOR PROPOSAL TO THE NATIONAL SCIENCE FOUNDATION

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| | | | | **183277938** | |

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|---|---|---|
| **521362650** | ☐ A RENEWAL<br>☐ AN ACCOMPLISHMENT-BASED RENEWAL | |

| | |
|---|---|
| NAME OF ORGANIZATION TO WHICH AWARD SHOULD BE MADE<br>**Incorporated Research Institutions for Seismology** | ADDRESS OF AWARDEE ORGANIZATION, INCLUDING 9 DIGIT ZIP CODE<br>**Incorporated Research Institutions for Seismology**<br>**1200 New York Avenue, NW**<br>**Washington, DC. 20005** |
| AWARDEE ORGANIZATION CODE (IF KNOWN)<br>**4076212000** | |
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| PERFORMING ORGANIZATION CODE (IF KNOWN) | |

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☐ FOR-PROFIT ORGANIZATION ☐ WOMAN-OWNED BUSINESS
☐ IF THIS IS A PRELIMINARY PROPOSAL THEN CHECK HERE

TITLE OF PROPOSED PROJECT **Collaborative Research: Earthscope-Acquisition, Construction, and Facility Management \(Earthscope Facility Office\)**

| REQUESTED AMOUNT | PROPOSED DURATION (1-60 MONTHS) | REQUESTED STARTING DATE | SHOW RELATED PRELIMINARY PROPOSAL NO. IF APPLICABLE |
|---|---|---|---|
| $ **5,581,754** | **60** months | **07/01/03** | |

CHECK APPROPRIATE BOX(ES) IF THIS PROPOSAL INCLUDES ANY OF THE ITEMS LISTED BELOW

- ☐ BEGINNING INVESTIGATOR (GPG I.A)
- ☒ DISCLOSURE OF LOBBYING ACTIVITIES (GPG II.C)
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- ☐ SMALL GRANT FOR EXPLOR. RESEARCH (SGER) (GPG II.C.11)
- ☐ VERTEBRATE ANIMALS (GPG II.C.11) IACUC App. Date ______
- ☐ HUMAN SUBJECTS (GPG II.C.11) Exemption Subsection ______ or IRB App. Date ______
- ☐ INTERNATIONAL COOPERATIVE ACTIVITIES: COUNTRY/COUNTRIES INVOLVED (GPG II.C.9) ______
- ☐ HIGH RESOLUTION GRAPHICS/OTHER GRAPHICS WHERE EXACT COLOR REPRESENTATION IS REQUIRED FOR PROPER INTERPRETATION (GPG I.E.1)

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TPI 6218601

# CERTIFICATION PAGE

## Certification for Authorized Organizational Representative or Individual Applicant:

By signing and submitting this proposal, the individual applicant or the authorized official of the applicant institution is: (1) certifying that statements made herein are true and complete to the best of his/her knowledge; and (2) agreeing to accept the obligation to comply with NSF award terms and conditions if an award is made as a result of this application. Further, the applicant is hereby providing certifications regarding debarment and suspension, drug-free workplace, and lobbying activities (see below), as set forth in Grant Proposal Guide (GPG), NSF 03-2. Willful provision of false information in this application and its supporting documents or in reports required under an ensuing award is a criminal offense (U. S. Code, Title 18, Section 1001).

In addition, if the applicant institution employs more than fifty persons, the authorized official of the applicant institution is certifying that the institution has implemented a written and enforced conflict of interest policy that is consistent with the provisions of Grant Policy Manual Section 510; that to the best of his/her knowledge, all financial disclosures required by that conflict of interest policy have been made; and that all identified conflicts of interest will have been satisfactorily managed, reduced or eliminated prior to the institution's expenditure of any funds under the award, in accordance with the institution's conflict of interest policy. Conflicts which cannot be satisfactorily managed, reduced or eliminated must be disclosed to NSF.

### Drug Free Work Place Certification

By electronically signing the NSF Proposal Cover Sheet, the Authorized Organizational Representative or Individual Applicant is providing the Drug Free Work Place Certification contained in Appendix A of the Grant Proposal Guide.

### Debarment and Suspension Certification

(If answer "yes", please provide explanation.)

Is the organization or its principals presently debarred, suspended, proposed for debarment, declared ineligible, or voluntarily excluded from covered transactions by any Federal department or agency? Yes ☐ No ☒

By electronically signing the NSF Proposal Cover Sheet, the Authorized Organizational Representative or Individual Applicant is providing the Debarment and Suspension Certification contained in Appendix B of the Grant Proposal Guide.

### Certification Regarding Lobbying

This certification is required for an award of a Federal contract, grant, or cooperative agreement exceeding $100,000 and for an award of a Federal loan or a commitment providing for the United States to insure or guarantee a loan exceeding $150,000.

### Certification for Contracts, Grants, Loans and Cooperative Agreements

The undersigned certifies, to the best of his or her knowledge and belief, that:

(1) No federal appropriated funds have been paid or will be paid, by or on behalf of the undersigned, to any person for influencing or attempting to influence an officer or employee of any agency, a Member of Congress, an officer or employee of Congress, or an employee of a Member of Congress in connection with the awarding of any federal contract, the making of any Federal grant, the making of any Federal loan, the entering into of any cooperative agreement, and the extension, continuation, renewal, amendment, or modification of any Federal contract, grant, loan, or cooperative agreement.

(2) If any funds other than Federal appropriated funds have been paid or will be paid to any person for influencing or attempting to influence an officer or employee of any agency, a Member of Congress, an officer or employee of Congress, or an employee of a Member of Congress in connection with this Federal contract, grant, loan, or cooperative agreement, the undersigned shall complete and submit Standard Form-LLL, ''Disclosure of Lobbying Activities,'' in accordance with its instructions.

(3) The undersigned shall require that the language of this certification be included in the award documents for all subawards at all tiers including subcontracts, subgrants, and contracts under grants, loans, and cooperative agreements and that all subrecipients shall certify and disclose accordingly.

This certification is a material representation of fact upon which reliance was placed when this transaction was made or entered into. Submission of this certification is a prerequisite for making or entering into this transaction imposed by section 1352, Title 31, U.S. Code. Any person who fails to file the required certification shall be subject to a civil penalty of not less than $10,000 and not more than $100,000 for each such failure.

| AUTHORIZED ORGANIZATIONAL REPRESENTATIVE | SIGNATURE | DATE |
|---|---|---|
| NAME | | |

| TELEPHONE NUMBER | ELECTRONIC MAIL ADDRESS | FAX NUMBER |
|---|---|---|
| | | |

*SUBMISSION OF SOCIAL SECURITY NUMBERS IS VOLUNTARY AND WILL NOT AFFECT THE ORGANIZATION'S ELIGIBILITY FOR AN AWARD. HOWEVER, THEY ARE AN INTEGRAL PART OF THE INFORMATION SYSTEM AND ASSIST IN PROCESSING THE PROPOSAL. SSN SOLICITED UNDER NSF ACT OF 1950, AS AMENDED.

# EarthScope:
# Acquisition, Construction, Integration and Facility Management
# Project Summary

EarthScope is a scientific infrastructure initiative for new observational facilities that will address fundamental questions about the evolution of continents and the processes responsible for earthquakes and volcanic eruptions. The integrated observing systems that will comprise the EarthScope Observatory capitalize on recent developments in sensor technology and communications to provide Earth scientists with synoptic and high-resolution data derived from a variety of geophysical sensors. All data from the EarthScope Observatory will be openly available in real-time to maximize participation from the scientific community and to provide on-going educational outreach to students and the public.

The **intellectual merit** of EarthScope is derived from the coincidence of technological opportunity and scientific discovery. The design and implementation of the EarthScope Observatory has been shaped with input from a broad sector of the academic research community. Through a series of workshops and working groups, the research community, along with federal and state partners, has defined the tools they require to take the next steps in exploration of the fundamental processes that shape the structure and influence the deformation of continents.

The **broader impacts** of EarthScope will be achieved through applications in hazard assessment and resource management and through direct linkages with the EarthScope education and outreach program. While EarthScope is a national program, it will be installed and operated at a local level through interactions with literally hundreds of universities, schools and organizations across the nation. EarthScope will serve as a tool for communicating both scientific understanding, and perhaps as importantly, the nature of the scientific method. As EarthScope observatories are installed across the US, students and the public will be introduced to scientific questions and the role that their region plays in understanding the North American continent. Improved understanding of the natural environment is the first step towards improved land use, environmentally-sound development, and resiliency to natural hazards. The broad participation that is necessary for EarthScope to operate will provide clear pathways for underrepresented groups, especially in rural areas, to participate directly in a national experiment. Educational portals for EarthScope data will allow under-resourced schools to have equal access to state-of-the-art science and scientific infrastructure. EarthScope will provide a much-needed opportunity for students and the public to observe geological processes in real-time and to measure geological deformation within the time frame of an academic school year. EarthScope will provide the public with practical examples of how science advances as they see new data being collected and watch new theories being formulated and tested.

January 16, 2003

Dr. Herman Zimmerman
Director, Division of Earth Sciences
Geoscience Directorate
National Science Foundation
4201 Wilson Blvd.
Arlington, VA 22230

Dear Dr. Zimmerman

On behalf of the EarthScope Facilities Executive Committee we are pleased to submit a proposal entitled "EarthScope: Acquisition, Construction, Integration and Management" for funding through the Major Research Equipment and Facilities Construction Account."

As described in the attached "Note for Reviewers," this proposal is a comprehensive document that has been developed through lengthy interactions with a broad sector of the Earth science research community to support an exciting new initiative to study the structure and dynamics of the American continent.

To allow us to fully describe a project of this magnitude, we request your approval for deviation from the standard NSF format and restrictions on page length.

Yours sincerely


David W. Simpson
the IRIS Consortium

William Prescott
UNAVCO Inc

Mark Zoback
Stanford University


Approved: H. Zimmerman, Division of Earth Sciences
January 20, 2003

# EarthScope: Acquisition, Construction, Integration and Facility Management

## Note for Reviewers

This proposal for EarthScope has been developed by the broad community through numerous scientific workshops attended by hundreds of geoscientists representing over 50 universities and over a dozen federal and state agencies. We are submitting this proposal to the National Science Foundation's (NSF) Major Research Equipment and Facilities Construction (MREFC) Account, which "supports the acquisition, construction and commissioning of major research facilities and equipment that provide unique capabilities at the frontiers of science and engineering."

We propose that NSF fund the EarthScope facility through individual cooperative agreements with (1) the IRIS Consortium (for USArray), (2) UNAVCO (for PBO), and (3) Stanford University (for SAFOD). A fourth cooperative agreement, initially funded through IRIS (but with costs that are separately administered and identified) is proposed for funding the overall facility management structure including an EarthScope Facility Project Director. The proposal is only for the facility, as consistent with the intent and guidelines of NSF's MREFC Account.

The scientific research and educational opportunities associated with the facility will be funded to individuals and organizations through other proposals submitted to various agencies and programs including NSF's Research and Related Activities Program (R&RA), and the Education and Human Resources Program (EHR). As required by NSF guidelines, separate companion proposals are also being submitted to the R&RA Account for the associated Operations and Maintenance of each of the EarthScope facility components.

As this document is implicitly a proposal from the community as a whole, no individual citations have been referenced in the text. A list of the extensive scientific planning workshop reports and program plans that form the foundation of this proposal is appended to this note with a more extensive list at the end of Section III.

Section I of the proposal is an introduction and brief summary of the scientific rationale, including a specific discussion of EarthScope as an integrated observatory. The purpose of this section is not to repeat the justification for the science, as this has already been done for both the National Science Board and the National Academy of Sciences, but rather to demonstrate how the implementation plan will effectively meet both the scientific goals of the project and the broader infrastructure needs of the scientific and educational communities.

Section II contains detailed descriptions and budget summaries for the three EarthScope components: USArray, PBO, and SAFOD. These descriptions directly address the acquisition, installation, operation, and management of the three EarthScope elements and will form the basis for the individual cooperative agreements between NSF and IRIS, UNAVCO, and Stanford University. As described in each of the sections, the plans for USArray, SAFOD, and PBO have been carefully coordinated so as to maximize the overall scientific return.

Section III explains the overall budget and how data, ideas, and people will be networked. While the individual EarthScope components will be funded directly through cooperative agreements, a strong overall management structure has been developed to provide program coordination. The management structure is based on the principles of broad and equal community representation, while providing NSF with a single point of contact. Specifically, we view EarthScope's project management as an "enabling technology" to help NSF dollars go further.

As a national initiative, over 500 organizations across the nation will be involved in the operation, collection, and use of EarthScope data. EarthScope is developing partnerships with the USGS, NASA, state agencies, regional seismic networks, scientific organizations in Mexico and Canada, and other scientific and educational organizations. Letters outlining the roles of a few of these partnerships have been included within Section III.

It is the intended policy of EarthScope that all data will be openly available without restriction, cost, or delay to maximize participation from the scientific community and to provide on-going educational opportunities for students at all grade levels. EarthScope's data policy, however, extends beyond the physical distribution of data. In all cases, when we talk about making data accessible, we mean making it accessible both physically and intellectually. In particular, we are committed to making EarthScope data available for non-specialists, non-scientists, educators, and students at all levels.

Our commitment to both the physical and intellectual distribution of data allows for a strong interface between the EarthScope facility that is being developed under the MREFC account and the separately funded education and outreach program that will exploit this facility. As EarthScope observatories are installed across the nation, students and the public will be introduced to scientific questions and the role that their region plays in understanding the formation of the North American continent. EarthScope will enable a broad range of students and the public to participate in a national experiment that is going on in their own backyard, and for the first time to observe and measure geological processes within the time frame of an academic school year.

The EarthScope facility has been proposed by the scientific community and approved by the National Science Board on the basis of the many fundamental discoveries that we expect to make about the structure and evolution of the continent, and the nature of earthquakes and volcanoes. Although it is not included within our proposals, one can not help but think that perhaps an equally exciting outcome of this project will be the discoveries that at this point remain unpredictable.

Community documents that have guided the development of this proposal include:

- EarthScope Project Plan
  www.earthscope.org/assets/es_proj_plan_lo.pdf
- EarthScope Workshop Report
  www.earthscope.org/assets/es_wksp_mar2002.pdf
- EarthScope Education and Outreach Program Plan
  www.earthscope.org/assets/es_eando_lo.pdf
- National Research Council's Review of EarthScope Integrated Science
  www.nap.edu/books/0309076447/html

# EarthScope

## Acquisition, Construction, Integration and Facility Management

A Collaborative Proposal to the National Science Foundation

Major Research Equipment and Facilities Construction Account


On behalf of the EarthScope Facilities Executive Committee:

- David Simpson, IRIS and EarthScope Project Director
- Göran Ekström, IRIS Board, Harvard University
- Steve Hickman, SAFOD team, USGS
- William Prescott, UNAVCO, Inc.
- Paul Silver, UNAVCO Board, Carnegie Institution of Washington
- Mark Zoback, SAFOD team, Stanford University

From:

- the IRIS Consortium for USArray
  David Simpson, Project Director
- UNAVCO, Inc. for the Plate Boundary Observatory
  William Prescott, Co-Project Director
- Stanford University for the San Andreas Fault Observatory at Depth
  Mark Zoback, Co-Project Director


| | |
|---|---|
| Submitted | as a Collaborative Proposal |
| Funded | as four Cooperative Agreements from NSF to IRIS, UNAVCO and Stanford |
| Managed | through the EarthScope Facilities Executive Committee |
| Linked | to the UNAVCO and IRIS Boards, the SAFOD Project Team and the EarthScope Science and Education Committee |

# Table of Contents

# Part I. Science Needs and Project Overview

# 1. Project Summary

EarthScope is a new Earth science initiative that will dramatically advance our physical understanding of the North American continent by exploring its three-dimensional structure in space and time. Many fundamental aspects of continental structure and dynamics, including those responsible for major hazards such as earthquakes and volcanic eruptions, have resisted clear understanding. In part, this is because most major Earth processes act, and interact with one another, on much larger and longer scales than are accessible to a single individual or discipline. By integrating scientific information derived from geology, seismology, geodesy, and remote sensing, EarthScope has the potential to reveal the detailed structure and properties of the North America at depth, to monitor plate deformation at a continental scale, and to directly study the processes at depth associated with earthquakes on the San Andreas fault.

EarthScope's seismology, geodesy, and remote sensing observational facilities will be linked through high-speed, high-performance computing and telecommunications networks. The new facilities build on existing strengths in these fields, as well a strong tradition of excellence in field observations and laboratory research in the broader Earth sciences. EarthScope's coupled facility components include:

- USArray (United States Seismic Array): Continental scale, portable seismic arrays will map the structure and composition of the continent and the underlying mantle at high resolution;
- SAFOD (San Andreas Fault Observatory at Depth): A geophysical observatory within the active San Andreas Fault will measure subsurface conditions that give rise to earthquakes and deformation in the crust;
- PBO (Plate Boundary Observatory): A fixed array of GPS receivers and strainmeters will map ongoing deformation of the western half of the continent with a resolution of one millimeter or better over regional baselines, and geologic and paleoseismic investigations will examine the strain field over longer time scales; and
- InSAR (Interferometric Synthetic Aperture Radar): A remote-sensing technique that will provide spatially continuous strain measurements over wide geographic areas with decimeter to centimeter resolution.

The overall EarthScope project has been developed jointly by the scientific community and the National Science Foundation (NSF), in partnership with other science and mission-oriented agencies including the U.S. Geological Survey (USGS) and the National Aeronautics and Space Administration (NASA), and with strong links to existing regional networks and state-based agencies. This proposal to NSF's Major Research Equipment and Facilities Construction (MREFC) program is for acquisition and installation of EarthScope's first three elements: USArray, SAFOD, and PBO. Plans for a dedicated satellite for EarthScope's InSAR component are being developed separately.

The EarthScope facilities, combined with support for integrated Earth science research and education, provide a unique framework for basic and applied geological research across the United States and North America. EarthScope will address scientific targets in a number of critical areas of active research, each with several fundamental questions that still need to be solved:

- Fault properties and the earthquake process. How do earthquakes start, rupture and stop? How does strain accumulate and how is it released at the boundaries (and interior) of the North American plate? What structural and geological factors give rise to intraplate regions of seismic hazard such as the New Madrid zone?

- Fluids and magmas in the crust and upper mantle. How can better methods be developed for the prediction of volcanic eruptions and hazard mitigation? How does magma originate and how is it transported in the subsurface?
- Crustal strain transfer. What kinds of transient movements occur at depth? How does crust and mantle rheology vary with depth and influence deformation? How does it vary near active fault zones and affect the earthquake process? How do faults interact with one another? What is the state of stress in the lithosphere?
- Convergent margin processes. What is the nature of the plate boundary megathrusts in the Pacific Northwest and Alaska and how does it affect the seismic cycle? What is the structure of the deeper slab and how does it affect earthquakes and the overall subduction process? How is strain partitioning accomplished in the forearc and what controls it?
- Large-scale continental deformation. What are the spatial and temporal scales of intraplate deformation? What is the lithospheric strength profile and what controls it? What is the composition of the lithosphere and how are fluids distributed through it?
- Continental structure and evolution. What is a continent? How does continental lithosphere form? How are continental structure and deformation related?
- Deep Earth structure. How is the evolution of continental lithosphere related to upper mantle processes? How and where are forces generated in the upper mantle and how and where are they transferred to the crust? What is the nature of the lowermost mantle?

With EarthScope, it will no longer be necessary to limit the study of these questions to a single approach or technique. EarthScope's seismic and magnetotelluric component (USArray) will observe both detailed seismicity and crust/mantle structure. EarthScope's geodetic components (PBO) will measure surface motions at a variety of spatial and temporal scales. Deep drilling into the San Andreas fault (SAFOD) will directly determine stress conditions and rock properties in the seismogenic zone of a major fault and observe *in situ* what happens before, during, and after crustal earthquakes. The combination of these direct measurements with supporting geological, geochronological, geochemical, experimental, and theoretical studies can be expected to provide the clearest picture yet of the dynamic actions of our home continent. EarthScope thus offers the potential for a decade-long effort of unprecedented discovery and a model for a future of truly integrative multidisciplinary research in the solid Earth sciences.

EarthScope resources will be accessible to the entire scientific and educational communities. Data acquired from the new observational facilities will be transmitted in near real-time to central processing facilities and made freely and openly available to the research community, government agencies, educators, and the public and private sectors. End users also will have on-line access to software that will aid in data integration, manipulation, and visualization. EarthScope provides an excellent opportunity to improve science literacy in the United States through a comprehensive education and outreach program extending across the country and continuing throughout and beyond the lifetime of the program. Earth science naturally integrates fundamental concepts in mathematics, physics, chemistry, and biology. EarthScope will capitalize on the public's interest in earthquakes and volcanoes by demonstrating how active geologic processes shape our modern environment and concentrate natural resources. EarthScope has the potential to make these subjects relevant on a region-by-region basis as continental-scale results emerge, including both overarching and regional scientific issues as well as links between science and society.

Implementation, operation, and maintenance of EarthScope's USArray, PBO, and SAFOD facilities will be carried out under the direction of three community-based organizations: the IRIS Consortium, UNAVCO Inc., and Stanford/USGS. Each of these organizations has well-established management and technical staff, a solid mechanism to incorporate input from the user community, and a demonstrated commitment to operating community facilities. An EarthScope Facilities Office, including an EarthScope Facilities Executive Committee and EarthScope Facilities Project Director, will serve as the primary operational point of contact with NSF and the user community. The office will coordinate the component facilities and interact with NSF to ensure that the EarthScope project remains in compliance with NSF policies and procedures and is on-track and on-budget. This EarthScope Facilities Office will also work closely with the EarthScope Science and Education Committee, composed of representatives from the Earth science community at large, to foster science integration, education, and outreach, and ensure that the facilities remain responsive to the evolving needs of the research community.

EarthScope is a set of integrated observational systems of unprecedented precision that will provide data linking the surface expression of North America to the forces at work in the interior of our planet.

# 2. EarthScope Overview

## 2.1. Scientific Needs and Opportunities

The development of plate tectonic theory during the last half-century provided geoscientists with a framework for explaining, to first order, the structure of continents, the origin of mountain belts, and the distribution of earthquakes and volcanoes. Despite the elegance and utility of this paradigm, important questions concerning the active processes that deform continents remain unanswered. For example, while we know that continental crust grows progressively outward, we know little about the driving mechanism of plate tectonics, how surface features relate to structural, compositional, and thermal differences in Earth's interior, or how plate tectonic stresses are transferred to individual faults.

Plate tectonic theory was built upon a diverse set of global observations from which plate motions could be inferred rather than from direct measurements of oceanic and continental crustal displacements. Although we have made major progress over the past decade in understanding how faults rupture and what ground motions earthquakes generate, our understanding of what controls earthquake size, why great earthquakes occasionally strike plate interiors, and when and where the next major events are likely to occur remains remarkably incomplete. Moreover, the rules that govern plate motion do not apply, in simple fashion, to broad plate boundary zones such as western North America from the Rocky Mountains to the Pacific Ocean, where strain is distributed and inhomogeneous.

EarthScope offers an opportunity to observe and measure Earth deformation on a human time scale and continental spatial scale, permitting us to decipher the cause and effect of these plate movements. Measuring crustal motions and how those motions are communicated across plates will allow us to examine Earth at scales commensurate with geologic processes. These opportunities arise now as the result of a number of critical factors:

- Development of high-precision instruments capable of being placed in remote locations for extended periods of time;
- Availability of radio and satellite telemetry that allows remote instruments to communicate directly and constantly with operational support bases;
- An expanded capability for drilling, sampling, and taking measurements in active fault zones and the ability to instrument these holes to extract key information on the physical conditions within earthquake nucleation zones;
- Widespread computer networks that bring real-time data to the desktop and are capable of connecting scientists and educators across the country into a united research and educational enterprise;
- Analytical improvements in geochronology that provide both higher precision and application to a wider age range of events;
- Expanding data archival systems capable of storing and manipulating huge data streams arriving from large instrument arrays;
- A mature national infrastructure of Earth science organizations and consortia that have developed considerable experience in managing facilities similar to those in EarthScope.

EarthScope facilities will use these new techniques, approaches, and data technologies to provide a framework for broad, integrated studies across the Earth sciences. The new USArray, SAFOD, and PBO observational systems will provide direct observations of the spatial distribution and evolution of plate-boundary deformation, the space-time pattern of earthquake occurrence, the initiation and rupture sequence of earthquakes, and the dynamics of magma rise, intrusion, and eruption. In addition to advancing our understanding of earthquake and volcano hazards, EarthScope elements will contribute to a number of important problems in continental geodynamics and tectonics. These problems include determining the mechanisms of continent formation and breakup, relationship between crustal tectonic provinces and upper mantle structure, rheological stratification and lateral heterogeneity in the lithosphere, role of fluids (magmas, hydrothermal, meteoric) in the crust, intraplate stress distribution and its relationship to modern structures and seismicity, development of dynamic topography, and feedbacks between surficial and tectonic processes.

EarthScope also provides new opportunities to engage in integrated studies of whole systems. For example, with coordinated geological, geochemical, and geodetic studies, EarthScope's new observational facilities will allow study of the continental arc system in the Cascades from the subducting slab at their base to the volcanoes at their surface, mapping out magmatic plumbing systems and modification of the lithosphere through magmatic and accretional processes; examination of the deep roots of the North American craton and paleotectonics by which the craton was formed; examination of both ancient and modern orogens and rifts to explore the variability in continental tectonics and the role of the mantle lithosphere during orogenesis and rifting.

Integrating geology, geochronology, and geophysics within EarthScope will also provide us with an approach to investigate the structure of the North American continent in four dimensions. Understanding a particular geodynamic process and predicting its behavior requires knowledge of Earth materials, rates and magnitudes of motion, and the structures on which the motion is taking place. Satellite-based interferometric synthetic aperture radar can map decimeter- to centimeter-level deformation due to strain buildup and release along faults, magma inflation of volcanoes, and ground subsidence over areas tens to hundreds of kilometers wide. Moreover, these images of the strain field complement even more precise ground-based arrays of continuously operating GPS receivers with millimeter precision over baselines of thousands of kilometers. For example, GPS arrays can be used to map long-term strain rates across plate boundaries, such as in western United States, and short-term deformations associated with earthquakes and volcanoes. Strainmeters, the most sensitive of the geodetic techniques, can be used to detect any pre-event transients associated with these potentially catastrophic phenomena. Finally, geologic and paleoseismic investigations extend the time dependence of dynamic geosystems back in time, providing a baseline with which to compare modern kinematic data.

The next major advances in our understanding of how the dynamic Earth works, and how humankind can best deal with both the beneficial resources and the dramatic hazards Earth provides, must come by expansion of our observational network to the scale of plate tectonics. EarthScope will provide this step for the continental United States. A national program on the scale of EarthScope, integrating geologic, geodetic, seismological, and remote-sensing data from continent-wide observation systems, will catalyze solid Earth science research in the United States and provide a new view of the North American continent and its active tectonic environment. Moreover, the scientific and organizational structure underlying this interdisciplinary effort can serve as a national model for Earth science studies in continental dynamics.

# 3. EarthScope Facility Components

## 3.1. USArray: United States Seismic Array

USArray data will dramatically improve the resolution of seismic images of the continental lithosphere and deeper mantle. EarthScope scientists will integrate these images with a diversity of geological data to address significant unresolved issues of continental structure, evolution, and dynamics. A hierarchical design achieves imaging capabilities that span the continuous range of scales from global, to lithospheric and crustal, to local. The core of USArray is a transportable telemetered array of 400 broadband seismometers designed to provide real-time data from a regular grid with dense and uniform station spacing of ~70 km and an aperture of ~1400 km. The array will record local, regional, and teleseismic earthquakes, producing significant new insights into the earthquake process, and providing resolution of crustal and upper mantle structure on the order of tens of kilometers and increasing the resolution of structures in the lower mantle and at the core-mantle boundary. The Transportable Array will roll across the country with 1-2 year deployments at each site. Multiple deployments will cover the entire continental United States over a period of 8-10 years. When completed, this will provide unprecedented coverage for 3-D imaging from ~2000 seismograph stations. While the initial focus of USArray is coverage within the United States, extensions of the array into neighboring countries and onto the continental margins in collaboration with scientists from Canada, Mexico, and the ocean science community would be natural additions to the initiative.

An important second element of USArray is a pool of ~2400 portable instruments (a mix of broadband, short period, and high-frequency sensors) that can be deployed using flexible source-receiver geometries. These instruments will allow for high-density, shorter-term observations, using both natural and explosive sources, of key targets within the footprint of the larger Transportable Array. Many important geologic targets are amenable to investigation with the Flexible Array including: the depth

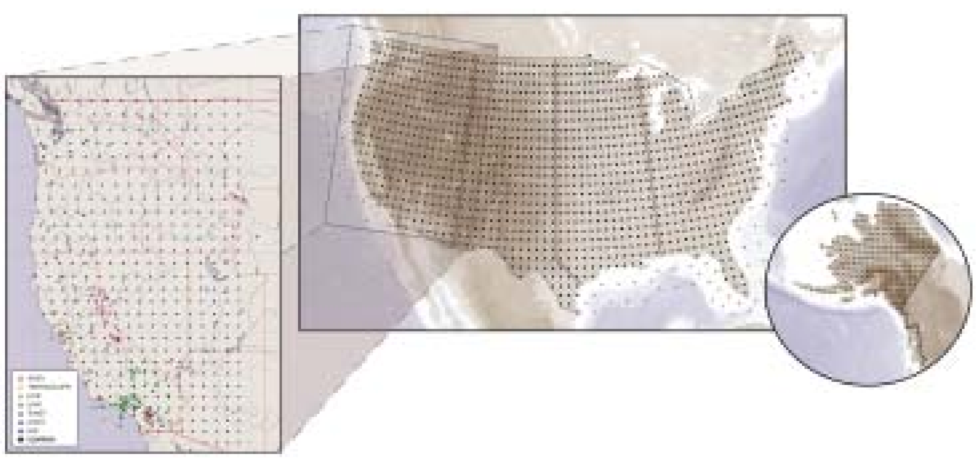


Figure I-1. At the core of USArray will be a transportable array of 400 instruments that will gradually roll across the entire United States over a ten-year period, making observations for one to two years at some 2000 sites. A permanent network of approximately 120 stations will provide long-term continuity, linking together data from the temporary deployments. Additional high-resolution instruments will permit special experiments in areas of particular geological interest.

extent of faults, magma chamber dimensions beneath active volcanoes, the relationship between crustal tectonic provinces and mantle structure, the shape of terrane boundaries, the deep structure of sedimentary basins and mountain belts, and the structure and magmatic plumbing of continental rifts. Linked with coordinated geological, geochemical, and geodetic studies, this USArray component can address a wide range of problems in continental geodynamics, tectonics, and earthquake processes. Examples include imaging the continental arc system in the Cascades from slab to edifice, examining the deep roots of the North American craton and paleotectonics by which the craton was formed, imaging both ancient and modern orogens and rifts to explore variability in continental tectonics, identifying the role of the mantle lithosphere during orogenesis and rifting, and unraveling the relationship between deep processes and surface features.

A third element of USArray is the addition of 40 permanent stations in an augmentation of the National Seismic Network, operated by the USGS. Relatively dense, high-quality observations from a continental network of approximately 130 stations, with uniform spacing of 300-350 km, is important for tomographic imaging of deep Earth structure, providing a platform for continuous long-term observations, and establishing fixed reference points for calibration of the Transportable Array. This Backbone Network component of USArray will be coordinated with the USGS and complements the initiative underway at the USGS to install an Advanced National Seismic System (ANSS).

## 3.2. SAFOD: The San Andreas Fault Observatory at Depth

SAFOD is a project designed to directly monitor a creeping and seismically active fault zone at depth, to sample fault zone materials (rock and fluids), and to measure a wide variety of fault-zone properties. A 4-km-deep hole will be drilled through the San Andreas fault zone close to the hypocenter of

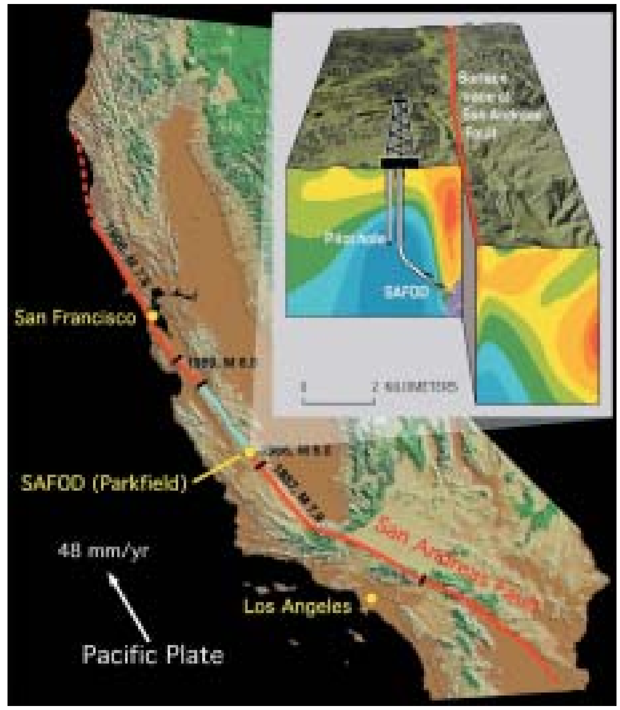



Figure I-2. Deep within an active fault zone, the San Andreas Fault Observatory at Depth (SAFOD) will measure changes in rock properties before, during, and after earthquakes. Linked to other EarthScope measurements at the surface, these direct observations will, for the first time, monitor how an active fault and its environment respond to regional and local changes in stress. Recorded over a decade, this combination of measurements will provide important new insights on earthquake nucleation and rupture.

the 1966 M~6 Parkfield earthquake, where the San Andreas fault slips through a combination of small- to moderate-magnitude earthquakes and aseismic creep (Figure I-2).

Even after decades of intensive research, numerous fundamental questions about the physical and chemical processes acting within the San Andreas and other major plate-bounding faults remain unanswered. SAFOD will provide new insights into the composition and physical properties of fault zone materials at depth, and the constitutive laws governing fault behavior. It also will provide direct knowledge of the stress conditions under which earthquakes initiate and propagate. Although it is often proposed that high pore fluid pressure exists within the San Andreas fault zone at depth and that variations in pore pressure strongly affect fault behavior, these hypotheses are unproven and the origin of overpressured fluids, if they exist, is unknown. As a result, myriad untested and unconstrained laboratory and theoretical models related to the physics of faulting and earthquake generation fill the scientific literature. Drilling, sampling and downhole measurements directly within the San Andreas fault zone will substantially advance our understanding of earthquakes by providing direct observations on the composition, physical state, and mechanical behavior of a major active fault zone at hypocentral depths. In addition to retrieval of fault zone rock and fluids for laboratory analyses, intensive downhole geophysical measurements and long-term monitoring are planned within and adjacent to the active fault zone. Observatory-mode monitoring activities will include near-field, wide-dynamic-range seismological observations of earthquake nucleation and rupture and continuous monitoring of pore pressure, temperature, and strain during the earthquake cycle. Directly evaluating the roles of fluid pressure, intrinsic rock friction, chemical reactions, in situ stress and other parameters in the earthquake process will provide opportunities to simulate earthquakes in the laboratory and on the computer using representative fault zone properties and physical conditions.

## 3.3. PBO: Plate Boundary Observatory

The Plate Boundary Observatory (PBO) is a geodetic observatory designed to study the three-dimensional strain field resulting from plate boundary deformation. This requires that plate boundary deformation be adequately characterized over the maximum ranges of spatial and temporal scales common to active continental tectonic processes. The geodetic instrumentation must provide: (a) sufficient coverage of the plate boundary zone so as to capture the secular tectonic component, (b) appropriate station density for detecting localized (e.g., seismic or magmatic) phenomena, and (c) the necessary bandwidth (hours to decades) to detect plausible transient phenomena ranging from fast and slow earthquakes to interseismic strain buildup and post-seismic viscoelastic relaxation.

To address a range of scientific issues including plate boundary dynamics, active tectonics, and seismic and magmatic processes, a continuously recording, telemetered strain observatory will be installed along the Pacific/North American plate boundary, building upon and greatly expanding

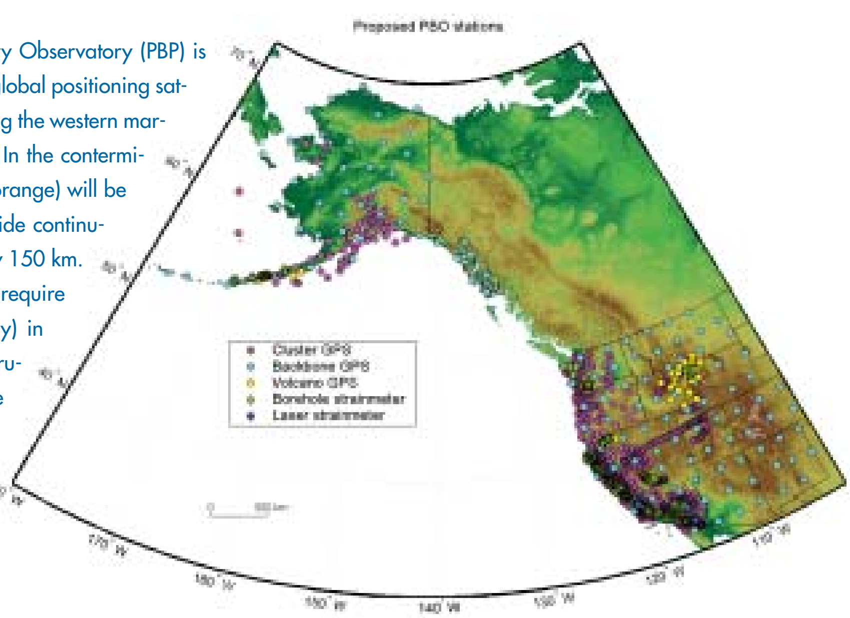



Figure I-3. The backbone of the Plate Boundary Observatory (PBP) is an array of permanent stations equipped with global positioning satellite receivers and strainmeters, extending along the western margin of North America from Mexico to Alaska. In the conterminous United States and Alaska, existing sites (orange) will be augmented with 800 new sites (black) to provide continuous observations at a spacing of approximately 150 km. Complete coverage of the plate boundary will require collaborative programs to install stations (gray) in Canada and Mexico. Clusters of additional instruments will be installed on volcanoes, along the San Andreas fault system and near other major faults, to provide increased resolution in areas of rapid deformation.

the capabilities of the SCIGN, BARD, EBAR, NBAR, SBAR, PANGA, and AKDA specialized geodetic networks.

PBO will consist of four elements. The first is a backbone network of GPS receivers to provide a long-wavelength, long-period synoptic view of the entire plate boundary zone. The network will extend from Alaska to Mexico and from the west coast to the eastern edge of the North American Cordillera. Receiver spacing will be approximately 200 km, and the data will be integrated with InSAR data (see next section), when and where available, to define the regional component of the strain field.

PBO's second element consists of focused dense deployments in tectonically active areas, such as along the San Andreas fault system and around young magmatic systems. These regions require the greatest temporal resolution, and thus integrated networks of borehole strainmeters and GPS receivers will be deployed around these features with instrument spacing of 5-10 km. On the order of 1000 observing sites (5 long base strainmeters, 175 borehole strainmeters and 800 GPS receivers) will be required to cover the most active tectonic regions of western conterminous United States and southern Alaska, and about 100 GPS receivers to complete the backbone network.

PBO's third element is a pool of 100 portable GPS receivers for temporary deployment for densifying areas not sufficiently covered by continuous GPS. These systems will provide observations in unmonitored regions and provide a rapid response capability to detect strain transients following earthquakes and volcanic eruptions.

The fourth element of PBO will include the establishment of a national center for the storage and retrieval of digital imagery and geochronological facilities to support geologic and paleoseismic studies in the PBO.

## 3.4. InSAR: Interferometric Synthetic Aperture Radar

Although not included under this request for MREFC support, an Interferometric Synthetic Aperture Radar (InSAR) satellite mission would provide spatially continuous strain measurements over wide geographic areas. Plans are underway to develop a dedicated InSAR mission as an integral part of the EarthScope Observatory. This new capability will enable: (a) synoptic mapping of surface displacements before, during, and after earthquakes or volcanic eruptions, (b) imaging the time evolution of these geologic systems, providing unique insights into the mechanics of fault loading and earthquake rupture, (c) mapping of strain accumulation across broad tectonic zones, potentially highlighting zones of strain concentration, (d) inferences to be made about the sources, migration, and dynamics of magma movement through a volcanic system that may lead to an eruption, and (e) improvements in our understanding of the rheology of the crust and upper mantle. InSAR images will also provide a tool for mapping subsidence induced by petroleum production and ground water withdrawal, as well as for studying poroelastic effects induced by fault movements and other forms of crustal deformation.

InSAR will be an important contributor to PBO in that spatially continuous, but intermittent, InSAR images complement continuous GPS point measurements. A dedicated InSAR mission would greatly enhance PBO science objectives. The optimum characteristics are dense spatial (100 m) and temporal (every 8 days) coverage of the entire plate boundary with vector solutions accurate to 1 mm over all terrain types. Existing and planned international SAR missions cannot deliver the required data. Also, free and open distribution of these data to the scientific community is fundamental to the rapid progress of InSAR and PBO science. This has not been the case for previously planned and existing SAR missions. Thus, recognizing the leading role NASA will play in a possible SAR mission, and the long lead time for mission development, the Earth sciences community has started to work with NASA, NSF, and the USGS to begin planning for a science-driven mission.

## 3.5. Synergy Among EarthScope Components

The design of the EarthScope Observatory, both the choice of instrumentation and deployment strategy, follows directly from the scientific questions that we seek to solve. The primary measurements are seismic ground motion and crustal deformation at temporal scales ranging from fractions of a second to millennia, and spatial scales from meters to thousands of kilometers. The design of the observatory and its components are not constrained by technical limitations of the sensor elements. Rather, the design is primarily constrained by the tradeoff in cost and logistical complexity related to making the multitude of observations at the necessary spatial and temporal resolution over the entire continent. The observatory has been designed to maximize the scientific return, while remaining tractable with respect to cost and logistics. The science and design characteristics have been the subject of several workshops and form the basis of the implementation plans discussed in Part III of this proposal.

Each scientific question has its own set of required observations, and most of these use observations from at least two Earthscope Observatory components. For example, constraining the evolution and dynamics of the North American continent requires the synoptic imaging of the continental lithospheric and underlying mantle seismic velocity over the entire continent, so as to provide first-order estimates of regional-scale variations in structure and physical properties. High-resolution seismic imaging of the crust and mantle must be linked with surface manifestations of these deep structures, through detailed geological analyses. Actively deforming westernmost North America offers a special opportunity to observe the processes that change the continents in real time. In this case, geodesy provides a new class of observations. In particular, measurements of decadal surface deformation will provide a detailed map of the present-day strain-rate field over the entire tectonically active plate boundary zone. Detailed characterization of post-seismic deformation of large earthquakes (or other known sources of stress) provides a means of estimating vertical variations in the continent's rheology. Comparisons between decadal estimates of strain rate and geologic estimates of long-term (Holocene and Quaternary) strain rates provides a direct constraint on the recent evolution of western North America.

The study of magmatic processes necessitates an image of the magmatic system at depth, as well as the observation of transient deformation within the crust, transient deformation that is the direct result of the general movement of magma and associated fluids at depth, as well as a result of the eruption process. This requires the measurement of deformation with high spatial resolution at the surface (through GPS, borehole strainmeters and InSAR) and at depth (through observations of seismicity), the ability to measure strain transients with time constants ranging from seconds to decades, and the high-resolution seismic imaging of the magmatic system in the crust and upper mantle.

Of the scientific problems described earlier that can be addressed by the integrated Earthscope Observatory, we will use the study of earthquake physics as one example of how the design of the Earthscope Observatory yields a powerful collection of interconnected geophysical and geological observations. A significant increase in our understanding of the earthquake process requires detailed images of the fault system in the crust and upper mantle, a characterization of the interseismic (decadal and longer) strain field, deformation transients related to the occurrence of seismic events (at the surface and at depth), the history of faulting over several earthquake cycles, and the direct measurement of fault properties, such as stress and pore pressure.

The Earthscope Observatory provides a means of obtaining all of these observations. Our study of the San Andreas fault system illustrates this comprehensiveness. It is our primary natural laboratory for studying the earthquake process, because of its accessibility to observation and relatively high level of current knowledge. It is thus an area of concentrated EarthScope instrumentation. It constitutes the largest geodetic cluster contained within the observatory, it will also be the primary imaging target of USArray in western North America, and will be the site of SAFOD. It provides an illustration of how the EarthScope observatory has been designed, and how its components fit together.

Measuring earthquake-related deformation. The plate boundary zone across the San Andreas system is on the order of 100 km wide and contains from one to three primary active faults, with numerous lower-slip-rate faults. We seek to accurately resolve, through the deployment of GPS receivers, the decadal deformation associated with the various faults; this consideration has guided the proposed cross-fault station density. Observation of transient deformation requires both strainmeters and GPS receivers, which will be deployed in clusters along and across the fault system. To maximize event detection, these dense networks will be deployed on sections of the San Andreas fault system where slip rates are high and instrumentation can be located closest to zones of earthquake nucleation and aseismic slip. These point estimates of deformation will be augmented by broad-scale images of the fault system provided by InSAR.

Retrieving seismic images of the crust and mantle. It is essential to obtain a detailed seismic image of the San Andreas fault system. We expect that an entire suite of fault imaging studies will be conducted such as detailed tomographic images of the fault zone as well as fault-produced offsets in the Moho and other reflectors (through active source seismic experiments). Regional studies of the structure of the deeper crust and upper mantle beneath and near the fault system will provide important constraints on variations in crustal composition and rheology that are essential to understanding the driving mechanism for the geodetically defined deformational field.

Measuring stress/material properties of the seismogenic crust. While we can accurately measure deformation at the surface, and observe seismicity at depth as a proxy for deformation, we ultimately seek the physical basis for these variations, and the stresses that produce fault-related deformation. In order to link deformation to stress requires knowledge of fault rheology. SAFOD provides such information as well as direct measurements of seismogenic stress.

Paleoseismology. A full understanding of the earthquake process requires constraints on the history of deformation over several earthquake cycles. An intensive paleoseismic component of Earthscope will provide this essential, long-term history of the faulting process.

Seismicity. The EarthScope Observatory will greatly benefit from existing instrumentation systems within the Earthscope deployment region. One excellent example of this is observations of seismicity. Seismicity is currently the most direct constraint available regarding deformation occurring at seismogenic depths within the crust; these observations complement surface observations. Seismicity will be monitored in two ways: (1) three-component borehole seismometers will be deployed with each of the borehole strainmeters, providing some coverage in seismogenic and magmatically active areas, and (2) whenever possible, GPS receivers will be collocated with the existing regional seismic networks of the ANSS, so that detailed seismicity maps will be available wherever there are concentrations of geodetic instrumentation. There are nearly 600 sites where such collocation appears feasible and PBO and USArray are working closely with the USGS and regional networks to take full advantage of this opportunity.

# 4. Project Planning and Development

## 4.1. Planning Workshops

### Development of the USArray Initiative

Over the past few years, there has been discussion within the seismology community of the opportunities, both scientific and technical, for an initiative to improve the resolution at which we can image the structure of the continental lithosphere and mantle, and to merge seismological results with other Earth science investigations. At the same time, there is growing interest in the use of dense deployments of broadband seismometers to investigate deep Earth structure. These discussions culminated in a workshop in March 1999 in Albuquerque, NM. Over 90 Earth scientists, with representatives from academia, the USGS, regional seismic networks, and NSF, attended the workshop, jointly sponsored by NSF and the IRIS Consortium.

At the first USArray workshop, seismologists and geologists discussed the design and implementation of an ambitious plan to explore, image, and develop an integrated understanding of North American geology and deep Earth structure. Workshop participants helped define the technical components of the USArray facility, identified scientific goals, and discussed an operation and management scheme for the facility. The Albuquerque workshop led to substantial enthusiasm and momentum for USArray and increased recognition that this initiative should integrate geological and geophysical investigations into a single unified effort to best achieve its scientific goals.

The community held a second workshop in September 1999 in Houston, TX to integrate a diverse group of Earth scientists into the early planning stages of the USArray initiative to enhance its scientific goals, better define its multidisciplinary character, and identify ways in which USArray can best be used to advance Earth science research, education, and outreach. The workshop also included discussions of how the Earth science community can work together with NSF to enhance support for our research endeavors—through development of compelling scientific studies, through integrative community projects such as USArray, through clear statements of our long-term science goals, and through enhanced public appreciation for Earth science research. Workshop attendees provided NSF with a white paper (see www.EarthScope.org/usarray/usarray_assets/USArray_wtpaper.pdf) summarizing the results of the USArray workshops, which served as one component of the EarthScope planning process.

### Development of the PBO Initiative

The PBO initiative got its start in 1995 with two meetings, one at the Carnegie Institution of Washington, and another at the IRIS Annual Workshop. The focus of these meetings was to establish a comprehensive system for observing deformation along the Pacific-North American plate boundary. It was clear that a variety of first-order scientific questions required such a system, from the physics of earthquakes and magmatic systems to the evolution and dynamics of the plate boundary system. This initiative was discussed further at the IRIS instrumentation workshop in the fall of 1997. In January 1998, leaders of the geophysics community sent a letter to NSF advocating the establishment of a Plate Boundary Observatory.


Figure I-4. Top. A New View Into Earth, April 2001, 9 pp. This summary of the EarthScope project was written for general audiences. Bottom. A New View Into Earth: EarthScope Project Plan, October 2001, 36 pp. An overview of the EarthScope project, including descriptions of science themes, component observational systems, data management, education and outreach, and implementation plans. Go to www.earthscope.org/links_pubs/index.html to download a copy of these documents.

In response to increased community interest in the initiative, and with the encouragement of NSF, 160 participants attended the first PBO workshop in October 1999 (sponsored by NSF, USGS, NASA, SCEC, UNAVCO, IGPP-Scripps). The presentations and discussions at that meeting provided the basis for the PBO White Paper, published in March 2000. This document laid out the scientific justification and general deployment strategy for the PBO initiative (http://www.earthscope.org/pbo/related_pubs/rel_pubs.html). This effort was followed up by a second workshop in October 2000, attended by more than 120 participants (sponsored by NSF, USGS, NASA, SCEC, UNAVCO, IRIS). The primary goal of this second workshop was to develop a more focused deployment plan that would maximize PBO's scientific return. Participants accomplished this task in a novel way, by proposing, in advance of the meeting, the placement of instrumentation to address particular scientific problems. The workshop steering committee received more than 50 such mini-proposals (http://www.scec.org/pbo). They were judged on the basis of scientific merit by two panels, and with the assistance of representatives from NSF. The present deployment plan given in this proposal is the direct result of that process. At this meeting, participants also recommended that PBO should be managed by the UNAVCO Consortium. This recommendation forms the basis of the current PBO management plan.

There have been subsequent workshops which focused on specific PBP components. For example, the geological component (geoPBO), critical for understanding the long-term deformational history of the plate boundary, held a workshop in May 2001. In fall 2002, the community held a workshop on magmatic systems. Small workshops in March 2002 in Seattle, and May 2002 in La Jolla, ensured that there would be close collaboration with our Canadian and Mexican colleagues.

Through this series of workshops, the PBO initiative has benefited from the combined expertise of a broad segment of the geophysical and geological community. Guided by a dedicated steering committee over the last three years, this initiative now enjoys the enthusiastic support of the Earth science community.

## Development of the SAFOD Initiative

While the idea of drilling into the San Andreas fault has arisen many times over the past several decades, the SAFOD project had its origin in December 1992 with a workshop at the Asilomar Conference Center in Pacific Grove, California. The purpose of this workshop, attended by 113 scientists and engineers from seven countries, was to initiate a broad-based scientific discussion of the issues that could be addressed by drilling and experimentation within the San Andreas fault zone, to identify potential drilling sites, and to identify technological developments required to make this drilling possible. Soon after the Asilomar Conference, the SAFOD working group devised an experimental plan for SAFOD to penetrate the San Andreas fault zone at 4 km depth and at a place where the fault is currently slipping through a combination of small to moderate earthquakes and fault creep. By targeting an "active" patch of the fault, such an experiment allows us to address a number of important issues related to the physics of earthquake rupture nucleation and propagation and to the transition from creeping to locked fault behavior. Also, we can use the ongoing deformation and seismicity to tell us the precise location of the active trace of the fault where it is penetrated by the borehole—an important parameter in interpreting data and samples obtained from the fault zone.

Participants identified eighteen segments of the San Andreas fault system at the Asilomar Conference as being potentially suitable for fault-zone drilling. Starting in 1993 we then held three site-characterization workshops at the USGS in Menlo Park and one conference at the Marconi conference center in Marshall, California. The final site for the SAFOD experiment was then decided upon, when it became clear that the Middle Mountain site at Parkfield was the best place to conduct the proposed experiment because surface creep and abundant shallow seismicity allow us to accurately target the subsurface position of the fault. Also, there is a clear geologic contrast across the fault, with shallow granitic rocks on the west side of the fault and Franciscan melange on the east. The granitic rocks provide for good drilling conditions. Finally, this segment of the fault has been the subject of an extensive suite of investigations establishing its geological and geophysical framework and is centered within the most intensively instrumented part of a major plate-bounding fault anywhere in the world, as a consequence of the Parkfield Earthquake Prediction Experiment. A critical review of this experiment is the subject of the Hager Committee Report (1994) to the National Earthquake Prediction Evaluation Council, in which it was concluded that "Parkfield remains the best identified locale to trap an earthquake."

Once the Middle mountain area was selected as the optimum area for the project, a series of intensive geophysical and geological studies were performed to select the optimal drill site. These included a high-resolution seismic reflection survey, an active source MT profile, closely spaced aeromagnetic profiles were flown over the site area and dense gravity measurements were collected. Once these data were synthesized with geologic information a comprehensive model of the shallow crust in the likely drilling area was developed.

In June/July 2002 a successful 2-km-deep pilot hole was drilled at the site that was judged to be optimal for the possible location of SAFOD. Site preparation, drilling and logging costs for this project were provided by the International Continental Drilling Program (ICDP). Drilling was accomplished without appreciable difficulty, the geologic model developed for the site was confirmed, a series of geophysical measurements were obtained in the borehole and a vertical array of seismometers was deployed in the borehole.

## 4.2. Exploring Science Opportunities

Definition of targets and opportunities for EarthScope science was a key component of each of the early planning workshops during the evolution of EarthScope. The reports of these meetings provide a component-specific summary of the research needs that USArray, PBO, and SAFOD were designed to support. To continue to develop ways to most fully exploit the measurements provided by the various observational components of EarthScope, approximately 200 Earth scientists assembled in Snowbird, UT on October 10-12, 2001 for the first "pan-EarthScope" science workshop. Discussions in working groups centered on the ways that EarthScope could contribute to solving fundamental questions of continental structure and evolution, ranging in temporal scale from those events responsible for forming North America over the last 4 billion years to those sudden events that sweep away the concept of a "stable" Earth—the earthquakes, landslides, and volcanic eruptions that constitute substantial hazards to humanity. The report "Scientific Targets for the World's Largest Observatory Pointed at the Solid Earth" (Figure I-5) provides a broad-ranging examination of the major issues of continent formation and the factors controlling its current dynamic behavior, and explores the many ways in which EarthScope can contribute to answering these fundamental questions including discussion of what additional datasets, modeling efforts, and education and outreach are necessary to maximize the scientific return from EarthScope.

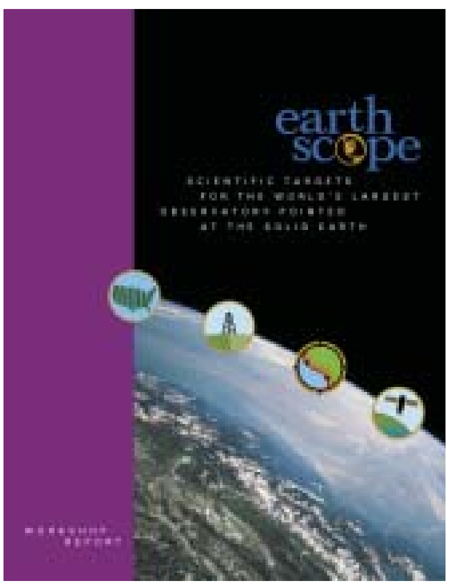



Figure I-5. EarthScope Workshop Report: Scientific Targets for the World's Largest Observatory Pointed at the Solid Earth, March 2002, 56 pp. This is a report of the workshop held in Snowbird, UT, and attended by 200 Earth scientists. The report summarizes the workshop discussions, divided according to the broad scientific themes. Go to www.earthscope.org/links_pubs/index.html to download a copy of this document.

## 4.3. Interagency and International Collaboration and Coordination

EarthScope is a multi-agency, national program with important roles being played by NSF, USGS, NASA, and other federal agencies. Partnerships are being developed with state agencies, regional seismic networks, organizations in Mexico and Canada, and the ICDP. EarthScope activities are built on a number of existing interactions among university research groups and federal agencies and a wide range of current and planned research projects involving numerous scientists at national and international institutions. In particular, resources from Earth observing and monitoring programs at the USGS and NASA will be extensively used to maximize EarthScope's scientific return.

As PBO instruments are installed and USArray systematically traverses the continent, there will be numerous opportunities for a wide variety of interactions between academic researchers and federal and state agencies involved in research, education, public policy, and resource assessment. Much of the EarthScope data and results will be of interest to state geologists in hazard evaluation (seismic, volcanic, landslides), and assessment of mineral and water resources. Lithospheric imaging will add to our fundamental knowledge about Earth structure and provide data directly to, and benefit from, state geological mapping projects. EarthScope—especially as manifested in USArray and PBO—is intended to provide an evolving regional framework for a broad spectrum of Earth science investigations.

The PBO array will depend on regional networks being installed or already in place—400 continuous GPS and 45 borehole strainmeters. Their installation was done with support from NSF, USGS, NASA, and the W.M. Keck Foundation. Support for operation and maintenance of these systems is currently being provided through a partnership of NSF, USGS, and NASA, and will continue as a contribution to PBO. A further NASA contribution is support of the International GPS Service (IGS), which provides precise satellite positions essential for PBO data analysis. The PBO community has been working with NOAA/National Geodetic Survey to formally develop GPS references as legal benchmarks for the surveying community in regions of active crustal deformation such as southern California. This invaluable civil-use concept will be applied to the entire PBO GPS array.

USArray's instrumentation and scientific goals complement initiatives underway by the USGS and state partners to install the Advanced National Seismic System (ANSS). The USGS is working with state and university partners to develop ANSS to meet mission requirements in earthquake hazard assessment and mitigation. A significant component of ANSS focuses on urban areas with high seismic hazard. USArray goals are to illuminate structure and understand dynamics of the lithosphere and deeper mantle, which requires densification of the USGS National Seismic Network (a part of ANSS) and uniform coverage of the continent. There is a clear synergy between ANSS and the requirements of the Backbone Network for USArray. The coordination between ANSS and USArray will create a single, integrated network of ~130 high-quality, permanent broadband seismic stations across the country to meet the goals of all constituencies. All data from this integrated network will be available in a single data stream to both communities. Coordination of these two initiatives is an excellent example of interagency cooperation and cost sharing and continues the long-standing working relationship between NSF, the USGS, and state agencies in the support of permanent seismic networks.

The SAFOD community has been working with USGS, various universities, LLNL, and Sandia to develop a prototype downhole instrument package that will be an integrated multiple sensor system within a single re-deployable module. A 3-km hole in Long Valley, California and a SAFOD pilot hole are being used as test sites for downhole instrument development. Together, SAFOD, PBO, and USArray instruments deployed in the region, in addition to the existing USGS facilities deployed at the surface, will result in an unparalleled and extraordinarily comprehensive earthquake monitoring system. The SAFOD project will be carried out in collaboration with, and with logistical support from, the ICDP. The ICDP is a consortium of nine countries engaged in a variety of types of scientific drilling projects around the world. The comprehensive data base system, real-time cuttings and gas monitoring capabilities and engineering expertise were quite valuable in the pilot hole experiment and will be extremely valuable in the SAFOD experiment.

While EarthScope is focused primarily on the development of facilities to probe the continental lithosphere of the United States, the structures and processes to be studied are not limited by geographical or political borders. Discussions have been initiated with Canada and Mexico to extend the observations north and south of the U.S. border and links to the oceanographic community are being pursued to provide offshore observations on the continental shelf and beyond. The Canadian Earth science community is completing a national project, Lithoprobe, that has served, in part, as a model for EarthScope. Collaborative U.S.-Canadian projects were carried out as part of Lithoprobe and provide a basis for future interactions. A recently funded project, "POLARIS," is based on scientific targets and technologies that are similar to USArray and discussions have already been held to combine resources and merge observations. Observations in Canada will be essential to a full study of the western North America plate boundary and Canadian representatives have been included in the planning workshops for PBO.

# 5. Management and Implementation

## 5.1. Management of Project Execution

The EarthScope facility management will oversee the installation and operation of the EarthScope facility as funded by NSF through the MREFC program under cooperative agreements with IRIS, UNAVCO, and Stanford University. The separate task of coordinating EarthScope science and education activities for NSF will occur through the EarthScope Science and Education Committee.

The management structure for the EarthScope facility is designed to ensure that the project is in compliance with NSF policies and procedures and federal regulations, and to be both representative and accountable to the community at large. It is based on the principles of broad and equal community representation for the major components of EarthScope, while providing NSF with a single point of contact.

The EarthScope facility will be managed by the EarthScope Facility Office, an independent legal organization with by-laws. Management of the EarthScope facilities will be vested in the EarthScope Facilities Executive Committee. The Executive Committee will be chaired by the EarthScope Facility Project Director. The EarthScope Facility Project Director will serve as the single point of contact for NSF on overall management of the EarthScope facility. The Project Director will submit quarterly reports and provide quarterly briefings to NSF, identifying progress made relative to the timelines and milestones identified in the EarthScope program plan. The Executive Committee will consist of seven members: the EarthScope Facility Project Director, the Principal Investigators of the USArray, PBO, and SAFOD programs, and a selected representative from the IRIS Executive Committee, the UNAVCO Board, and the SAFOD management team. The Executive Committee will perform on-going evaluations to determine progress against the Baseline Project Definitions. They will review the on-going management procedures, work breakdown schedules, milestones, and risk mitigation strategies. The Executive Committee will review any significant deviations from the original design plans and critical risk mitigation decisions, and make recommendations to NSF through the EarthScope Facility Project Director to ensure that the project remains on schedule and within cost and that it meets intended design goals and infrastructure needs of the scientific community.

## 5.2. Education and Outreach

Although the primary motivation for EarthScope is grounded in fundamental advances in scientific discovery, the initiative also provides a spectacular opportunity for a focused education and outreach program that will reach the general public, K-16 students and faculty, and Earth science professionals. EarthScope will capitalize on the public's natural curiosity about our dynamic planet by providing all Americans with new insights into how Earth works. The national scope of instrument deployments will provide education and outreach opportunities across the country for many years, while the local nature of the deployments will make the initiative's scientific investigations and discoveries relevant for educational efforts on a region-by-region basis.

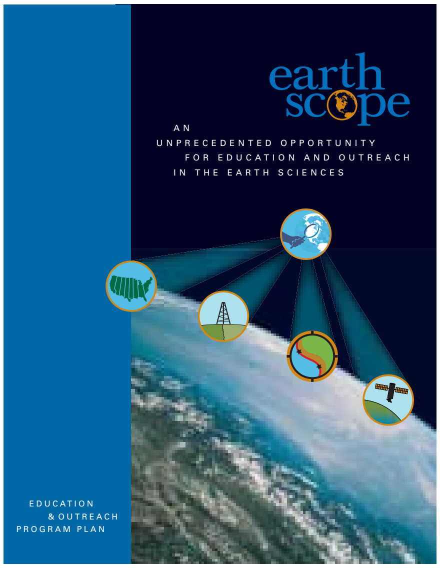



Figure I-6. EarthScope Education & Outreach Program Plan: An Unprecedented Opportunity for Education and Outreach in the Earth Sciences, November 2002, 52 pp. This is a detailed plan includes a proposed EarthScope Education and Outreach Network (EON), consisting of a national EON office, a variety of local EON alliances, and numerous partners. Go to www.earthscope.org/links_pubs/index.html to download a copy of this documents.

EarthScope is emerging at a time when there is growing national awareness of the need to improve science education, coupled with an appreciation of the opportunities offered by Earth sciences to engage students at all levels in the exploration of the world around them. The nature of the decade-long experiment will provide many opportunities for citizens of all ages to participate in scientific inquiry and discovery alongside EarthScope scientists. With strong encouragement and support from NSF and other federal agencies, education programs are becoming an integral part of Earth science facilities and research programs. The Earth science community—from major research facilities to professional societies, government agencies, and individual scientists—is building educational links to resources primarily established for research. In addition, a growing number of Earth scientists are actively pursuing educational initiatives as a formal part of their research. Providing real-time access to the rich data sets, along with tools and materials that create opportunities for citizens to explore and understand these data, will be an important EarthScope activity.

EarthScope's national scale and breadth of associated research is unprecedented in the Earth sciences. It has the potential to spawn new areas of discovery in ways similar to the Human Genome project for the biological sciences. We anticipate an education and outreach program that conveys both the exciting results that emerge from EarthScope's national scientific effort, and perhaps as importantly, the nature of our scientific method. For example, as USArray moves from region to region, the education and outreach efforts will highlight both important regional questions and an emerging (and changing) continental-scale picture. This process will provide a genuine example of how our scientific thinking often changes as new data become available. In addition, the rich data sets will provide new ways to help students make their own discoveries, thereby understanding Earth more deeply. EarthScope will be able to capitalize on the excitement created by a huge science experiment in one's own backyard.

## 5.3. Anticipated Products and Results

As a NSF facilities program, a primary responsibility of EarthScope will be to serve and enhance the scientific research programs of the Foundation's Directorate for Geosciences and Division of Earth Sciences. The data collected by EarthScope will serve as a primary resource for the next decade for geophysical and geological studies of North America and the entire Earth—from crust, to mantle and core—for investigations of continental deformation, and for improving our understanding of earthquakes. EarthScope offers us an opportunity for a new integrated approach to the way we conduct Earth science experiments in North America. A national program on the scale of EarthScope can catalyze solid-Earth science research and help organize this discipline's contribution to Earth system science in North America.

The resources and results from EarthScope will find wide application in a variety of issues of growing societal need by advancing our understanding of natural hazards and natural resources throughout North America. The USArray's Flexible Array will be a powerful tool for focussed studies of natural hazards such as magma movement around active volcanoes in the Pacific Northwest. The Flexible Array will also extend the instrumentation available for attacking a wide range of problems in fundamental studies in earthquake dynamics, fault zone imaging, characterization of fault zone properties, and movement on faults in seismically active regions. The flexible component of USArray will also provide a unique resource for basin studies to characterize the potential for strong ground motions in urban areas.

Different EarthScope elements will also provide information on local and regional scales useful to resource managers. The high-frequency instruments in USArray's Flexible Array will be available for three-dimensional regional groundwater resource assessment and management studies. For example, studies of the detailed geometry of aquifers around major western metropolitan areas are underway, but will be strengthened by the ability to study specific basin bounding faults, ground subsidence, and basin velocity and density structure. Exploration for oil and gas and mineral resources has traditionally been the job of private industry, but using the Canadian Lithoprobe Experiment as an analog, the flexible array can be used to help improve our understanding of subsurface structures beneath basins. Industry and state geological surveys will be able to use the detailed tectonic framework of the continent that emerges from EarthScope as a resource for mineral and energy exploration.

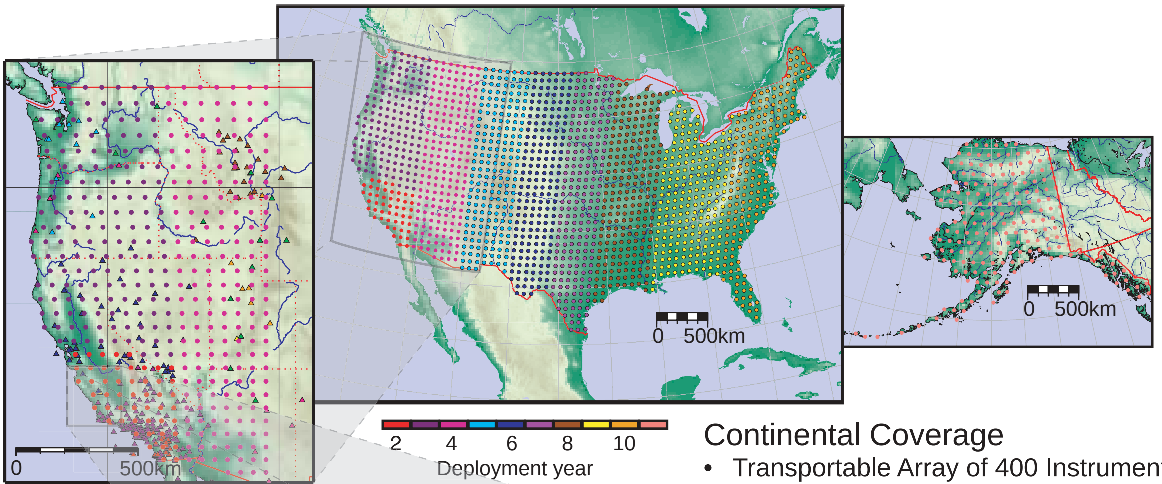
The most fundamental PBO product will be daily position estimates and strainmeter time series. For borehole strainmeter data, a daily time series will be produced that applies corrections for solid Earth tides, barometric pressure corrections, and any exponential trends resulting from grout curing and known seasonal signals. For long baseline strainmeters, the data product will be an edited time series with bad data points removed, spurious offsets removed (strain measurement, and end-monument corrections from the anchors) and end-monument motions, laser frequency, and vacuum level corrections applied to the series. A PBO station velocity and strain map that will be updated on a regular basis. Some level of geophysical modeling of the PBO data may also take place to guarantee the quality and sufficiency of the data to meet PBO research goals. In addition, geophysical modeling and development of model products will be a component of the associated PBO research program.

All EarthScope components will have direct links to programs in earthquake research carried out by USGS and other federal and state agencies. In some cases, the link will be direct, as in the siting and operation of permanent stations and coordination in station siting and data exchange between regional networks and the Transportable Array. In other cases, the links will be indirect, as in the feedback between improvements in crustal velocity models and the earthquake location capabilities of national and regional networks. The USGS and the university community have a long and fruitful history of cooperative studies under the National Earthquake Hazards Reduction Program (NEHRP), and EarthScope's resources will greatly extend these interactions. Plans for USArray and PBO have been carefully coordinated with the USGS and regional networks responsible for monitoring of earthquakes and crustal deformation, especially during the development of the USGS's ANSS. The ANSS plan is directed primarily at permanent seismic stations to provide continuous observation of earthquake and their effects across the nation, in support of the USGS mission as part of NEHRP. EarthScope will expand the data and facilities available for earthquake studies in both routine operations with permanent stations and in targeted studies of faults and earthquake dynamics using portable instruments. The instruments of the flexible component of USArray will provide a unique resource for basin studies, in the tradition of those carried out recently in Seattle and Los Angeles with portable instruments and joint NSF/USGS funding. These will be important in characterizing the potential for strong ground motions in urban areas.

# Part II. The EarthScope Observatory

# 1. USArray
# United States Seismic Array

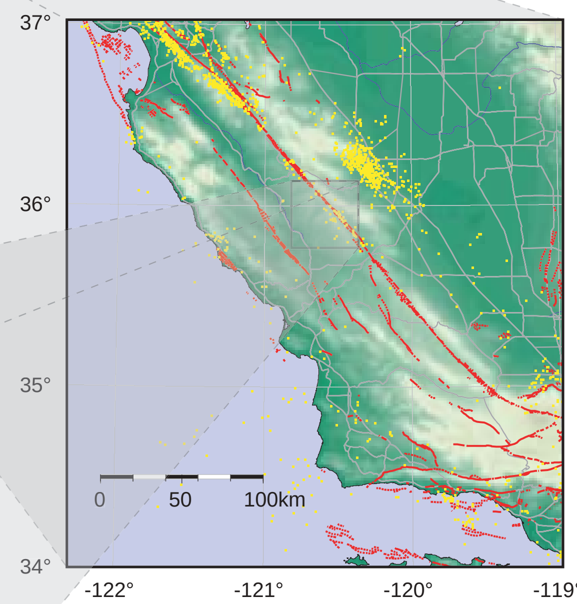
# Continental Structure & Evolution at all Scales



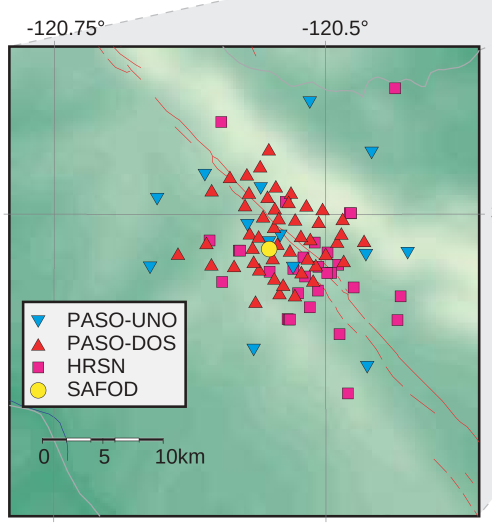

### Continental Coverage
- Transportable Array of 400 Instruments
  *2,000+ sites in 10 years*

### Regional Deployment
- Single Deployment of the Transportable Array
  *covers 1-2 million km$^2$ for 1-2 years*

earthscope
USArray




### Field Laboratories
- Special Targets for Detailed Study
  *e.g. SAFOD site at Parkfield, CA*




### Detailed Structure
- Flexible Component of USArray
  *Additional instruments for high-resolution observations of earthquakes and artificial sources*

# 1.1. Overview

EarthScope is a set of integrated and distributed multi-purpose geophysical instrumentation that will provide the observational data needed to significantly advance our knowledge and understanding of the structure and dynamics of the North American continent. One element of EarthScope is USArray, a dense array of high-capability seismometers, to improve greatly our resolution of the continental lithosphere and deeper mantle. USArray's hierarchical design will allow us to capture images that span the continuous range of scales from global, through lithospheric and crustal, and from regional to local.

USArray consists of three major elements: (1) a Transportable Array, (2) a Flexible Array, and (3) a Backbone Network of permanent stations.

1. The core of USArray is the Transportable Array, a telemetered array of 400 broadband seismometers, deployed in the United States. The array is designed to provide real-time data from a regular grid with dense and uniform station spacing of ~70 km and an aperture of ~1400 km. The Transportable Array will record local, regional, and teleseismic earthquakes to produce significant new insights into the earthquake process, provide resolution of crustal and upper mantle structure on the order of tens of kilometers, and increase the resolution of structures in the lower mantle and at the core-mantle boundary. The Transportable Array will roll across the country with 18-24 month deployments at each site. Multiple deployments will cover the entire continental United States and Alaska over a period of 10-12 years. When completed, the array will provide unprecedented coverage for 3-D imaging from ~2000 seismograph stations. While the initial focus of USArray is coverage within the United States, extensions of the array into neighboring countries and onto the continental margins in collaboration with scientists from Canada, Mexico, and the ocean sciences community would be natural additions to the initiative.

2. As a complement to the Transportable Array, USArray's Flexible Array will include a pool of ~2400 portable instruments (a mix of broadband, short period, and high frequency sensors) that can be deployed using flexible source-receiver geometries. These instruments will permit high-density, shorter-term observations, using both natural and explosive sources, of key geological targets within the footprint of the larger Transportable Array, for example, at the SAFOD site. Many important targets are amenable to investigation with the Flexible Array, including: the depth extent of faults, magma chamber dimensions beneath active volcanoes, the relation between crustal tectonic provinces and mantle structure, the shape of terrane boundaries, the deep structure of sedimentary basins and mountain belts, and the structure and magmatic plumbing of continental rifts. Linked with coordinated geological, geochemical, and geodetic studies through the broader EarthScope initiative, this USArray component can address a wide range of problems in continental geodynamics, tectonics, and earthquake processes. Examples include imaging the continental arc system in the Cascades from slab to edifice, examining the deep roots of the North American craton and paleotectonics by which the craton was formed, imaging both ancient and modern orogens and rifts to explore variability in continental tectonics, identifying the role of the mantle lithosphere during orogenesis and rifting, and unraveling the relationship between deep processes and surface features.

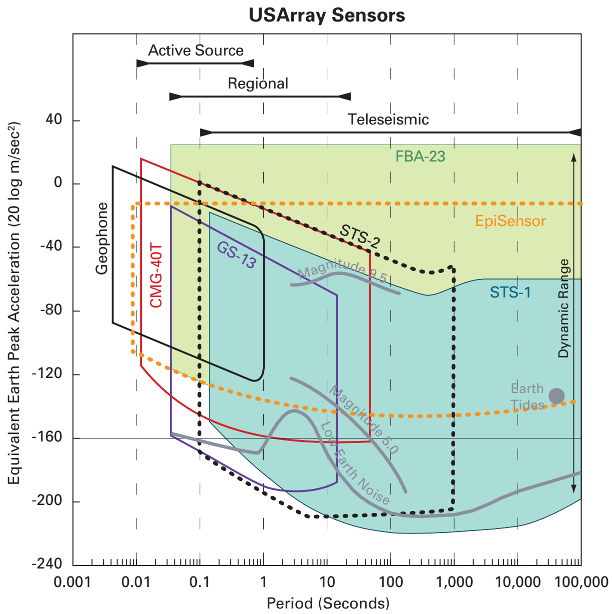



Figure II-1.1: Spectral amplitude response characteristics of typical seismometers, some or all of which will be deployed in USArray. As one example, the very broadband Streckeisen STS-1 sensor can resolve both ambient Earth ground noise, as well as record on scale Earth tides and a magnitude 9.5 earthquake 4,500 km away.

3. A third element of USArray is the development of a Backbone Network, through augmentation of permanent stations of the USGS National Seismic Network (NSN) and the IRIS/USGS Global Seismographic Network (GSN). Relatively dense, high-quality observations from a continental network with uniform spacing of 300-350 km are important for tomographic imaging of deep Earth structure, providing a platform for continuous long-term observations, and establishing fixed reference points for calibration of the Transportable Array. Some stations of the Backbone Network will be equipped with continuous GPS receivers. This permanent component of USArray will be coordinated with the USGS and complements the initiative underway at the USGS to install an Advanced National Seismic System (ANSS).

Thirty magnetotelluric (MT) field systems will be included in the Transportable Array, and ten will be installed at selected stations of the Backbone Network. The MT method measures electrical and magnetic signals related to natural fluctuations of electromagnetic fields at Earth's surface. Time variations of magnetic sources that are external to Earth induce telluric currents in the conducting Earth. The fields diffuse into Earth and are scattered back from heterogeneities in electrical resistivity. Because resistivity depends strongly on factors such as temperature and fluid content, the MT method is a valuable complement to seismology.

The IRIS programs in permanent and portable broadband seismological observations (the Global Seismic Network (GSN) and the Program for Array Studies of the Continental Lithosphere (PASSCAL)) have been extremely successful in revealing the details of global and regional variations in Earth structure. For example, a suite of recent PASSCAL experiments in the western United States has revolutionized our understanding of the tectonics and evolution of the Pacific margin of North America. In addition, the USGS NSN has added significantly to our knowledge of seismicity and structure. There remain, however, significant gaps in coverage by permanent seismic stations, and there are large areas of the United States where the details of lithospheric structure and the relationship between adjoining regions at intermediate scales remain unknown.

USArray, along with existing permanent regional and national networks, will extend uniform coverage to the entire country allowing for a thorough and systematic seismological/ geophysical/geological study of the conterminous United States. The combined networks of USArray will create a powerful tool for the Earth sciences at all scales and will be a natural avenue for pursuing education and outreach. The concept is to develop a region of focused study (with the associated specialized equipment) and move it across the country, bringing truly integrated investigation to one region after another. Building on the concept of field laboratories, a combination of permanent and transportable observatories will serve as platforms for a diverse suite of studies. The special appeal of this approach is that every part of our nation will be used as a laboratory in some aspect of important and interesting geoscience study. Virtually every educational institution will have the opportunity to take an active role in the investigation and, through coordinated education and outreach efforts, encourage an interest in "real" local geology among K-12 students and the public.

A continent-sized array will be a powerful large-aperture telescope offering an unprecedented window into Earth's interior. The U.S. is an excellent location for such a window because of the ideal source-receiver distance from the intense seismicity of the western Pacific and South America. Broad-scale tomography of the upper mantle beneath North America will benefit greatly from the permanent station spacing on the order of 300 km, while much higher resolution imaging of lithospheric structure will emerge through active and passive source seismic studies, accompanied by an appropriate mix of other geophysical observations, using the portable broadband array. The expanded network of permanent stations, reporting in real time to the USGS, will improve the detection, location, and source characterization of both U.S. and global seismicity.

By itself, USArray is an experiment in seismology and geophysics. As a framework for a coordinated program of broad, interdisciplinary studies of structure of a continent, it can form the basis for a unifying experiment which is essentially geodynamic in nature and which encompasses the entire Earth sciences. As EarthScope evolves, each USArray deployment, targeted at individual geologic provinces, can be the observational core for an integrated field laboratory for the full spectrum of geoscience investigations.

# 1.2. Management

USArray will be implemented through extensions to the existing core programs operated by the IRIS Consortium (www.iris.edu). The complex mix of USArray technologies, operations, and management will all be based on the well-established structures and procedures that have evolved over the past 15 years as part of IRIS operations and through IRIS's successful long-term partnerships with the U.S. Geological Survey. As described later in this section, the facilities to be developed as part of USArray represent an approximate doubling of the current IRIS infrastructure in terms of numbers of instruments and data volume.

The IRIS/USGS Global Seismographic Network (GSN) now consists of 126 stations distributed worldwide. The instrumentation covers the complete seismic band—from free oscillation periods of thousands of seconds to a high-frequency limit of 15 Hz, and from the amplitude range of ground noise at the quietest sites to the largest ground motions expected from regional earthquakes. Nominal station spacing for the GSN is 2000 km. USArray's Backbone Network will be based on GSN technology and operational model and provide enhanced coverage at the station spacing of 300 km, over the continental United States.

The IRIS Program for Array Seismic Studies of the Continental Lithosphere (PASSCAL) provides portable seismic instrumentation for temporary deployments. The transportable and flexible components of USArray will be based on the two modes of operation that have evolved within PASSCAL. The Flexible Array will operate in the traditional PASSCAL mode, in which instruments are scheduled for use in individual experiments. The Transportable Array will operate based on PASSCAL experience with the Broadband Telemetered Array, which has successfully developed instrumentation and procedures for augmentation of traditional PASSCAL instrumentation with radio or satellite communications for real-time data collection. The real-time capability greatly facilitates data collection and network operation, and significantly improves data quality by allowing continuous monitoring of station operations.

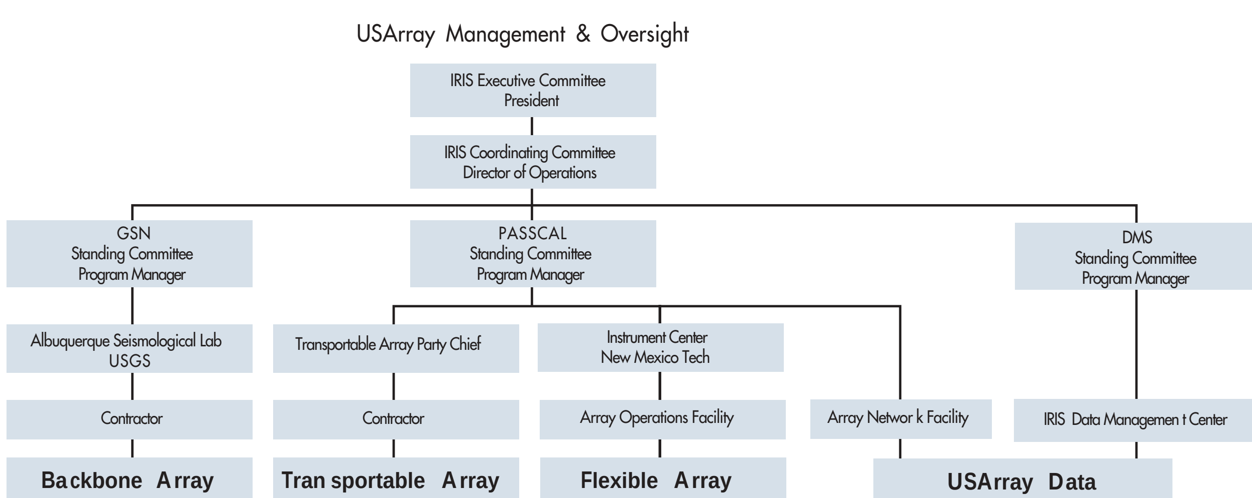



Figure II-1.2. USArray management and oversight as related to IRIS management and governance.

The IRIS Data Management System (DMS) is the repository and distribution point for all IRIS data. The IRIS archive now contains more than 28 terabytes of waveform data from the GSN, PASSCAL, and contributing networks. All primary data, station metadata, and earthquake information are linked through a relational database management system that provides full access to all data. An extensive array of user tools, and a collection of standardized data packages, have been developed to improve the data selection process for both research and education. All USArray data will be archived and distributed by the IRIS DMS.

Management of the USArray operations (Figure II-1.2) will occur through the existing IRIS structures, with community input and guidance coming from three IRIS Standing Committees: the GSN Standing Committee, the PASSCAL Standing Committee, and the DMS Standing Committee. The IRIS Director of Operations and the IRIS Program Coordination Committee will be responsible for integrating USArray activities among programs and for interacting with the EarthScope Facilities management structure. The Program Coordination Committee is chaired by the Vice Chair of the IRIS Executive Committee and consists of the IRIS Program Managers, the Chairs of the Program Standing Committees, a representative from the IRIS Executive Committee and the IRIS President. USArray integration within the EarthScope operations will be coordinated with the EarthScope Facilities Executive Committee and the EarthScope Facilities Project Director, and reviewed by the EarthScope Science and Education Committee.

The Backbone Network will be installed and operated in partnership with the USGS as part of the GSN and the ANSS. The equipment and operational arrangements will be similar to those currently adopted by the GSN. Installation will be carried out by contractors working under the direction of the USGS staff at the Albuquerque Seismological Laboratory of the USGS.

# 1.3. Field Systems

## Transportable Array

The Transportable Array, or "Bigfoot" array, consists of 400 broadband seismic stations and 30 magnetotelluric systems. The seismic systems will be based on standardized instrumentation configurations developed under the PASSCAL program for use in telemetered broadband arrays. USArray will establish the Array Operations Facility (AOF) at the New Mexico Institute of Mining and Technology, where it will be managed through the PASSCAL program and coordinated with the PASSCAL Instrument Center. The AOF will be responsible for both Bigfoot and Flexible Array support, system integration, testing, shipping, and maintenance. Full-time professional contract crews, managed by the PASSCAL program and coordinated with the AOF, will carry out the Bigfoot field installations. In areas where there are existing regional networks for earthquake monitoring, USArray will collaborate closely with regional network operators in site selection and installation, and the regional networks will have high priority access to all data.

The Transportable Array will be operated by a dedicated field crew. The 400 stations will be deployed in a grid with a station spacing of ~70 km and for a period of ~18 months. The array will advance across the country in a roll-along fashion. Data from the stations will be telemetered to a central site. The exact form of the telemetry will vary depending on practical considerations at the sites. All forms of telemetry used in USArray will be designed so that the waveform data enter the processing system via a TCP/IP interface. The Array Network Facility (ANF) will be established to monitor real-time data collection from the Transportable Array, carry out both preliminary and advanced data quality inspections that will provide feedback to array operations in the field, and coordinate data delivery to the IRIS Data Management Center (DMC). Real-time feeds of the data will be available to all interested scientists. As part of the preliminary quality control, events will be located

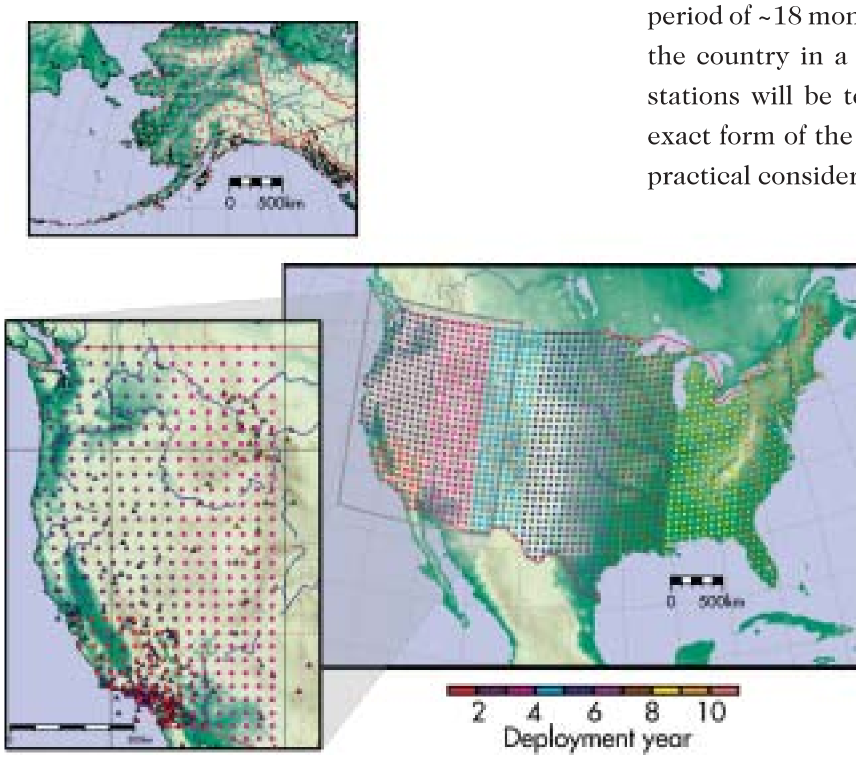



Figure II-1.3: Deployment strategy for the Transportable Array. The underlying grid shows a regular spacing of 70 km, resulting in approximately 1600 sites in the lower 48 states. Four complete deployments of the 400 instruments are required to cover the lower 48 states. USArray begins operations along the west coast, extending from Mexico to Canada and encompassing the SAFOD site at Parkfield. Western US detail shows the nominal coverage for the first full deployment of the 400 instruments of the Transportable Array. Included on this map as colored symbols are existing sites of broadband and short-period instruments in regional networks.

in near-real-time. Event-segmented data will be archived when authoritative event location solutions have been published by the regional networks.

## Flexible Array

The Flexible Array consists of 200 broadband seismic stations, 200 short-period stations, and 2000 single-channel active-source instruments. The systems will be based on standardized instrumentation configurations developed under the PASSCAL program for use in temporary deployments for earthquake studies and short-term active source (explosion) experiments. The Flexible Array will be used for individual PI-driven research experiments. All or part of the pool can be used in multiple experiments of various size and duration. USArray personnel stationed at the AOF will be responsible for equipment integration and maintenance, and they will provide technical assistance with deployment and data collection. The primary responsibility for deployment and operation of the instruments, however, will rest with principal investigators of individual research programs.

The flexible pool of instruments is scheduled to operate in a mode similar to the current PASSCAL operations. Investigators will propose special experiments, via standard NSF grant procedures, to use the Flexible Array instruments in special high-resolution studies. The majority of experiments will aim to enhance data gathered by the Transportable Array while it is located in a specific area. In this mode of operation, the PI will furnish the bulk of the crew for operations, as is now done for PASSCAL experiments. The AOF will furnish training, logistical support, and initial quality control and data formatting support. Many of the instruments will be deployed with telemetry. All telemetered data will be handled in a manner similar to data from Transportable Array sites. Data will be archived in the DMC as quickly as possible, and will be available through the DMC. The guidelines for how experiments are defined and selected, and the data policy for Flexible Array experiments, will be established by NSF through solicitations and program announcements related to the overall EarthScope program.

All equipment used in Flexible Array experiments will be tested at the AOF before it is shipped to the field. Once the equipment arrives in the field, AOF personnel who are assisting the experiment will conduct further tests to verify the operation of the sensors and recorders. The AOF personnel will maintain the equipment to ensure it is operational.

## Backbone Network

USArray's Backbone Network serves as a reference for the continental-scale imaging being performed by USArray's transportable components. Each of the Transportable Array "footprints" and focused Flexible Array experiments deployed for 18-24 months will ultimately be connected through the reference Backbone Network. The Backbone Network, in turn, is itself linked within the framework of the ANSS and the GSN.

As an integrated resource both for EarthScope science and seismic monitoring, the Backbone Network has been designed in close collaboration with the USGS ANSS (see www.ANSS.org). The proposed national network part of the ANSS will consist of approximately 130 stations, of which USArray will contribute 13 GSN-quality stations and 27 NSN-quality stations. Permanent GPS receivers will be installed at 16 of the stations, and 10 stations will include magnetotelluric systems. The seismic equipment at these stations will be based on systems developed by IRIS in partnership with the USGS. The USGS Albuquerque Seismological Laboratory (ASL) currently operates and maintains about two-thirds of the 126 GSN stations. ASL will have primary responsibility for installing the Backbone Network. Data will flow openly in real time through communication and data delivery systems which currently exist as part of IRIS and USGS programs.

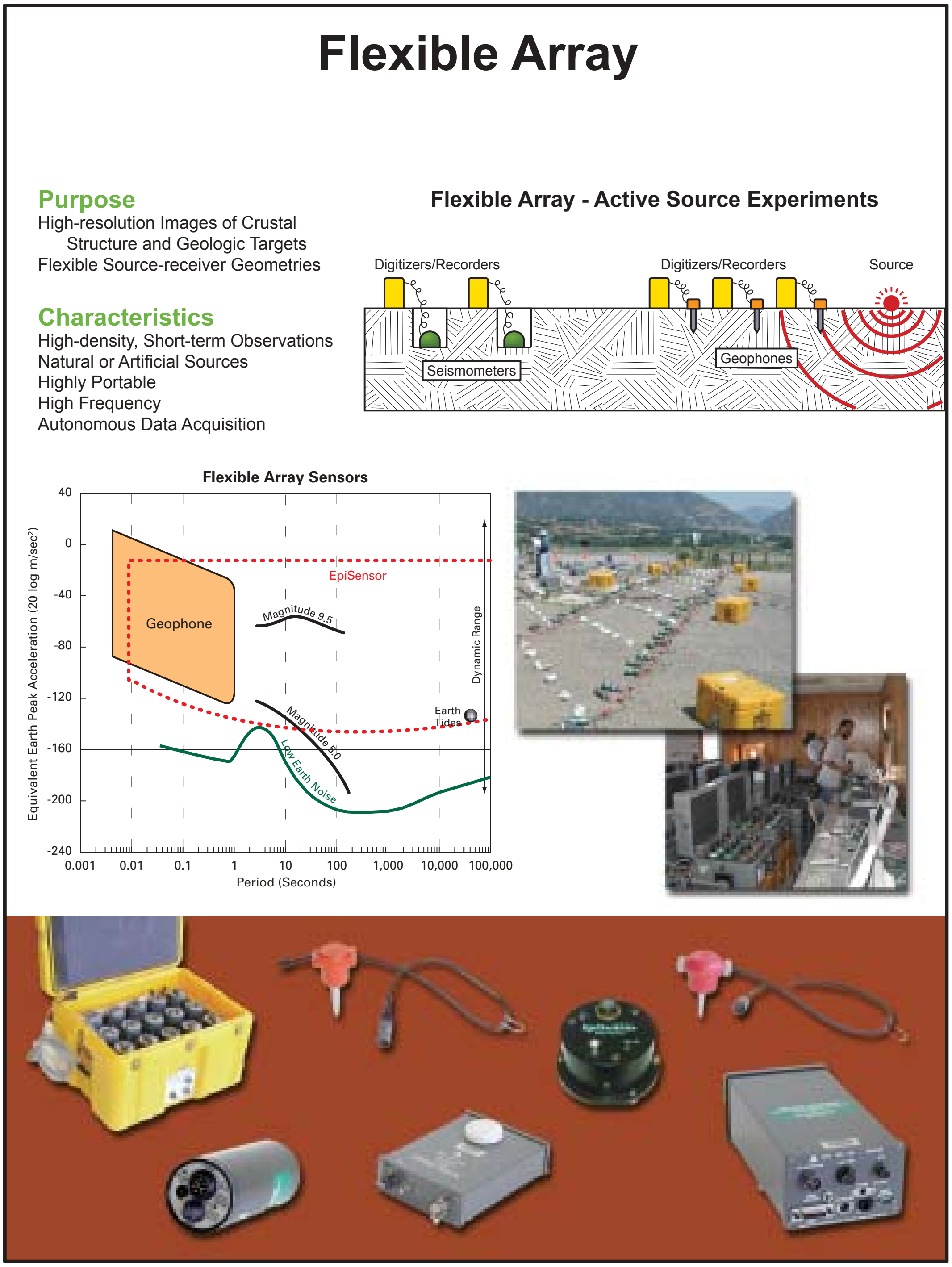



Figure II-1.4: Flexible Array montage showing schematic of field layout, amplitude vs. frequency response of sensors, instrumentation, and typical deployments. Each sensor has its own digitizer/recorder with internal batteries. The recorders can be set to start/stop recording if the time of a nearby man-made seismic source is known. The geophones may be laid out in linear arrays, with station spacing from a meter to kilometers. The amplitude response (cf. Figure II-1.1 for comparison with other USArray sensors) of the geophones is well-suited to recording the high-frequency, energetic signals from man-made sources. The lowermost photograph shows, from left-to-right, shipping box filled with single channel "Texan" digitizer/recorders, Texan digitizer/recorder, geophone, single-channel digitizer/recorder, 3-component geophone, 3-channel digitizer/recorder.

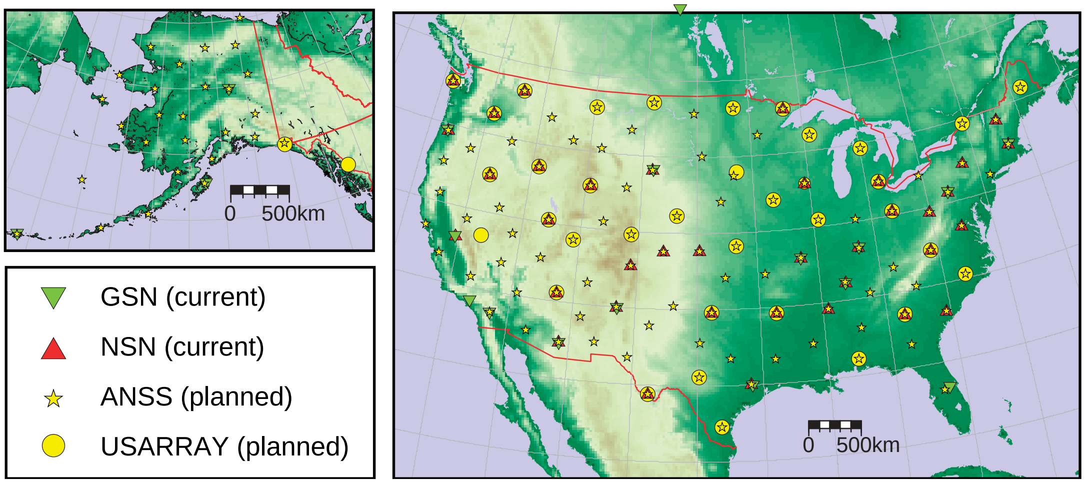



Figure II-1.5: The Backbone Network, consisting of USArray stations included in this proposal, plus existing and planned stations of the GSN and the USGS Advanced National Seismic System. The complete network provides uniform coverage across the conterminous United States and Alaska at an average spacing of approximately 300 km.

The sensors selected for the Backbone Network sites meet ANSS design goals for NSN stations, with a broadband (100 sec to 15 Hz) seismometer augmented with a low-gain sensor for recording strong ground motion (up to 2 g) on scale without clipping. A uniformly distributed subset of 13 sites of the Backbone Network will meet the more demanding GSN standards, which includes ultra-long period (to 1,000 sec) sensors at extra-quiet locations. When completed, the NSN-quality component of the Backbone Network will have nearly uniform coverage at a scale of about 300 km. The GSN-quality component of the Backbone Network will have coverage at the 1000-km scale to augment global GSN coverage (about 2000 km spacing). The resulting array focuses progressively from global to national scale, and then merges at the regional and local scales with the Transportable and Flexible Arrays.

The Backbone Network must be built quickly to begin serving as the reference network for Bigfoot. In building the GSN, IRIS has already had experience with such deployments. With funding from Congress in expectation of the Comprehensive Nuclear Test Ban Treaty, 50 GSN stations were installed globally in just three years. Installation of the Backbone Network will be completed in three years, and then turned over to ANSS for operations. With the USGS we will first upgrade to existing NSN stations, and then install new sites.

The Backbone Network incorporates and upgrades existing seismic stations, and deploys new stations to fill the holes in current U.S. coverage. Due to varying circumstance and types of equipment already installed, there are five broad categories of Backbone Network sites. These are summarized in Figures II-1.5 and II-1.6.

1. Four existing stations in Wyoming, Nevada, Texas, and the Aleutian Islands of Alaska are part of the Comprehensive Nuclear Test Ban Treaty Organization's International Monitoring System (IMS) and also operate as part of the U.S. Atomic Energy Detection System (AEDS). Operated by the Air Force and Southern Methodist University, these systems already meet GSN design goals for broadband instrumentation. Cognizant organizations have agreed to affiliate with the Backbone Network.

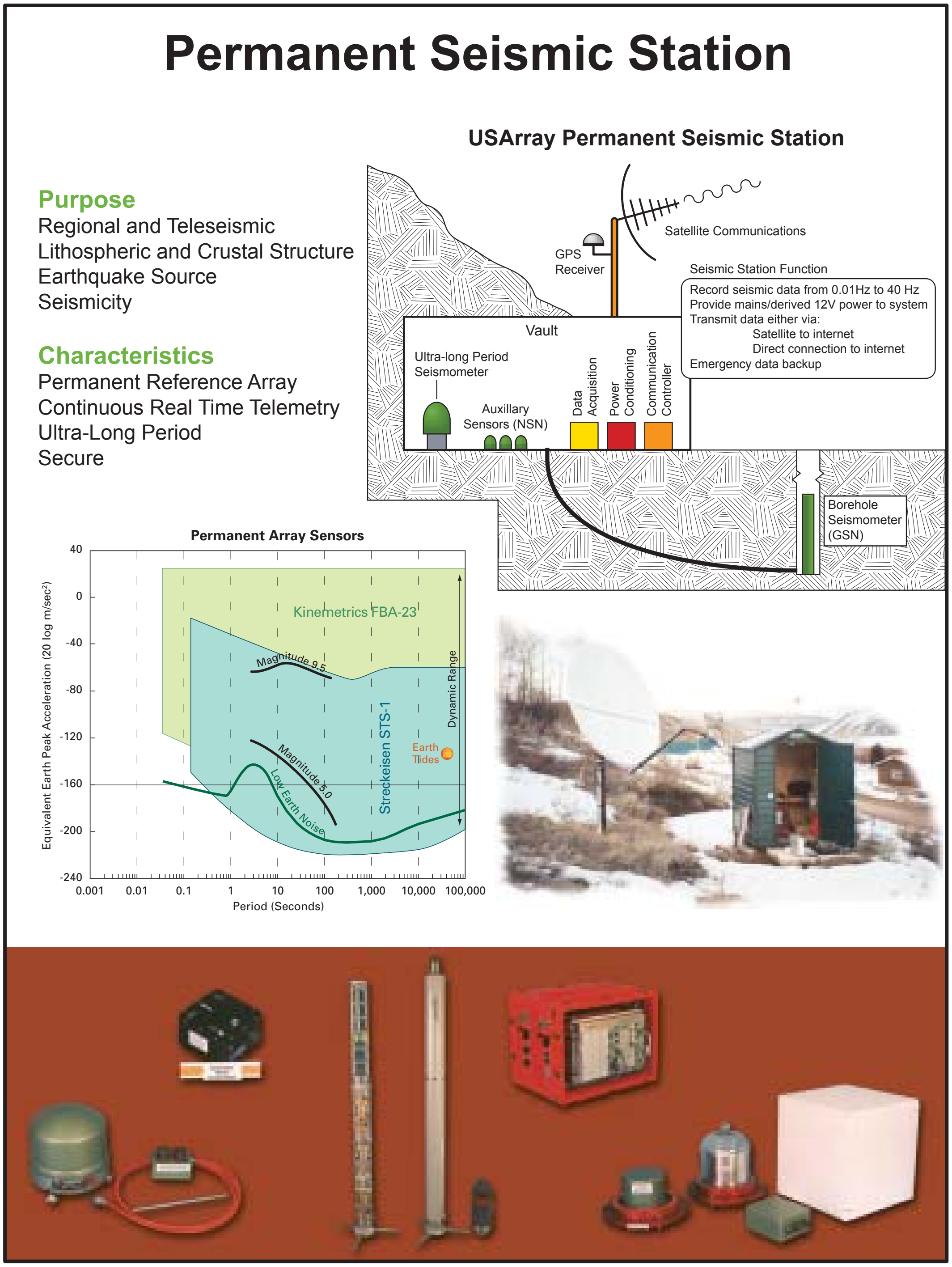



Figure II-1.6: Backbone Network montage. The deployment of a typical station includes a vault to protect the ultra-long-period seismometers and auxiliary sensors, digitizer/recorder, power systems and communications controllers. The vault also supports a mast for the GPS receiver which provides timing to the recorder, and a data telemetry system. Some sites will use a borehole seismometer instead of the ultra-long period vault sensor. The amplitude response (cf. Figure II-1.1) shows the full broadband spectral response of these systems. The lowermost photograph shows, from left-to-right, Streckeisen STS-2 seismometer, accelerometer, borehole seismometer, digitizer/recorder, and 3-component Streckeisen STS-1 seismometer. The white box is a thermal insulation cover that fits over the STS-1 to reduce noise induced by air currents within the vault.

2. Five existing NSN stations will be upgraded with GSN-quality sensors. These sites augment current GSN distribution. Some station enhancements are budgeted to mitigate noise.

3. Four new GSN sites will be installed to fill gaps in GSN coverage. Three of these sites are located in the mid-continent. Borehole seismometer installations are planned to provide optimum noise performance, as no bedrock outcrops are present across the Great Plains. A site using an abandoned mine tunnel is planned in southeastern Alaska.

4. Fourteen existing NSN sites will be upgraded with new sensors to improve long-period (100 sec) performance. Some station enhancements are budgeted to mitigate noise.

5. Thirteen new NSN sites will be installed to provide uniform coverage across the conterminous United States.

Real-time data flow from the Backbone Network will be integrated with other elements of the USArray and EarthScope. Data from IMS/AEDS sites are quality-controlled by the Air Force. All other Backbone Network data will be quality-controlled by ASL. In all cases, data are forwarded to the IRIS DMC for archiving and distribution.

## Major Equipment Components

Each USArray station will include the instrumentation necessary to continuously sense, record, and transmit ground motions from a wide range of seismic sources including local and distant earthquakes, artificial explosions, volcanic eruptions and other natural and human induced activities. Specialized sensor, signal conditioning, and timing systems with high sensitivity, wide dynamic range, and high precision, are required to detect and record the low-level ground motions of interest to research seismology (Figure II-1.1). The marketplace, however, for the seismological components of USArray is relatively limited. In contrast, the communications and data management systems required to transmit and archive the data can draw from a much broader market sector, although even in these areas, constraints on low power, high data volumes, and specialized software challenge the commercial sector. While there are differences in the characteristics and technical specifications among the Flexible Array, Transportable Array, and Backbone Network, the primary components are similar:

Over the wide frequency range of seismic waves transmitted through Earth (hundreds of seconds to tens of cycles per second), the sensors of the Backbone Network and mobile arrays must be capable of resolving the smallest background motions at the quietest of sites, while remaining "on-scale" for all but the largest ground motions from regional earthquakes (Figure II-1.1). For applications in which the Flexible Array is used for observations of artificial sources (explosions or vibrators) at short ranges, the longer periods (below 1 sec) are less important, but higher frequencies (up to 100 Hz) must be recoverable for high-resolution studies.

To allow merging and direct correlation of the signals from multiple stations, the absolute timing of each recorded data sample must be known to within a few milliseconds and the location of each instrument must be know to within 10 meters. Both precise timing and accurate locations will be obtained through the use of GPS receivers.

For the Transportable Array and Backbone Network stations, data will be recorded continuously. Wherever possible, data will be transmitted in real time from the remote field locations to a central recording facility, greatly facilitating the process of data collection, analysis, and quality control. For some applications using the Flexible Array, where artificial explosions may be detonated at known times,

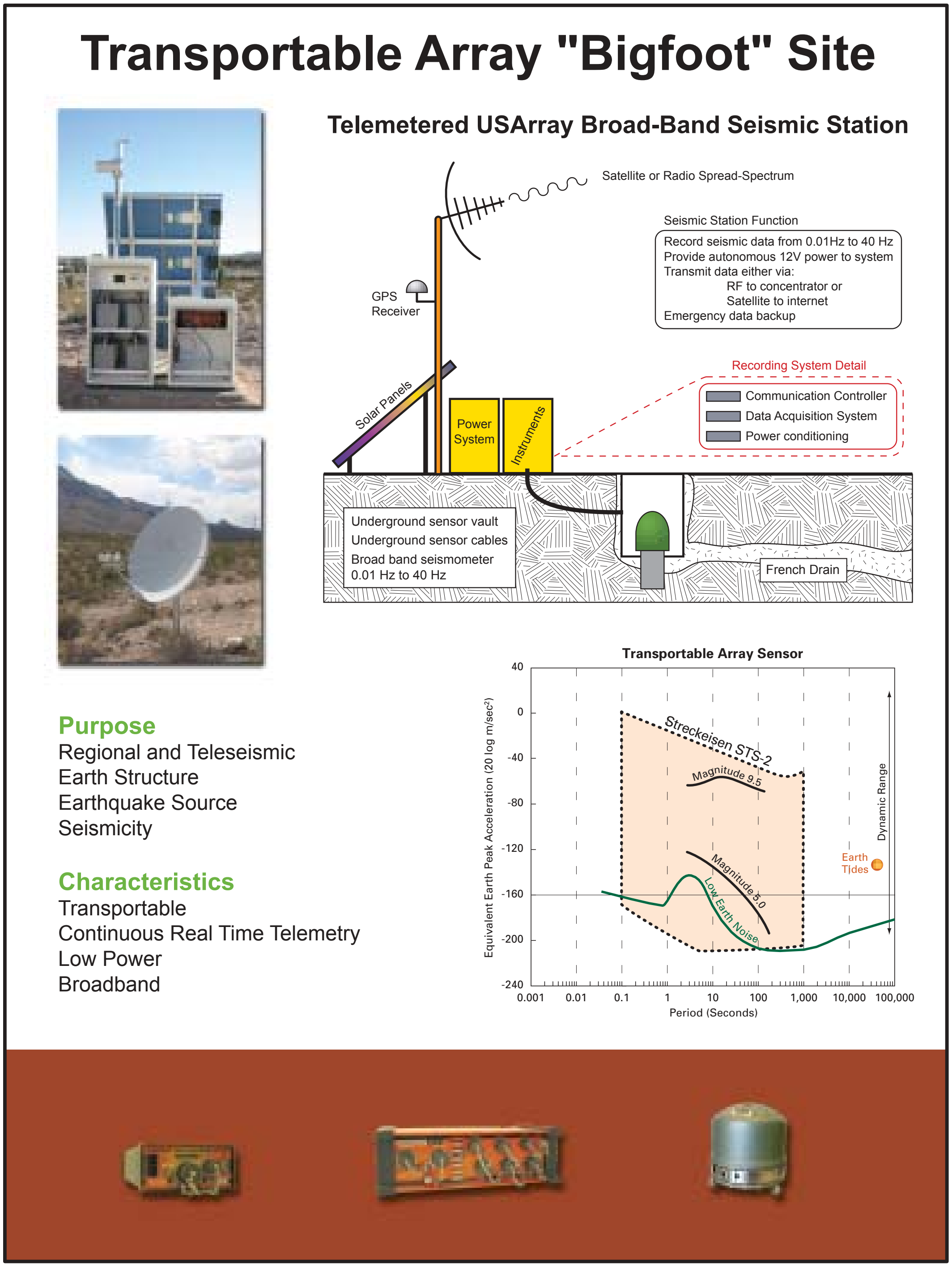



Figure II-1.7: Transportable Array montage. The deployment of a typical station includes a shallow vault to protect the broadband seismometer, digitizer/recorder, power (battery and solar) systems and communications controllers. The GPS receiver provides accurate timing to the recorder, and a data telemetry system. The amplitude response (cf. Figure II-1.1) shows the broadband response of these systems, but with limited very long period response compared to the permanent installations. The lowermost photograph shows, from left-to-right, Kinemetrics Baler (recorder and communications controller), Kinemetrics Q330 (digitizer), and Streckeisen STS-2 broadband seismometer.

segmented recording is acceptable and the instruments can be set to turn on and off at predetermined intervals.

The main system components at each USArray station include:

- Sensor. The primary sensors of the Backbone Network and Transportable and Flexible Arrays will be broadband three-component seismometers capable of sensing ground motions over the frequency band 0.01 Hz (100 sec) to 15 Hz. A subset of sites of the Backbone Network will be equipped with ultra-long-period seismometers to extend the range to 1000 seconds. The Flexible Array will also include more rugged sensors that cover higher frequency bands (0.1 Hz to 100 Hz) and are better suited for multiple deployments during short-term experiments.

- Signal conditioning and timing. To provide the fidelity and dynamic range necessary to capture the full amplitude range of interest, all signals will be processed with low-noise amplifiers and encoded using 24-bit high-resolution digitizers.

- Telemetry. To provide near-real-time data access for all interested parties, the Backbone Network and Transportable Array will transmit data continuously to a central site from which they will be immediately accessible. The type of telemetry will vary from site to site, depending on local conditions and communications infrastructure. In some cases, access to the Internet may be available, either directly or via a short radio link. At others sites, cellular or satellite technology may be the only, or more cost effective, option. Whatever the mode of telemetry, a level of uniformity will be provided by the use of industry standard communication protocols such as TCP/IP.

- Recording. On-site disk storage will be used to provide backup recorders in case of problems with the communication system, or to provide full data recovery in those cases where telemetry is not possible.

- Power system. Most of the sites will be in remote areas where access to commercial power systems may not be possible. All of the field systems will be low power and capable of unattended operation from batteries and solar panels.

## Communications

A primary goal of USArray's Transportable Array and Backbone Network is to deliver all data from the field systems to a central collection and distribution center in near-real-time, (i.e., with only those delays introduced by data buffering and communication protocols), usually within tens of seconds of acquisition. Near-real-time data communication is beneficial for station maintenance and troubleshooting, and overall data availability and quality, as well as the streamlining of downstream data quality control and processing. To the maximum extent possible, the field systems are designed to be "telemetry capable," with industry standard I/O interfaces (e.g., TCP/IP) that allow various types of communication devices to be used, depending on the conditions at each site. The Backbone Network stations will use the communications infrastructure established for the ANSS, which is already in use by IRIS for GSN sites in the United States (see "Technical Guidelines for the Implementation of the Advanced National Seismic System" www.anss.org/reports.html). This system is based on a direct Internet connection or a USGS-managed Very Small Aperture Terminal (VSAT) network.

Telemetry from stations of the Transportable Array poses a significant challenge. Because of the wide extent of the array, the remote location of many sites, and the tremendous variability in access to standard communication infrastructure across the United States, the mode of telemetry will vary greatly depending on the local conditions at each site. Given the considerable geographic extent and variable conditions under which both USArray and Plate Boundary Observatory (PBO) systems will be installed, there will be close coordination in the selection and development of communication systems between these EarthScope components. In both cases, a tiered approach for data communications will be required:

- Direct Internet connectivity will be the preferred choice of data communications at each station.

- If a suitable Internet connection is not available within proximity to the station, radio modems/ radio repeaters will be used to transfer data to an Internet node.

- If the distance to an Internet node exceeds the distance capability of radio modems, then a satellite-based Internet connection (e.g., Starband) will be used.

- If a satellite-based Internet connection is not an option based on local conditions, a VSAT system will be used. VSAT may also be used as a local hub for small-scale sub-networks within the Flexible Array; a VSAT download Hub will be available at the ANF, and others may be established based on need and specific satellite footprint, for example, for Alaska.

- If none of the above options for quasi-real-time data communications are viable, on-site recording will be used with periodic manual downloads by the Transportable Array staff.

## Site Selection and Permitting

Seismic stations require sites that are quiet, secure, and relatively accessible. A quiet seismic site is one that is distant from noise sources—both natural, such as wind and rivers, and cultural, such as traffic, railroads, and heavy industry. Coupling with the ground is best when stations are sited on hard rock and preferably buried or installed in a borehole or underground vault. Finding sites that meet these requirements, but are also secure and accessible, is often difficult. Selecting and permitting good sites will be a significant part of the USArray effort and will require close interactions among operators, outreach specialists, private landowners, and federal and state agencies.

A typical site for the Transportable Array (Figure II-1.7) will occupy approximately 100 square meters of land. The seismic sensor will be installed in a small vault, with the rest of the equipment housed in a weather-tight, surface-mounted enclosure. The batteries will have separate ventilation from the rest of the electronics. All cables will be buried underground in conduit and the mounting structures for the antennas and solar panels will be located as far from the sensor vault a practical to reduce noise from wind-buffeted structures. The most visible surface feature will be a solar panel and communications antenna.

Sites for the Backbone Network (Figure II-1.6) will be similar in construction, but more robust and designed for long-term occupation. To achieve the lowest noise characteristics, the sensors at permanent stations will be installed in deep (100 m) boreholes or underground vaults. Location close to facilities that can provide power and security will be more important for the permanent stations than for the 1-2 year deployments of the Transportable Array.

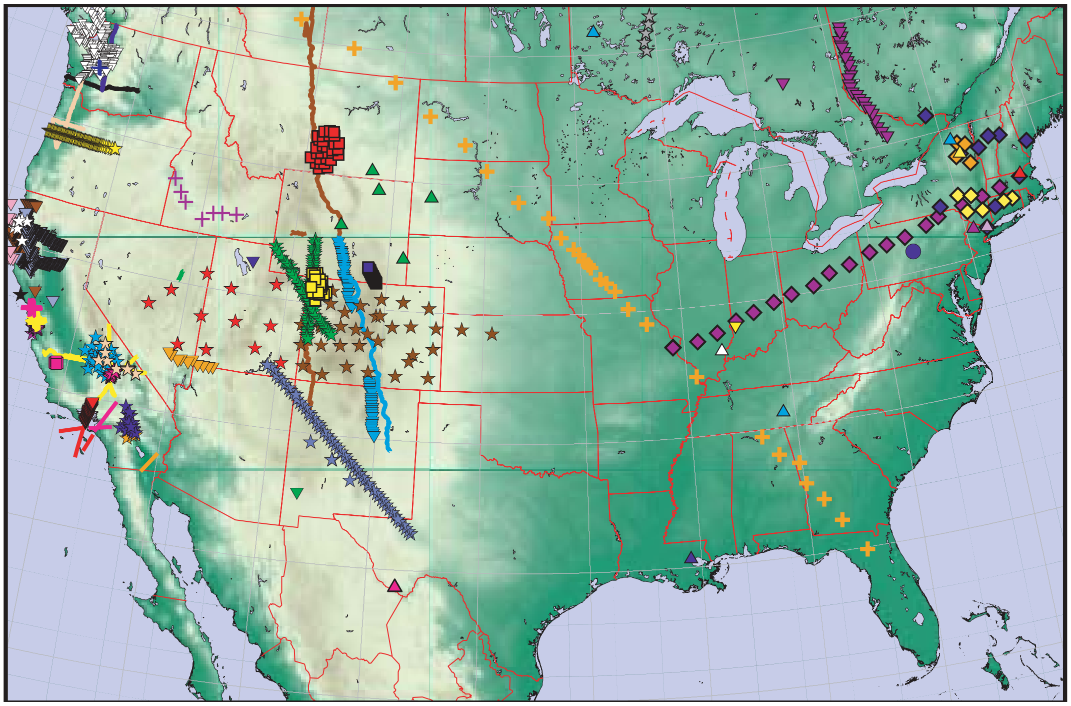


Figure II-1.8: Map of lower 48 states of the United States showing some of the deployments of portable active-source and passive PASSCAL instruments since 1985. Many of these deployments mimic the siting conditions and station spacing that will be required for USArray Transportable and Flexible Array stations. For the sites that lie within a reasonable distance from proposed Bigfoot sites, the knowledge from previous PASSCAL experiments will reduce the workload in seeking permits for Bigfoot sites.

# 1.4. Data Management

Among the fundamental principles underlying the collection and distribution of EarthScope/USArray data are that:

- All data will be freely and openly available to all interested parties.
- Wherever possible, data will be collected and distributed in near-real-time.
- Data (including both time series from sensors and associated metadata) will be reviewed to ensure quality.
- All data will be archived at the IRIS Data Management Center (DMC).
- All data will be distributed by the IRIS DMC using both traditional and newer Data Handling Interface (DHI)-based data distribution methods.

In the same way that many of the technical standards underlying the USArray field systems have emerged from the PASSCAL and GSN programs, the collection, distribution, and archiving of USArray data will be based on procedures developed by the IRIS Data Management System (DMS). Hardware and software systems now in use for handling PASSCAL and GSN data will be augmented and expanded to incorporate USArray data. In addition to leveraging investments already made by NSF in developing the DMS, this will also ensure that users will be able to merge USArray data with existing data resources in a simple manner, and access to USArray data will be via familiar and well-tested procedures and tools

## Data Volumes

Table II-1.1 summarizes the anticipated data volumes from the three components of USArray. The aggregate data flow rate is estimated to 4.2 terabytes per year. The IRIS DMC currently archives approximately 3.5 terabytes per year of seismic waveform data so that the total output from the fully installed USArray will roughly double the DMC's current rate of data collection and archiving. Because of the modular hardware configuration and highly automated procedures established at the DMC, this increase in data flow can be incorporated with relatively minor increases in staffing and hardware.

For operational, backup, and data security reasons, the IRIS DMC makes five copies of each sample of waveform data. Data are stored in a time and station sorted order to optimize servicing of data requests, a second copy of each of the time and station sort orders is also archived for redundancy, and one copy of the data is stored off-site on DLT tape for safekeeping. These safeguards effectively increase the archiving requirement by a factor of five, making our mass storage system requirement 30 terabytes per year and our offsite DLT storage another 7.5 terabytes per year. There is no intention to change this basic data archiving strategy.

The current mass store system at the DMC has an installed capacity of 180 terabytes and with modular expansion can be increased to 360 terabytes, sufficient to service all USArray data in addition to existing data sources. The incorporation of higher density tape drives can increase this capacity to more than one petabyte.

## Data Distribution and Archiving

The building and handling of the data products for USArray waveforms will be based on a variety of archiving and distribution capabilities that have been developed over the past 15 years to serve the needs of the research community. The primary goal is to provide users with a complete and continuous archive of quality controlled information (waveforms and associated metadata) from all USArray instal-

| | Contributing Sites | Number of Channels | Sample Rate, Hz | Duty Cycle % | Data Rate KB/sec | Data Rate MB/day | Data Rate GB/yr |
|---|---|---|---|---|---|---|---|
| **Transportable Array** | | | | | | | |
| Broadband | 400 | 3 | 40 | 100 | 375 | 3955 | 1410 |
| Long-Period | 400 | 3 | 1 | 100 | 9 | 99 | 35 |
| **Flexible Array** | | | | | | | |
| Broadband | 200 | 3 | 40 | 90 | 169 | 1780 | 634 |
| Long-Period | 200 | 3 | 1 | 90 | 4 | 44 | 16 |
| Short-Period | 200 | 3 | 100 | 90 | 422 | 4449 | 1586 |
| High-Frequency | 2000 | 1 | 250 | 2 | 78 | 824 | 294 |
| **Permanent Array (new GSN)** | | | | | | | |
| Broadband | 13 | 3 | 40 | 100 | 12 | 129 | 46 |
| Long-Period | 13 | 3 | 20 | 100 | 6 | 64 | 23 |
| Ultra-Long Period | 13 | 3 | 1 | 100 | 0 | 3 | 1 |
| **Permanent Array (new and existing NSN)** | | | | | | | |
| Broadband | 27 | 3 | 40 | 100 | 25 | 267 | 95 |
| Long-Period | 27 | 3 | 20 | 100 | 13 | 133 | 48 |
| **Total** | | | | | 1114 | 11748 | 4188 |

Table II-1.1: The amount of data estimated to be produced by USArray components is shown in the above table. A total of 4.2 terabytes per year will be generated by USArray. The total rate of generation of USArray data is 1.114 megabits/second with the Transportable Array generating 384 kilobits per second. Since Bigfoot will most likely be telemetered in real time to the ANF and the DMC, these are realistic rates to achieve. The values assume average compression of the data to 1 byte per sample. The Transportable Array will consist of 400 instruments recording 3 channels continuously at 40 samples/second and 3 channels continuously at 1 sample per second.

lations. In developing this complete archive, two pathways have evolved to serve the most common requests:

- Event windowed vs. Continuous. Many seismological investigations are based on analysis of all available data from specific events (earthquakes or explosions). Once the origin information (location and time) of an event is known, simple tools can be used to extract the time windows of interest for waves arriving at any seismic station. Since these data segments represent a small fraction of the total archive, they can be stored in on-line disks for rapid access. At the IRIS DMC, these on-line resources have been called FARM (Fast Access Recovery Method, for quality controlled data from the archive) and SPYDER® (for access to near-real-time data from events, before complete quality control). Since it takes time (minutes to weeks) to create event catalogs and collect data from all stations, these on-line data resources grow with time following an event. This is especially true for the FARM archive, which depends on the completion of quality control procedures.

- Immediate vs. Quality Controlled. In general, most research experiments look for the highest quality, most complete data available, In the case of the DMC, the resource of choice is the permanent archive of continuous data, or the FARM for event-windowed data. There are applications, however, especially in earthquake monitoring and education, where immediate access is more important than completeness or final quality control. To service these types of requests, the IRIS DMC, in collaboration with the USGS, has developed a variety of user tools that

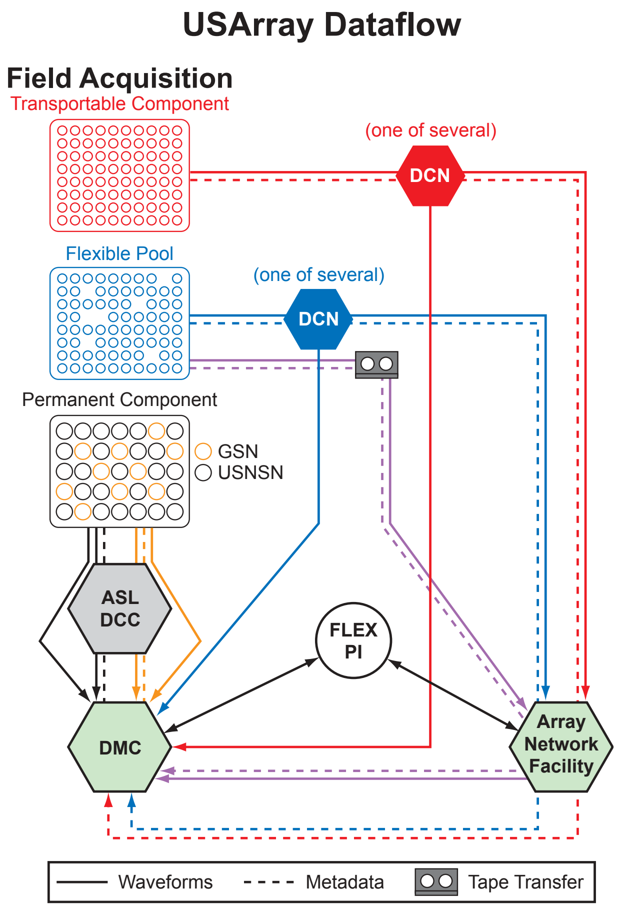



Figure II-1.9: Data will flow from the various USArray components to the Array Network Facility and to the IRIS DMC. Data Concentrator Nodes (DCNs) will forward data simultaneously to the Array Network Facility and the DMC for both the Transportable Component and the Flexible Component when real time connections are possible. Tape based transfer will flow through the Array Network Facility node and then to the DMC. Metadata generation will be the responsibility of the Array Network Facility. Backbone Network data will flow in real time to the USGS facility in Albuquerque ASL and to the DMC.

collect event-related waveforms immediately following notification of an event by the National Earthquake Information Center (NEIC). The core of this system is SPYDER®, which uses the NEIC location information to determine the appropriate time segments and gathers waveforms from stations that are available either on-line or via dial-up modem.

The USArray data will be processed and stored in a manner compatible with the way in which all other data are managed at the DMC. Waveform data entering the DMC will be handled using well-established international standards for formats and metadata (SEED and miniSEED). Procedures are in place to exchange metadata information with network operators to update needed information related to station configuration. The waveforms will be stored for four months in an on-line disk-based RAID system and the metadata will be managed in an Oracle Database Management System in a manner analogous to the way all other passive source data are archived. Data that are acquired from active source experiments will be received and stored in SEG-Y format and distributed as special volumes of "assembled data sets."

## USArray Data Flow to the DMC

### Data Flow From the Transportable Array

Data from the Transportable Array will be sent from the field in real time using TCP/IP communications protocols. Data from stations will flow from the stations to a Data Concentrator Node (DCN) that will be located where it can be connected to the Internet with high speed, reliable links. Often these links may be located at existing U.S. regional network data centers. From the concentrator, the data will simultaneously flow to the Array Network Facility (ANF) and the IRIS DMC. In the event that circuits from the DCN to either the DMC or the ANF fail, a dedicated frame relay link between the ANF and DMC will be used as a redundant communications path to the other center.

At the DMC, the data will be managed in a parallel system, dedicated to the management of USArray data. The data will flow into a Buffer for Uniform Data (BUD) system, similar to that used currently for reception of various data streams into the DMC. The data can then be made available through the BUD real-time data access methods and through the WILBER interface to the SPYDER® products.

IRIS is presently developing methods to automatically implement routine procedures to check data quality. Data from the BUD system will flow through these quality assurance tools and into the primary DMC archive. With about a five-week delay, data for larger events will be extracted from the archive and FARM products will be formed.

### Data Flow From the Permanent Array

Data flow from the permanent stations of the Backbone Network will be similar to that for the Transportable Array but will use communications systems established for the GSN and ANSS. Since the ANSS serves an essential role in operational monitoring of national and global earthquake activity, the data collection for these stations provides for additional redundancy and includes a direct node at the NEIC.

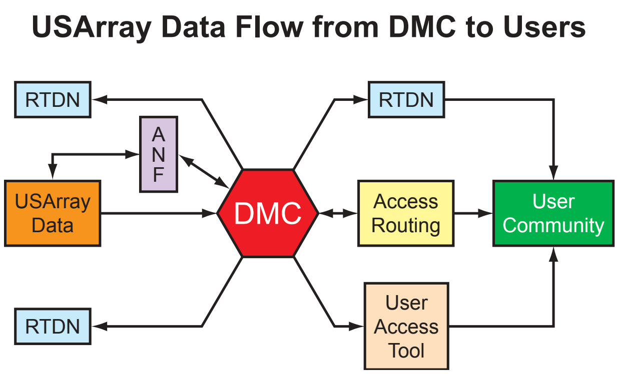



Figure II-1.10: The combined real time data rate from USArray may be more than 1.1 megabits per second (see Table II-1.1). Even data from the Transportable Array itself will be about 400 kilobits/second, one-quarter of a T1 circuit. As such it will not be likely that a single distribution point will be able to distribute all USArray data in real time. A data distribution system built upon the IRIS DHI model will be needed. The concept is to populate several Real Time Data Nodes (RTDNs) with copies of the real time data. Distribution to the community can be done from this distributed system. Real time data requestors will connect with a Access Routing server at the IRIS DMC to determine where to connect for real-time data streams. Non-real time data users will access data through traditional User Access Tools from the DMC. A hierarchical system of secondary and tertiary RTDNs could also be easily built using this system. Similar in concept to the Unidata Internet Data Distribution (IDD) System, this system would also support streaming data. See Figure II-1.11 for more detailed view of DMC archives and User Access Tools.

As the primary operator for the permanent USArray stations, the ASL will be responsible for monitoring operational status and for preliminary quality control. The data will then be forwarded to the IRIS DMC for archiving and distribution.

### Data Flow From the Flexible Array

As the name implies, the Flexible Array will be deployed in a variety of sizes, station geometries, and implementation modes. Data collection will vary significantly from one experiment to another and will be largely defined by the needs of the individual experiment and the Principal Investigator. Data from the Flexible Array will sometimes be telemetered and in other experiments will be locally recorded at the station site.

In telemetry mode, the data flow will be similar to that used for the Transportable Array, and data will be sent to the ANF, where quality control and reformatting will take place, and forwarded to both the IRIS DMC and the Principal Investigators. At the DMC, these data will flow through DMC quality assurance tools and then be archived with the other DMC data.

In experiments where on-site recording is used, the resources and tools developed at the ANF and DMC for quality control and data assimilation will be used to insure uniform data quality. It will be the responsibility of the ANF working together with the PI to provide final data products for archiving at the DMC. The involvement of additional USArray resources for data collection and during the experiment, and the mode of delivery to the DMC archive, will be defined during the planning stage for each experiment.

## Management of Real-time Data

In response to the increased use of real-time data collection in the GSN and PASSCAL programs, and in anticipation of the USArray portion of

EarthScope, the IRIS Data Management System began the development of the BUD system to ingest and manage large amounts of real-time data. Real-time data from seismic stations and networks can arrive in a variety of formats and via various communication protocols. The BUD converts these data into a standard format for use internally within the DMC and to provide a standardized interface to provide external users with access to real-time data. The BUD system has been functioning since 2001, and currently handles more data in real time than any individual USArray component will generate. Therefore, IRIS now has a reliable and dependable system that can receive the anticipated real-time data from USArray and we anticipate little new software development will be required for data ingestion. Not only can the IRIS DMS draw upon BUD for data reception, a series of tools have already been developed that can distribute data in real time as well. All of the systems that have been developed are scalable—as new data streams are added and as demand warrants, additional processors and RAID disk subsystems can be added to handle the increased load in a straightforward manner.

To minimize the impact of USArray data flowing into the DMC, a complete clone of the BUD system will be installed in order that the new data streams do not overtax existing DMC systems. USArray will require the installation of at least one SUN Enterprise class server and RAID system to manage USArray data. BUD applications and utilities will be installed on the new system. Since USArray will generate a very valuable scientific asset, we as-

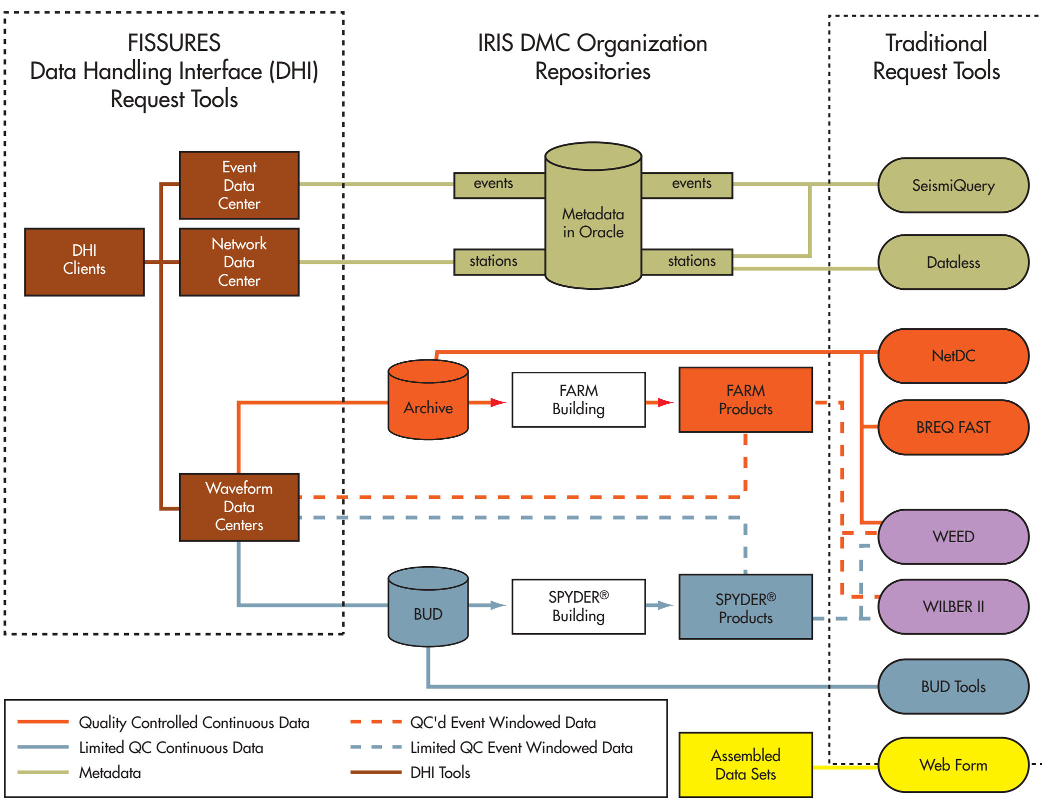



Figure II-1.11: This figure shows the four data repositories (Archive, BUD, FARM, and SPYDER®) that exist at the IRIS DMC. Continuous data are held in the Archive and the FARM; event-segmented products are in the FARM and SPYDER® systems. Data in the Archive and the FARM are quality controlled whereas BUD and SPYDER® data are real-time data with little or no quality control. USArray data will be available through a large variety of traditional data request tools supported at the IRIS DMC (as shown on the right) as well as the new FISSURES/DHI tools that support direct data access to clients from three types of Data Center Servers (Event, Network, and Waveform).

sume that users will generate an increased number of data requests for these data. To accommodate both the increased amount of data flowing into the DMC as well as an increase in the number of data requests, we anticipate increasing the throughput of the primary mass storage system by installing several more tape drives to the Powderhorn robotic system used in the DMC archive. This will allow more data to flow into and out of the primary mass storage system without degrading access to existing data sources.

## Distribution of USArray Data in Real Time

To a first approximation, USArray data from the Transportable Array will generate roughly one-quarter of a T1 data communications circuit. If only a small number of users wish to receive real-time feeds of the USArray data, the Internet connection at the IRIS DMC could become a bottleneck. IRIS has anticipated this and has begun to design systems that will need to be developed for a distributed system for real-time data.

Leveraging technology developed within the IRIS DMS FISSURES project, the Data Handling Interface (DHI) has become a viable method of distributing data in real time. In order to meet the anticipated real-time data distribution requirements of USArray, IRIS will develop a distributed data system for real-time data that will be built upon the DHI. Each node of this distributed system will consist of an inexpensive workstation and a disk buffer capable of holding one week of USArray data. DHI-based software will be installed on these systems and the turnkey systems can be installed at selected EarthScope participating universities as needed. This will be an effective was to ensure all desired USArray data is available to regional networks as desired. The universities will gain the advantage of having the USArray data available immediately from the local disk buffers.

The DHI-based software will transfer complete copies of the USArray data in real time from the IRIS DMC to each of the distributed nodes. DHI servers will also be installed at each of these nodes to provide full metadata and seismological waveform data as needed. IRIS will develop an intelligent DHI routing system whereby DHI-enabled clients will access a DHI server when the client wishes to gain access to real-time data streams from USArray. The server will determine the nature of the access desired and determine which of the distributed nodes can best serve the real-time data needs of the client. The server will direct the remote client to the most appropriate distributed node to meet its real-time needs. The client will then connect with the indicated server and transfer the requested waveform data or information from the RTDN to the client machine. The development of the real-time data distribution system will require funding from the Earthscope Operations and Maintenance as it is not specifically included as an MRE effort.

For non-real-time access to data, the powerful set of standard IRIS user tools will be available to access data from the archive (see Figure II-1.11 and www.iris.edu/manuals/DATutorial.htm). We project that the centralized node of the IRIS DMC should be able to continue servicing these requests directly through the existing DMC systems. As demand warrants additional resources can be installed at the DMC to scale the capabilities to meet user demands.

## Establishment of an EarthScope Data Portal

The UNAVCO and IRIS data handling systems are very mature and meet the needs of their respective communities very well. In the early stages of EarthScope activities we anticipate the two individual data management systems will continue to function well, in a manner similar to their operation today. Emphasis will be on scaling the existing systems to handle the increased data flow rather than the development of new technologies for data distribution or for integrating activities.

Of particular note within the respective systems are the UNAVCO Seamless Archive and the IRIS Networked Data Center concepts. Both of these systems are functioning and offer access to data in a distributed data center environment. UNAVCO can offer data from multiple GPS data providers in a one-stop shopping environment and the networked data centers system developed by IRIS offers access to seismological data residing in more than six different global and regional data centers.

As the initial step, we anticipate the development of an EarthScope portal through which the individual data management systems will be easily discovered and through which data are easily accessible. We will create this EarthScope data portal early in the process and will bring it on-line long before significant data from PBO or USArray begin to flow.

The development of the data portal and the support of the seamless archive and the networked data centers are the only parts of data distribution to end users that IRIS and UNAVCO propose to implement using MRE funding. All other development will rely upon Operations and Maintenance funds or funds that can be found from other sources such as Information Technology Research and/or Cyberinfrastructure.

## Integration of PBO and USArray Data

The CORBA based technology driving the IRIS DHI system is complicated but extremely powerful. It falls in a class of software reserved for Enterprise applications, such as EarthScope. One simple perspective of Enterprise systems such as CORBA is that the entire system is tightly controlled and understood by everyone involved in the development of servers and clients. In general such systems are not intended for casual, infrequent developers.

CORBA requires that well-defined interfaces exist to various kinds of data and information, and that client applications can access the various kinds of information. IRIS is experienced in developing the interfaces required to access most kinds of seismological data. Development of CORBA interfaces to GPS data has not yet been undertaken. UNAVCO and IRIS will jointly pursue the extension of FISSURES interfaces to geodetic data. In so doing, tight integration of seismological and geodetic data can be accomplished such that seamless access to both types of information will be possible.

While we believe CORBA to be a viable technology, developments in this area continue to take place at a rapid pace. For this reason we will examine other technologies, in addition to CORBA, to ensure that the technology we implement makes the most sense at the time we develop it. While we believe that choice today is CORBA, our solution may be different (XML, SOAP, XSLT) when the time for implementation comes.

Once the Interface Definition Language (IDL) or equivalent schema is designed for PBO and USArray data, staff at the IRIS DMC, UNAVCO Boulder Facility, or other university locations, will develop clients that will access the servers at IRIS and UNAVCO locations. These clients will provide seamless access to the GPS and seismological observations as well as the variety of data products and derived products generated using PBO and USArray data.

## EarthScope Products

The raw data from the core EarthScope PBO and USArray facilities will be large volumes of GPS and seismological waveforms and associated metadata. These primary observations are esoteric and only meaningful to experts in the particular sub-disciplines. However, there are routine products that come directly from the observations that are understood by a much broader community. For instance, catalogs of earthquake locations or crustal velocity models and images are well understood and very useful to a broad community. Similarly, experienced users of GPS data desire access to the raw phase data but these data are not of general Earth science use. However the routine calculation of precise locations or derived motion vectors is generally understood and possesses broad application. As an initial stage in the development of higher level EarthScope products related to USArray and PBO, the IRIS and UNAVCO data systems will develop systems to manage and distribute a wide variety of derived products or packages of primary observational data (such as the IRIS FARM) for easy access to and use by the scientific community.

The exact types of products need to be defined by a broad cross section of the Earth sciences community. As these products are defined, and processing methods developed to produce them, IRIS and UNAVCO will develop data management plans for these products under the Operations and Maintenance portion of EarthScope.

## Education and Outreach

All EarthScope components are committed to ensuring that the data collected by the facilities will be openly available to all interested parties—including the public and especially the educational sector. We are aware that to be useful to the K-16 educational community, it is not sufficient to simply declare the data “open” – it is essential that data be provided in formats and as products that are accessible to educators and students, and that there be appropriate teaching modules to allow the resources to be incorporated into an inquiry-based learning experience.

IRIS intends to provide educational linkages to USArray through both the existing IRIS Education and Outreach Program and through a larger EarthScope educational enterprise as it develops. Facilities and experience developed as part of the IRIS E&O Program provide a natural pathway for access to the seismological data produced as part of USArray and to resources developed to incorporate seismology into the K-16 learning environment. Broader EarthScope outreach activities (such as those proposed in the EarthScope Education and Outreach Program Plan) will place the seismological resources of USArray and IRIS in the broader context of the full EarthScope enterprise and the Earth sciences.

Seismology-related products designed for groups outside the scientific research community will continue to be developed by the IRIS Education and Outreach (E&O) program in cooperation with other EarthScope partners. Current IRIS E&O activities are targeted at audiences ranging from K-16 students to the general public, and are focused on areas where IRIS is well-positioned to make substantive contributions stemming from its strong research and data resources. Outreach to the general public includes a distinguished lecture program, and museum exhibits with real-time displays of earthquake locations and ground motion. Efforts that engage the wider education community include a range of K-16 teacher workshops, a new Educational Affiliate membership for undergraduate institutions, and widely distributed teaching modules and associated tools. Students can access earthquake locations and global seismic data from the IRIS Data Management System in near real time as well as by selecting events from the online archives. Students can also collect their own seismic data using a stand-alone, relatively inexpensive seismograph, or with research-quality broadband instruments with continuous network connections. Consortium members are currently developing new visualization tools and classroom activities using seismic data, and this will expanded to include data from USArray. Visualization tools include large-scale efforts like the Global Earthquake Explorer, which is being developed by IRIS E&O through a subcontract to the University of South Carolina and will provide an online seismic data analysis environment tailored to general public and educational users

As part of USArray, IRIS proposes to carry out the following core level education and outreach activities:

- Integration of USArray data into the educational data streams available from the IRIS DMC. This integration is a relatively straightforward task since most of the necessary resources are already under development.

- Interaction with the broader EarthScope E&O effort as it becomes defined. We anticipate that this will take the form of collaboration with the efforts of the EarthScope facilities, a variety of local educational alliances distributed across the country, and numerous partners representing national and local organizations with similar science, education, and outreach goals.

- Development of both generic and region-specific outreach materials related to USArray activities as the array installation proceeds across the continent. The deployment process will provide unique opportunities to introduce local residents to seismology and the Earth sciences. For example, the museum and distinguished lectureship programs, which currently are focused on large museums throughout the US, could effectively be expanded to also target the smaller communities where USArray stations are located. Providing educational seismographs to schools may be able to help to play a role in permitting USArray sites by establishing connections to local communities before the arrival of USArray. A short video designed for landowners and park officials could be produced to describe the purpose and requirements of a USArray site. All of these activities will be closely coordinated with UNAVCO in the deployment of PBO.

# 1.5. Budget Structure

The proposed USArray budget is assembled from program estimates and projections based on budgeting and cost experience with IRIS programs, under the current and previous Cooperative Agreements between IRIS and NSF, and estimates of expenses for future equipment and tasks based on present information. Although there are many factors that could significantly alter the mode of USArray operation and cost estimates, the combined five-year budgets in this MREFC proposal and the accompanying R&RA O&M proposal are provided to indicate the funding required to accomplish the work described in the USArray component of the EarthScope Project Plan.

Key assumptions in formulating this budget include:

- The Transportable Array and Permanent Array will be fully-supported systems with real-time telemetry and near real-time access to the seismological community. To provide close interactions with existing PASSCAL facilities, the Array Operations Facility will be established at the initiation of the EarthScope program through a core sub-award linked to the PASSCAL Instrument Center in Socorro New Mexico. A letter of support from New Mexico Tech, describing the construction of new facilities to be provided by the university, is included in this proposal.

- The Flexible Array will be an enhanced PASSCAL system, available for PI-driven deployments and offering real-time data and near real-time access to the seismological community wherever possible. Equipment for the Flexible Array will be acquired, supported and serviced by the Array Operations Facility in Socorro.

- To provide full coordination with the USGS during development of the Advanced National Seismic System, the Albuquerque Seismological Laboratory (ASL) will be the prime subaward for site surveying, preparation, installation for the Backbone Network. A letter from the USGS indicating their collaboration in the development of this permanent network is included in this proposal.

- An Array Network Facility will be established to coordinate the collection, quality assurance and forwarding to the DMC of all data from the Transportable Array and the Flexible Array. The Array Network Facility will be selected through a competitive process during the first year of the EarthScope project and will operated as a core facility sub-award through IRIS.

- All permanent equipment will be titled to NSF with inventory control through IRIS.

- The IRIS Data Management Center (DMC) will be the primary data archive and distribution node for all USArray data.

Operations of most IRIS facilities are carried out under subawards to other institutions. Except for the Data Management Center, which is operated and staffed by IRIS personnel, all of the major facility activities are managed with IRIS direction and oversight, but staffed and operated through subawards. This mode of operation will continue under EarthScope.

Types of sub-awards that will be used in USArray include:

- Operation of Core Facilities: These awards make up the primary operational component of the core USArray facilities operating under EarthScope. These sub-awards are intended to be long-term commitments, to provide operational stability, with annual review and renewal. The Array Operations Facility at New Mexico Tech, the subaward to the USGS ASL for the Backbone Network, and the subaward for operation of the Array Network Facility will be managed in the fashion.

- Supplemental Support for Co-operating Facilities: These will be awards for supplemental support of on-going activities at existing university or related centers. It is anticipated that some support for regional networks related to field support for the Transportable Array, the MT operations and Education and Outreach activities will be managed in this fashion.

- Commercial contract : The primary support for field operations for Bigfoot will be competed for services to be provided, under the direction of the PASSCAL Program Manager, by a commercial contractor experienced in the operation of large field support programs.

An overview of the USArray budget is given in Table II-1.2. The spreadsheet is an annual summary of the key budgetary items: Transportable Array hardware, Flexible Array hardware, Backbone Network hardware, IRIS facilities and management, and subawards. This budget summary is also shown diagrammatically in Figure II-1.12. Additional details on each of these major categories will be given in following sections.

The primary budget components are:
- More than 50% for field hardware.
- 37% for subawards for installation, O&M
- 12% for the IRIS DMC and management.

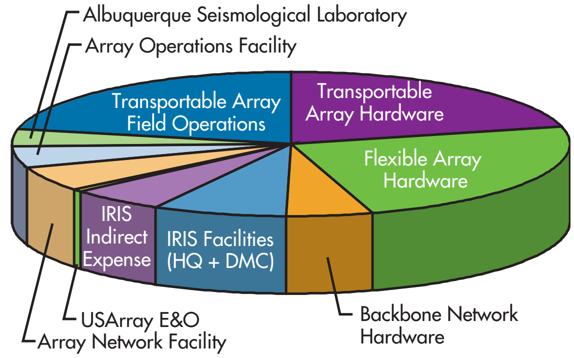


Figure II-1.12 Graphical representation of USArray costs

## Hardware Costs

The hardware items used to estimate the costs of the field systems are briefly summarized below. These estimates are based on commercially available components presently used in IRIS field systems that meet the standards established for the PASSCAL, ANSS, and GSN programs. It is anticipated that these components will be used for procurement during the initial phases of USArray construction, but, as technology evolves, the marketplace will be continually re-assessed to ensure that the most cost effective purchases are made. This will be especially true in the areas of communication, power systems and ancillary computer equipment. It is less likely that there will be significant changes in the makeup of the primary sensors and data acquisition systems.

### Transportable Array

The key components used to estimate the costs of the Transportable Array field station are those used in the current PASSCAL telemetered broadband array:
- 400 broadband sensors, digitizers, GPS, routers, Starband satellite communications systems, cables, solar-power cells, mini-vault, shipping cases.
- 30 MT instruments, GPS, power systems, enclosures, cable conduit.
- 10 data concentrators, lab equipment and field tools.

## Table II-1.2. USArray MREFC Budget Overview

| | Year 1 | Year 2 | Year 3 | Year 4 | Year 5 | MRE Total |
|---|---|---|---|---|---|---|
| **Transportable Array Hardware** | **$3,550,250** | **$3,725,280** | **$3,695,030** | **$3,664,780** | | **$14,635,340** |
| Equipment | | | | | | |
| 400 stations | $3,520,000 | $3,520,000 | $3,520,000 | $3,520,000 | | $14,080,000 |
| Concentrators, lab | $30,250 | $60,500 | $30,250 | | | $121,000 |
| 30 MT | | $144,780 | $144,780 | $144,780 | | $434,340 |
| **Flexible Array Hardware** | **$3,401,250** | **$3,434,500** | **$3,401,250** | **$3,368,000** | **$3,368,000** | **$16,973,000** |
| Equipment | | | | | | |
| 100 Broadband telemetered | $680,000 | $680,000 | $680,000 | $680,000 | $680,000 | $3,400,000 |
| 100 Broadband | $554,000 | $554,000 | $554,000 | $554,000 | $554,000 | $2,770,000 |
| 100 Short-period telemetered | $450,000 | $450,000 | $450,000 | $450,000 | $450,000 | $2,250,000 |
| 100 Short-period | $324,000 | $324,000 | $324,000 | $324,000 | $324,000 | $1,620,000 |
| 2000 Active source | $1,360,000 | $1,360,000 | $1,360,000 | $1,360,000 | $1,360,000 | $6,800,000 |
| Concentrators, lab, comms | $33,250 | $66,500 | $33,250 | | | $133,000 |
| **Backbone Network Hardware** | **$3,458,830** | | | | | **$3,458,830** |
| Equipment | | | | | | |
| 26 NSN - new and upgrades | $1,003,050 | | | | | $1,003,050 |
| 9 GSN - new and upgrades | $1,190,000 | | | | | $1,190,000 |
| 16 GPS | $404,000 | | | | | $404,000 |
| 10 MT | $144,780 | | | | | $144,780 |
| Spares | $717,000 | | | | | $717,000 |
| **IRIS Facilities** | **$1,440,670** | **$1,230,876** | **$1,219,764** | **$988,790** | **$1,008,271** | **$5,888,371** |
| Headquarters | | | | | | |
| Staff | $236,385 | $243,477 | $250,781 | $258,304 | $266,053 | $1,255,000 |
| Program Managers | $128,385 | $132,237 | $136,204 | $140,290 | $144,498 | $681,613 |
| Other Direct Costs | $337,600 | $347,800 | $373,200 | $166,200 | $166,200 | $1,391,000 |
| Data Management Center (DMS) | | | | | | |
| Staff | $283,500 | $292,005 | $300,765 | $250,781 | $258,304 | $1,385,355 |
| Other Direct Costs | $404,800 | $165,358 | $58,815 | $73,215 | $73,215 | $775,402 |
| E&O | $50,000 | $50,000 | $100,000 | $100,000 | $100,000 | $400,000 |
| **Subawards** | **$2,368,172** | **$4,794,368** | **$6,779,128** | **$7,332,581** | **$3,663,820** | **$24,938,069** |
| Array Operations Facility | | | | | | |
| Staff | $343,807 | $561,743 | $882,549 | $1,002,948 | $1,033,036 | $3,824,083 |
| Other Direct Costs | | | | | | |
| Array Network Facility | | | | | | |
| Staff | $309,248 | $567,373 | $670,516 | $690,631 | | $2,237,769 |
| Other Direct Costs | $411,995 | $301,291 | $122,655 | $135,235 | $100,640 | $1,071,816 |
| Albuquerque Seismological Laboratory (USGS) | | | | | | |
| Personnel | $264,640 | $430,427 | $361,332 | | | $1,056,399 |
| Other Direct Costs | $477,704 | $578,859 | $548,794 | | | $1,605,357 |
| Transportable Array field operations | | | | | | |
| Staff | $232,000 | $1,178,320 | $2,079,364 | $2,456,450 | $2,530,144 | $8,476,278 |
| Other Direct Costs | $328,778 | $1,176,356 | $2,113,918 | $3,047,316 | | $6,666,368 |
| **Subtotal - Direct Expenses** | **$14,219,172** | **$13,185,024** | **$15,095,173** | **$15,354,150** | **$8,040,091** | **$65,893,611** |
| **IRIS Indirect Expenses** | **$936,973** | **$804,473** | **$807,372** | **$756,905** | **$523,924** | **$3,829,647** |
| **Management Fee** | **$25,000** | **$25,000** | **$25,000** | **$25,000** | **$25,000** | **$125,000** |
| **Total** | **$15,181,145** | **$14,014,497** | **$15,927,545** | **$16,136,055** | **$8,589,015** | **$69,848,258** |

The unit purchase cost of hardware for each Transportable Array station is estimated to be:

| | Seismic | MT |
|---|---|---|
| Sensor | $ 14,500 | $ 33,000 |
| Digitizer | $ 10,000 | |
| Cables | $ 1,200 | |
| Telemetry | $ 3,500 | |
| Power | $ 4,000 | |
| Materials | $ 2,000 | $ 1,278 |
| **Total** | **$ 35,200** | **$ 34,278** |

## Flexible Array

The Flexible Array hardware is based on the elements used in the current PASSCAL systems for active source and temporary passive source experiments and the PASSCAL telemetered broadband array:

- 100 broadband sensors, digitizers, GPS, satellite communications systems, cables, solar power cells, mini-vault, shipping cases— for broadband telemetered recording.
- 100 short-period sensors, digitizers, GPS, satellite communications systems, cables, solar power cells, mini-vault, shipping cases—for short-period telemetered recording.
- 100 broadband sensors, digitizers, GPS, cables, solar power cells, mini-vault—for broadband on-site data recording.
- 100 short-period sensors, digitizers, GPS, cables, solar power cells, mini-vault—for short-period on-site data recording.
- 2000 4.5 Hz geophones, digitizers, cables—for active-source experiments.

The unit purchase cost of hardware for each configuration of a Flexible Array station is estimated to be:

| | Broadband | Short-period | Active Source |
|---|---|---|---|
| Sensor | $ 15,000 | $ 3,500 | $ 200 |
| Digitizer | $ 9,000 | $ 9,000 | $ 3,200 |
| Cables | $ 500 | $ 500 | |
| Telemetry | $ 3,500 | $ 3,500 | |
| Power | $ 4,000 | $ 4,000 | |
| Materials | $ 2,000 | $ 2,000 | |
| **Total** | **$ 34,000** | **$ 22,500** | **$ 3,400** |

## Backbone Network

The standard equipment adopted for use at GSN and ANSS stations will be the primary hardware components for the Backbone Network:

- 9 GSN-quality sensors, digitizers, communications and power systems.
- 27 NSN-quality sensors, digitizers, communications and power systems.
- 16 permanent GPS stations, receiver, choke-antenna, short-braced drill monument, power systems, cable conduit.
- 10 MT instruments, GPS, power systems, enclosures, cable conduit.
- Spares – 2 complete GSN systems, 5 complete NSN systems.

The unit purchase cost of hardware for a new ANSS-quality station and a GSN-quality borehole station is estimated to be:

| | New NSN | New GSN |
|---|---|---|
| Sensors | $ 18,000 | $ 149,000 |
| Digitizer | $ 10,000 | $ 21,000 |
| Microbarograph | $ 3,000 | |
| Cables | $ 1,200 | $ 2,000 |
| Telemetry | $ 5,000 | $ 7,000 |
| Power | $ 9,000 | $ 16,000 |
| **Total** | **$ 43,150** | **$ 198,000** |

### Sub-awards

Key sub-awards are given in Table II-1.2, and shown diagrammatically in Figure II-1.12.

- The Array Operations Facility at New Mexico Tech will be operated as a core facility sub-award through IRIS, and will be responsible for Transportable Array support and Flexible Array system integration, shipping and maintenance. A statement of work and budget from New Mexico Tech for this effort is included in the detailed budget section of this proposal.

- The subaward for the Array Network Facility will be issued based on a competitive process during the first year of the EarthScope program. It will be operated as a core facility subaward through IRIS and will be responsible for Transportable Array and Flexible Array real-time data collection, quality assurance, meta-data maintenance, data forwarding to the DMC, and real-time communications O&M. It will also be responsible for quality assurance and data handling of all field-recorded data in the Flexible Array, and forwarding of these data to the DMC.

- The Backbone Network installation will be performed under a core-facility subaward to ASL. A statement of work and budget for ASL is included in the detailed budget section of this proposal.

### IRIS Facilities

The additional burden of 4.2 Tb of data per year generated by USArray will require additional hardware and personnel resources at the Data Management Center (DMC) to provide a level of service commensurate with current requests. The basic infrastructure at the DMC has been designed in a way that allows relatively easy expansion to accommodate new data sources. In addition, the mass store at the core of the DMC archive can be expanded to incorporate the volumes of data expected from USArray. To meet the increased demand on the archive, DLT and 9940 tape drives will be added. A 3 Tb RAID and server will be required for servicing on-line data storage and requests. All hardware will be purchased in Year 1 to prepare for real-time data that will start to arrive at the DMC soon after the award is issued.

The DMC will require additional staffing commencing in Year 1 to deal with the integration of new archival and RAID hardware with current DMC resources. New data technicians will be required to ensure problem-free handling of the data as it arrives at the DMC.

### IRIS Management and Overhead

General and Administrative costs will cover the support of those administrative activities at IRIS headquarters required for USArray coordination, purchasing and business office activities.

## Staffing and Operations

Figure II-1.13 shows the staffing levels required for installation, operation and maintenance of USArray. The full complement of personnel required at peak activity is shown in this figure. The ramp-up in personnel (Figure II-1.14) will be commensurate with activities, as indicated in the budget detail section of this proposal. Five activity clusters are indicated:

### IRIS Personnel (DMC and Program Management)

The incremental USArray activities at the IRIS Data Management Center in Seattle will require a total of 7 FTE as additional data technicians and system administration support.

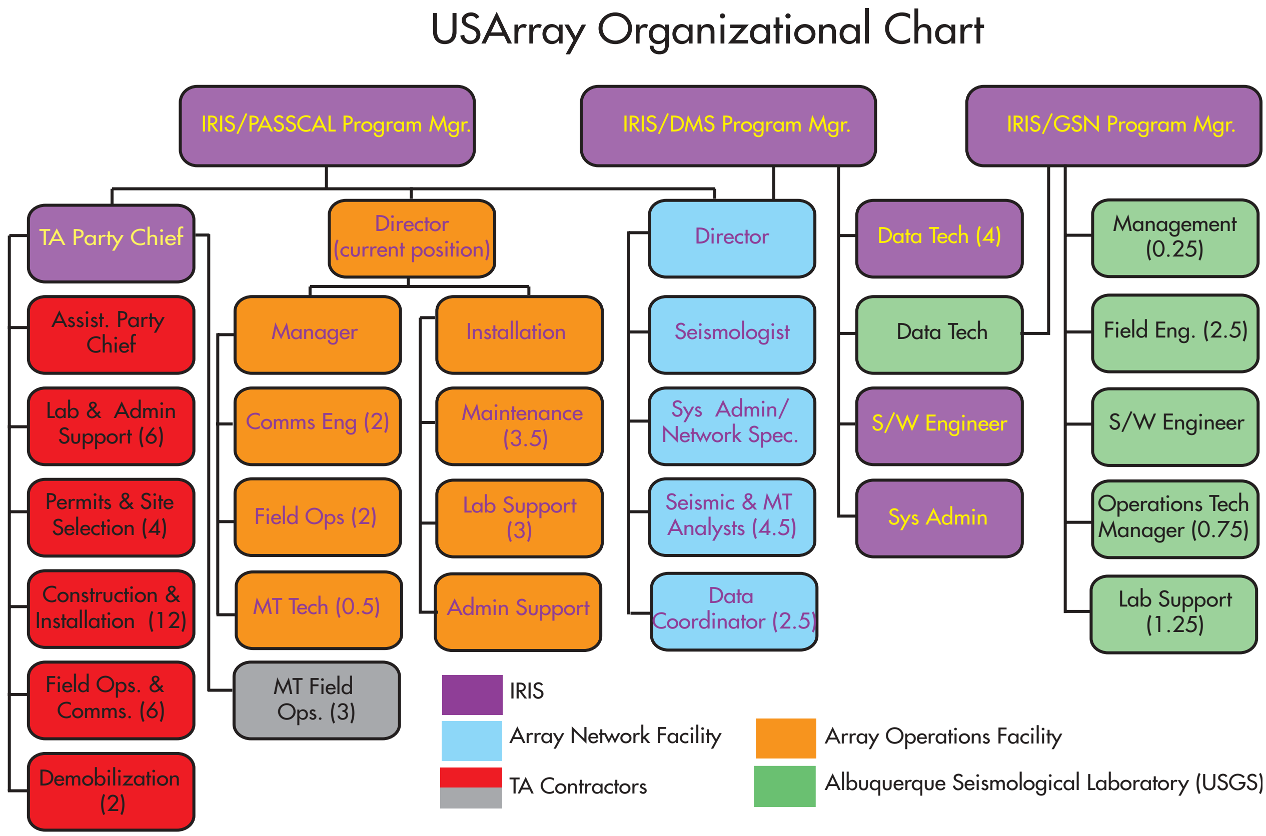



Figure II-1.13. Staffing requirements and organizational chart for USArray construction and operations at peak levels. Figure II-1.14 shows the way in which this staffing level ramps up and the separation between support from the MREFC account (for construction) and the R&RA account (for operations).

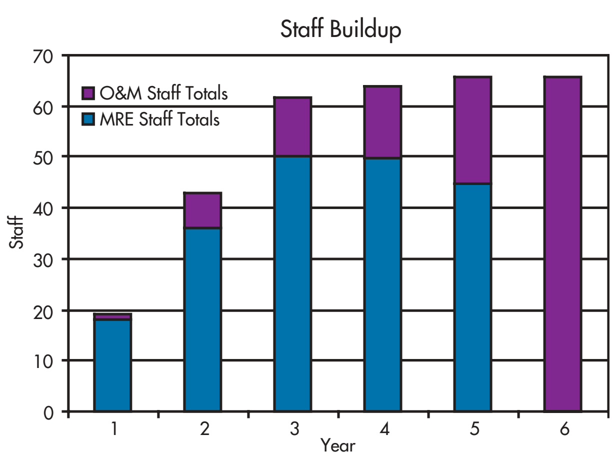



Figure II-1.14 Annual requirements for staffing of USArray construction and operations. MREFC staff funded through this proposal. O&M staff funded through the separate R&RA proposal.

Partial support for the IRIS Program Managers for PASSCAL, GSN, DMS E&O and full support for the Transportable Array Party Chief are included for oversight and management of USArray operations. Additional staff at IRIS headquarters (2 FTE) includes dedicated administrative and project support for USArray. Support for overall program direction, including senior management at IRIS headquarters, is covered through indirect cost recovery.

## Array Operations Facility (14 FTE)

The personnel required to staff the Array Operations Facility in Socorro will be hired under subaward to New Mexico Tech. This group will be responsible for services related to instrumentation for the Flexible Array and for partial support and maintenance of equipment for the Transportable Array. The details of the Array Operations Facility personnel and staffing build-up is included in the subaward proposal from New Mexico Tech included in the budget detail section of this proposal.

### Array Network Facility (10 FTE)

The Array Network Facility will monitor the real time communication of data from field stations to the DMC. It will carry out basic QC on the data, perform event locations, and provide the DMC with metadata related to station operations.

### Backbone Network Operations (5.75 FTE)

The installation and operation of the permanent stations of the Backbone Network will be carried out under subaward to the USGS ASL. Most of the FTEs involved in this operation will be contract personnel under the direction of USGS employees at ASL.

### Transportable Array Installation (31 FTE)

The field operations related to the installation of Bigfoot will be performed by contract personnel under the direction of IRIS staff (Array Party Chief and PASSCAL Program Manager). The use of contract personnel allows for the flexibility that will be required in the complex field operations as Bigfoot moves across the country. It is anticipated that a limited number of key contract personnel will have a long-term involvement in the project, but many of the members of the installation teams will be hired on a temporary basis as the array moves from one region to another.

## Implementation

Careful attention has been applied to the ramping-up of the USArray facilities so as to minimize recurring and personnel costs, yet be fully cognizant of the manufacturing capacity of the sensor and data acquisition vendors.

The general implementation plan include the following milestones:

- Orders for significant hardware are placed throughout Years 1-5. A large spike expenditure occurs in Year 1 with the purchase of all Backbone Network equipment. Hardware purchasing then remains level through Years 2-4, dropping in Year 5 when only Flexible Array equipment is purchased. Most of the equipment being purchased for the Transportable and Flexible Arrays is based on subsystems, with the Array Operations Facility being responsible for system integration and testing before deployment. A schedule for equipment purchasing is shown in Table II-1.3. It is anticipated that it could take

Table II-1.3. Proposed Schedule for Purchasing of USArray Field Hardware

| | Year 1 | Year 2 | Year 3 | Year 4 | Year 5 |
|---|---|---|---|---|---|
| **Transportable Array Hardware** | | | | | |
| 400 Broadband telemetered | 100 | 100 | 100 | 100 | |
| 30 MT | 0 | 10 | 10 | 10 | |
| **Flexible Array Hardware** | | | | | |
| 100 Broadband telemetered | 20 | 20 | 20 | 20 | 20 |
| 100 Broadband | 20 | 20 | 20 | 20 | 20 |
| 100 Short-period telemetered | 20 | 20 | 20 | 20 | 20 |
| 100 Short-period | 20 | 20 | 20 | 20 | 20 |
| 2000 Active source | 400 | 400 | 400 | 400 | 400 |
| **Backbone Network Hardware** | | | | | |
| NSN - new and upgrades | 27 | | | | |
| GSN - new and upgrades | 13 | | | | |
| GPS | 16 | | | | |
| MT | 10 | | | | |
| Spares | 8 | | | | |

up to 12 months to field the stations after equipment orders are placed in order to take delivery, perform systems integration and acceptance tests.

- Site selection, permitting, and documentation will start immediately upon announcement of EarthScope funding. Permitting has the longest lead-in time, and could precede actual field deployment by up to two years.

- Since hardware acquisition occurs early in the award, the subaward for the Array Operations Facility will be initiated early in Year 1. Because of the close links between USArray and PASSCAL operations, there are significant benefits to having this part of the USArray facility located at New Mexico Tech.

- Initial deployments of stations of the Transportable Array will be closely coordinated with regional networks in California and other parts of the southwestern U.S. The expertise available from local networks operators will greatly facilitate the siting and permitting of Bigfoot stations. Some of the early Bigfoot installation may be achieved through collocation of broadband instruments at regional network stations equipped with only short period sensors.

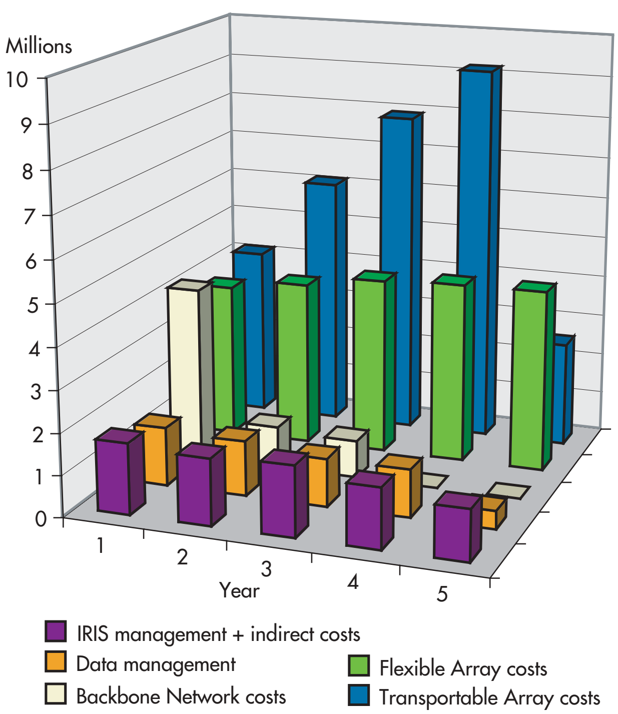



Figure II-1.15. USArray MREFC costs broken down by year and activity. Costs for each element include hardware and associated installation an personnel costs.

- Although a significant volume of new data will not be generated until Year 2 as new Transportable Array stations are installed, there will be opportunities in the early stages of EarthScope to interact with regional networks on the exchange of data from existing stations and to coordinate procedures for provision of Bigfoot data for use by the regional networks. To facilitate these interactions, it is important for enhancements at the DMC to begin in Year 1.

- Because data flow is not significant in Years 1-2, the building of the Array Network Facility can ramp up, following its initiation in Year 1, until it is fully functional in Year 3. Computers, mass-storage devices, and other equipment will be bought, along with software development in Years 1-2. Data analysts will not be required until Year 3.

- The Backbone Network installation will commence in Year 1 with the purchasing of equipment and the upgrading of existing NSN sites to GSN or ANSS-quality NSN. The remainder of the existing NSN sites will be upgraded in Year 2, with work commencing on new GSN and new NSN sites. The installation of the new sites will occur during Year 3. The GPS equipment will be collocated with the GSN stations, with implementation during Years 1-3 concurrent with the seismic station installations.

- Given the requirements for completing the first full deployment of the Transportable Array by the end of Year 4, and the complete deployment

Table II-1.4. Proposed Schedule for Deployment of USArray Field Stations

| | Year 1 | Year 2 | Year 3 | Year 4 | Year 5 |
|---|---|---|---|---|---|
| **Transportable Array** | | | | | |
| 400 Broadband telemetered | 20 | 80 | 140 | 160 | 200 (redeploy) |
| **Backbone Network** | | | | | |
| NSN - new and upgrades | 10 | 10 | 7 | | |
| GSN - new and upgrades | 3 | 5 | 5 | | |

of the Backbone Network by the end of Year 3, coupled with staffing and budgeting levels and the manufacturing capabilities of the vendor of equipment, Table II-1.4 estimates the number of Transportable Array and Backbone Network stations that will be brought on line during each of the first five years of the project.

## Operations and Maintenance

As the USArray facility is created, operational costs will be transitioned from the MREFC account to the Research and Related Activities (R&RA) account. NSF has indicated that separate proposals should be provided for the installation of USArray under the MREFC, and operations from the R&RA accounts. Details of the O&M costs for years 1-5, and an estimate of annual costs for years 6-10 are given in Table II-1.5. The O&M costs are closely integrated with the MRE budget (Table II-1.2), yet make a clear separation between the building of the facility and the routine operations and maintenance. This section defines operations and maintenance costs that will be incurred under the R&RA account during Years 1-5 of the MRE-funded facility building, and estimates the routine cost of O&M in the out-years. More details on the USArray O&M costs are to be found in the separate proposal being submitted to NSF for EarthScope Facility Operations and Maintenance.

Once each station within the Transportable Array is installed during the initial deployment, the station is declared to be running in a calibration mode. Data will be transmitted to the ANF and DMC, archived and distributed to the community on demand. During this calibration period, all maintenance site visits, communications costs, etc, will be covered by the MRE during this period. It is expected that late in Year 4 of the MRE the Transportable Array will be deemed fully operational, and all costs associated with operations and maintenance will be transferred to the R&RA funds. The Transportable Array will commence to "roll" in Year 5, and all costs associated with the redeployment of Transportable Array stations will be funded under O&M.

The Flexible Array follows the same model of current PASSCAL PI-driven experiments, with PIs funding deployments from their research grants.

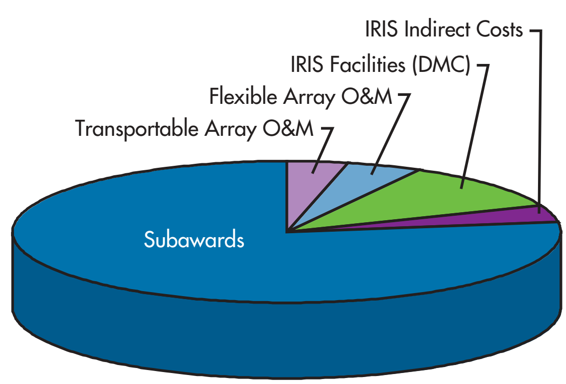



Figure II-1.16. Graphical representation of USArray Operations and Maintenance Budget

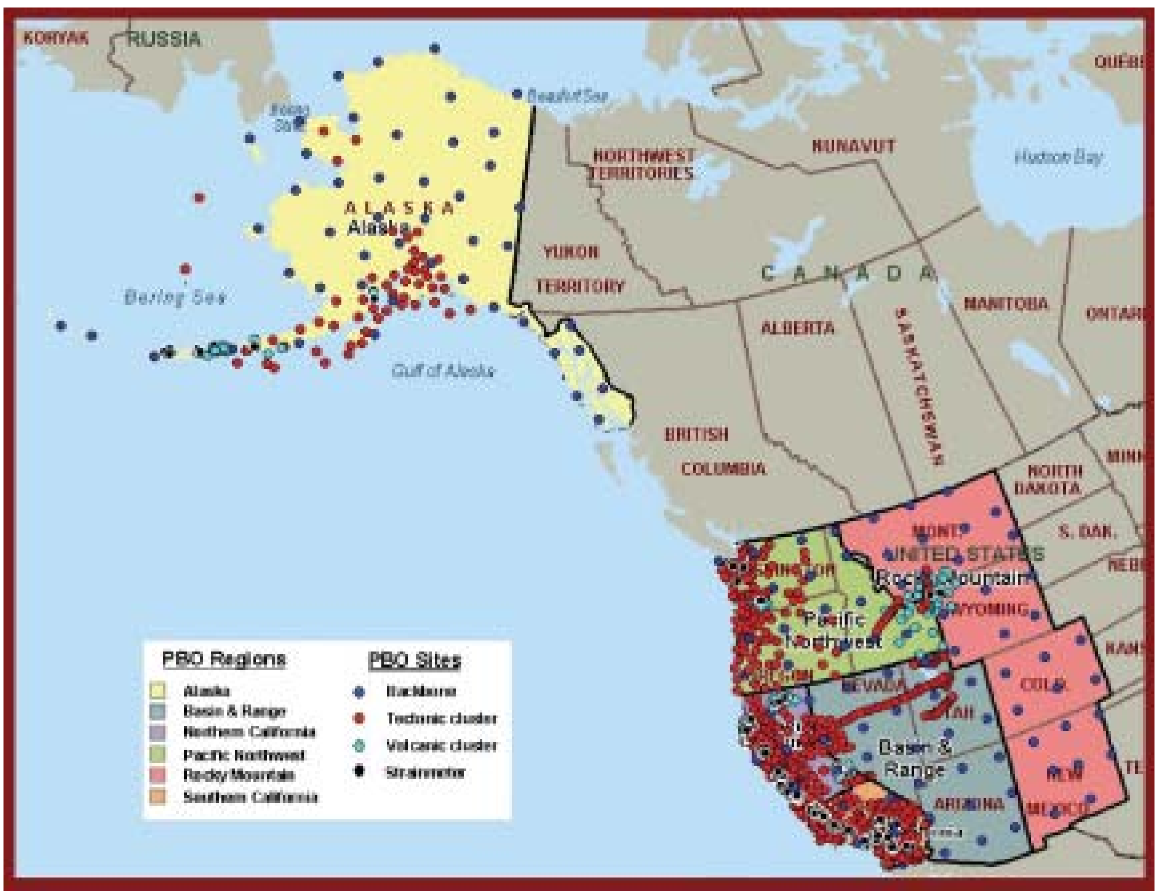
However, some operations and maintenance for the Flexible Array is to come from the R&RA account to cover maintenance of hardware at the Array Operations Facility, shipping, training of PIs, etc. The O&M budget includes a 3% of capitalization to cover Transportable Array and Flexible Array equipment maintenance.

It is anticipated that O&M for the Backbone Network will be funded by USGS following the five-year MRE operations, and all costs for the Backbone Network after Year 3 will be the responsibility of the USGS. Spares for the Backbone Network will be bought in Year 1 of the MRE in lieu of maintenance billing.

### Table II-1.5. Proposed USArray Operations and Maintenance Budget for Support Through a Separate R&RA Proposal, Years 1-5, and Estimate for Year 6

| | Year 1 | Year 2 | Year 3 | Year 4 | Year 5 | O&M Total | Year 6 |
|---|---|---|---|---|---|---|---|
| **Transportable Array Hardware** | **$106,508** | **$218,266** | **$329,117** | **$439,060** | **$439,060** | **$1,532,011** | **$452,232** |
| Maintenance (3% capital cost) | $106,508 | $218,266 | $329,117 | $439,060 | $439,060 | $1,532,011 | $452,232 |
| **Flexible Array Hardware** | **$102,038** | **$205,073** | **$307,110** | **$408,150** | **$509,190** | **$1,531,560** | **$524,466** |
| Maintenance (3% capital cost) | $102,038 | $205,073 | $307,110 | $408,150 | $509,190 | $1,531,560 | $524,466 |
| **IRIS Facilities** | **$-** | **$106,978** | **$273,289** | **$447,289** | **$456,583** | **$1,284,139** | **$1,494,492** |
| Headquarters | | | | | | | |
| Staff | | | | | | | $274,035 |
| Program Managers | | | | | | | $148,833 |
| Other Direct Costs | | | | | | | $166,200 |
| Data Management Center (DMS) | | | | | | | |
| Staff | | $55,620 | $186,188 | $309,788 | $319,082 | $870,678 | $594,708 |
| Other Direct Costs | | $51,358 | $87,101 | $137,501 | $137,501 | $413,462 | $210,716 |
| E&O | | | | | | | $100,000 |
| **Subawards** | **$121,662** | **$808,381** | **$1,330,215** | **$1,624,777** | **$5,643,094** | **$9,528,128** | **$9,4431,228** |
| Array Operations Facility | | | | | | | |
| Staff | $85,952 | $384,682 | $396,223 | $408,109 | $420,352 | $1,695,318 | $1,496,990 |
| Other Direct Costs | $14,470 | $21,705 | $28,940 | $43,410 | $43,410 | $151,935 | $43,410 |
| Array Network Facility | | | | | | | |
| Staff | | $125,419 | $399,849 | $500,549 | $1,226,916 | $2,252,734 | $1,263,724 |
| Other Direct Costs | | $18,870 | $31,450 | $157,250 | $191,845 | $399,415 | $229,585 |
| ASL Data Collection Center | | | | | | | |
| Personnel | $14,800 | $76,220 | $78,507 | $80,862 | $83,288 | $333,676 | $85,786 |
| Other Direct Costs | $6,440 | $33,165 | $34,160 | $35,185 | $36,240 | $145,189 | $37,327 |
| MT Install & Ops | | $148,320 | $361,087 | $399,412 | $406,493 | $1,315,312 | $413,786 |
| Transportable Array field operations | | | | | | | |
| Staff | | | | | $162,073 | $162,073 | $2,772,984 |
| Other Direct Costs | | | | | $3,072,476 | $3,072,476 | $3,097,636 |
| **Subtotal - Direct Expenses** | **$330,207** | **$1,338,698** | **$2,239,731** | **$2,919,276** | **$7,047,927** | **$13,875,838** | **$11,912,418** |
| **IRIS Indirect Expenses** | **$40,766** | **$100,851** | **$161,523** | **$223,120** | **$244,773** | **$1,542,065** | **$475,791** |
| **Total** | **$370,973** | **$1,439,549** | **$2,401,254** | **$3,142,396** | **$7,292,700** | **$14,646,871** | **$12,388,209** |

# 2. PBO: Plate Boundary Observatory


KORYAK
RUSSIA
Beaufort Sea
NORTHWEST TERRITORIES
NUNAVUT
Hudson Bay
ALASKA
Alaska
YUKON TERRITORY
CANADA
Bering Sea
ALBERTA
SASKATCHEWAN
MANITOBA
Gulf of Alaska
BRITISH COLUMBIA
NORTH DAKOTA
S. DAK.
UNITED STATES
Rocky Mountain
WYOMING
Pacific Northwest
Basin & Range
ARIZONA
PBO Regions
Alaska
Basin & Range
Northern California
Pacific Northwest
Rocky Mountain
Southern California
PBO Sites
Backbone
Tectonic cluster
Volcanic cluster
Strainmeter

# 2.1. Introduction and Proposal Summary

PBO is a geodetic observatory designed to study the three-dimensional strain field resulting from deformation across the active boundary zone between the Pacific and North American plates in the western United States. PBO will address the following scientific questions:

- What are the forces that drive plate-boundary deformation?
- What determines the spatial distribution of plate-boundary deformation?
- How has plate-boundary deformation evolved?
- What controls the space-time pattern of earthquake occurrence?
- How do earthquakes nucleate?
- What are the dynamics of magma rise, intrusion, and eruption?
- How can we reduce the hazards of earthquakes and volcanic eruptions?

Answering these questions will require that plate boundary deformation be adequately characterized over the maximum ranges of spatial and temporal scales common to active continental tectonic processes. This proposal requests funding for a Plate Boundary Observatory Facility to build a geodetic instrumentation network across this region to capture and quantify the deformation process. The geodetic instrumentation proposed for this facility must provide: (a) sufficient coverage of the plate boundary zone so as to capture the secular tectonic component, (b) appropriate station density for detecting localized (e.g., seismic or magmatic) phenomena, and (c) the necessary bandwidth (seconds to decades) to detect plausible transient phenomena ranging from fast and slow earthquakes to interseismic strain buildup and post-seismic viscoelastic relaxation. To address a range of scientific issues including plate boundary dynamics, active tectonics, and seismic and magmatic processes, a continuously recording, telemetered strain observatory will be installed along the Pacific/North American plate boundary.

The core instrumentation request is for a geodetic observatory consisting of a carefully designed and integrated network of borehole strainmeters (BSM), laser strainmeters (LSM), and Global Positioning System (GPS) receivers. Taken together these instrument types span the broad temporal and spatial spectrum of plate boundary deformation. The borehole strainmeters are ideal for recovering short-term transient deformation, phenomena with periods ranging from seconds to months, and will consequently play a central role in observing phenomena that accompany and precede earthquakes and volcanic eruptions. GPS is ideal for longer time scales, periods from days to decades, and large spatial scales, thus covering long-period transients such as those associated with viscoelastic relaxation following an earthquake, as well as decadal estimates of strain accumulation and plate motion and their spatial variations. Laser strain instruments have the high resolution of the borehole strain instruments combined with the long-term stability of GPS measurements. Thus, a few laser strainmeter instruments will be included in carefully chosen locations to provide complementary information to both the borehole and GPS systems. All three systems are sensitive in the period range characteristic of recent observations of slow earthquakes. Only an integrated deployment of these instrument types is capable of providing temporal resolution over the full set of time scales from minutes to decades at the necessary spatial resolution and areal coverage of the plate-boundary system.

The PBO Facility will consist of four elements. First, a backbone network of 100 new and 20 existing GPS receivers will provide a long-wavelength, long-period synoptic view of the entire plate boundary zone (Figure II-2.1). The backbone will cover western North America and Alaska at a receiver spacing of 200 km. The data will be integrated with Interferometric Synthetic Aperture Radar (InSAR) data, when and where available, to define the regional component of the strain field. The second element consists of focused dense deployments of 875 permanent GPS and 175 strainmeters in areas where active tectonic phenomena occur. Instrument spacing will be 5-10 km (Figure II-2.2). The third PBO element is a pool of 100 portable (campaign) GPS receivers for temporary deployment and rapid response. These instruments will be used for densifying areas not sufficiently covered by continuous GPS, and responding to volcanic and tectonic crises. The fourth element, called Geo-PBO, will include the establishment of a national center for the storage and retrieval of digital imagery, and housing of geochronology facilities to support geologic and paleoseismic studies in the PBO.

Building a dense geodetic network with the geographic extent of PBO will require a comprehensive, focused management structure and an unprecedented degree of coordination and cooperation among existing NSF facilities and regional scientific investigators. Underlying PBO are seven basic tenets:

- PBO is a single, seamless geophysical observatory managed by UNAVCO, Inc. UNAVCO, Inc. will provide a single point of accountability to sponsors and EarthScope collaborators.

- PBO will provide valuable new information and data types for scientists who study a range of phenomena to test and significantly extend our understanding of fundamental geophysical processes.

- PBO will build upon existing regional networks and use regional expertise for scientific input and building the network. Regional investigators will advise PBO staff to ensure that PBO and the broader EarthScope science goals are met. UNAVCO, Inc. employees will be responsible and accountable for station installation, maintenance, data flow, and timely archiving and data products for PBO.

- PBO will use the resources and expertise of the UNAVCO GPS Facility and other NSF funded facilities that fall under the EarthScope umbrella.

- PBO will use and build upon the existing expertise developed in geodetic and strainmeter arrays in western North America including the Mini-PBO GPS-Strainmeter Project, SCIGN (Southern California Integrated Geodetic Network), BARD (Bay Area Regional Deformation Network), BARGEN (Basin and Range Geodetic Network), EBRY (Eastern Basin and Range Network), PANGA (Pacific Northwest Geodetic Array), and AKDA (Alaska Deformation Array) networks.

- All data acquired under PBO will be freely available to the scientific community and the public at large. All software developed under PBO will be placed in the public domain. Use of PBO data for education of and outreach to K-12 students is crucial.

- PBO will share resources and actively collaborate with international investigators to extend the reach of PBO into Canada and Mexico.

The UNAVCO geodetic and strainmeter communities have spent the last three years refining the scientific targets for PBO in science justification and network planning workshops in 1999 and 2000, joint EarthScope science workshops in 2001, and information technology and education and outreach meetings in 2002. In the summary below and

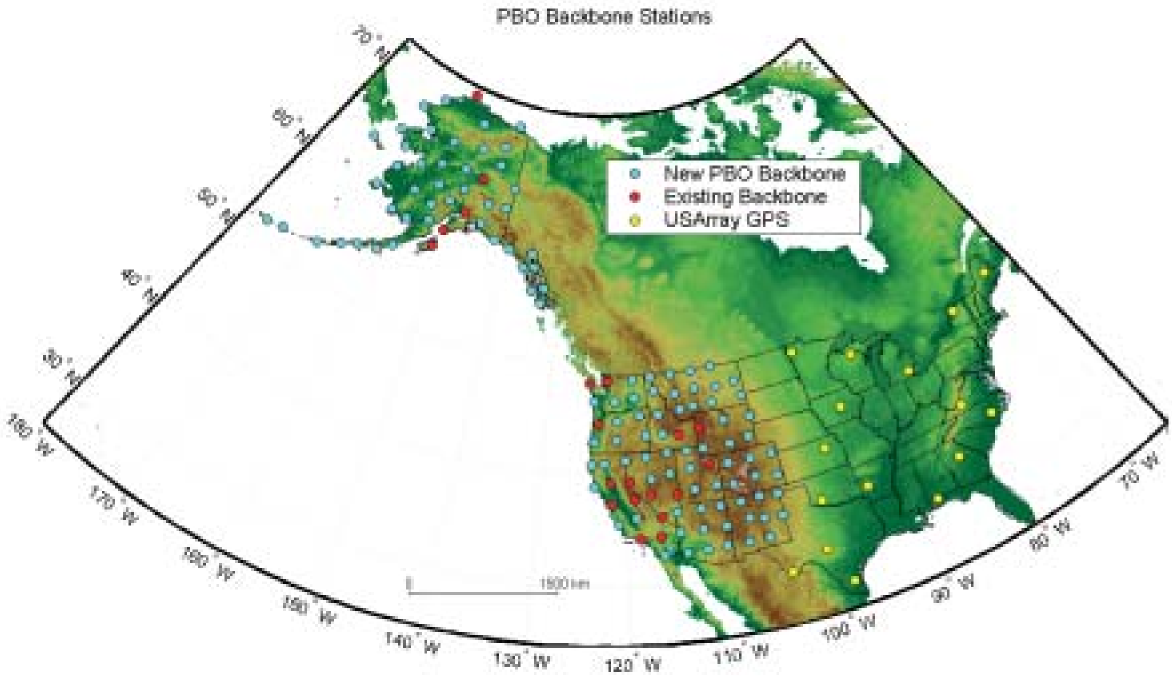



Figure II-2.1. Element 1 - Proposed PBO backbone stations at ~200 km spacing. Red dots represent existing and light blue dots indicate locations where suitable infrastructure exists for hosting new permanent GPS installations. Yellow dots indicate backbone sites located at USArray GSN sites.

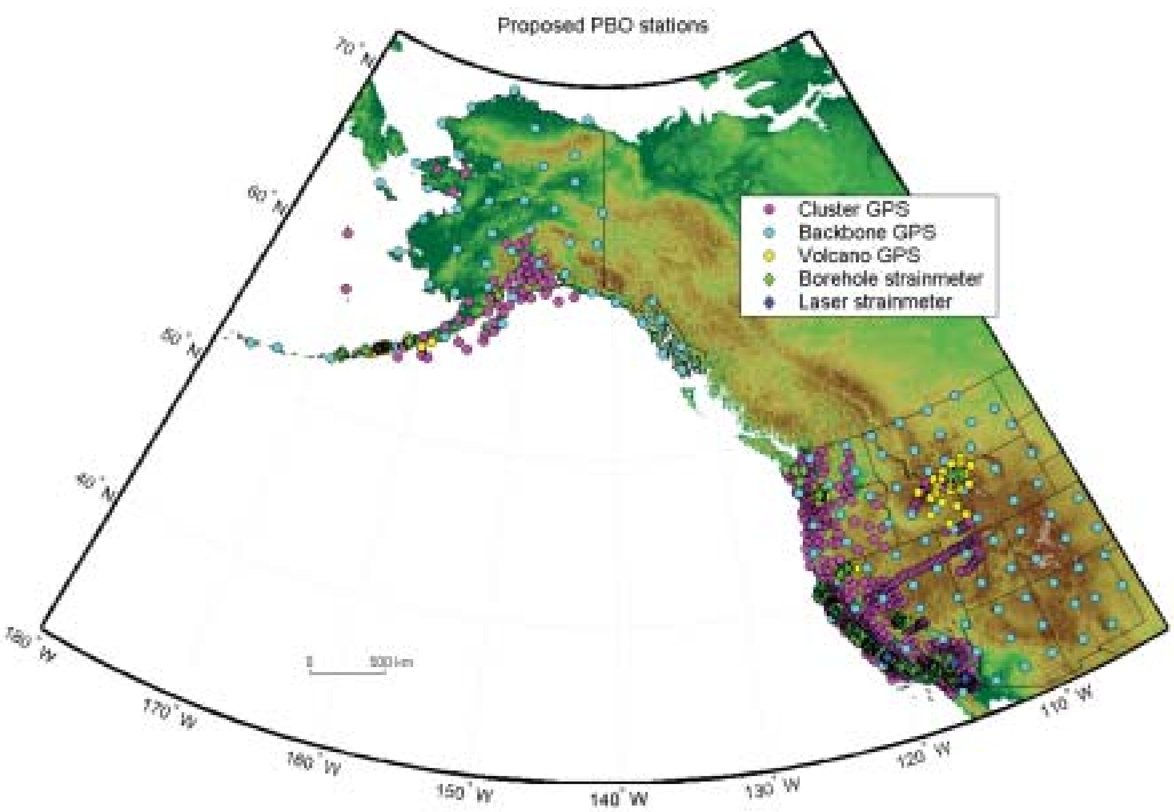



Figure II-2.2. Element 2 – Proposed volcanic (yellow circle) and tectonic (magenta circle) GPS permanent clusters and borehole (green triangle) and laser (dark blue triangle) strainmeter installations in the PBO network. Backbone network shown in light blue.

in the proposal that follows, the community-derived scientific targets and the guidelines presented above are used to develop a strategy for siting and building the PBO Observatory, and for deriving and distributing raw data and the required data products to the scientific community. A companion proposal will address the ongoing operations and maintenance of the network as installed stations come on line.

We propose to build the PBO using an efficient, accountable, and non-centralized management structure that is detailed in Section II-2.2 entitled *PBO Management*. This section describes the structure and functional positions required to accomplish the PBO. The observatory will be managed by a PBO Director who will rely on an Operations Manager to manage the equipment installation, operation, and maintenance aspects of PBO, and a Data Products Manager to oversee data flow, archiving, and GPS and strainmeter data product aspects of PBO. The observatory is broken down into regional centers where UNAVCO, Inc. Regional Engineers will install, operate, and maintain PBO and ensure that data flows from regional centers to data archives and processing facilities. Regional Engineers will rely heavily on five Science Advisory Committees composed of regional scientists to provide science input on all topics related to building PBO including siting and prioritization of station installations. More information about the Science Advisory Committees can be found in Section II-2.3 *Site Selection, Reconnaissance, and Permitting* and Section II-2.4 *Site Installation*.

A Data Products Manager will oversee the archiving and data processing aspects of PBO. The proposed Data Management and Archiving structure will use a modified GPS Seamless Archive Center (GSAC) model. Two PBO archive centers will be responsible for the long-term storage and distribution of PBO data and data products. The details can be found in Section II-2.7 entitled *Data Management and Archiving*.

Data products for PBO will closely follow the IGS Analysis Center model where a Solution Coordinator combines and monitors GPS and strainmeter products produced by two processing centers. The respective analysis centers will analyze raw campaign GPS, continuous GPS, laser and borehole strain data, and provide timely derivative products. Data products for PBO are discussed in Section II-2.8 entitled *PBO Data Analysis and Products*.

The installation of PBO will take five years (Table II-2.1). The first year will be used primarily for hiring and training new staff; initiating the selection and permitting of sites; purchasing equipment; and developing the data management structure. Major equipment purchases will be staged over the entire five-year period to take advantage of new technologies such as the addition of new civil frequencies to GPS and advances in strainmeter design and efficiencies in fabrication. Station installations will peak in Years 3 and 4 and be finalized in Year 5.

For efforts as large as PBO there are a number of potential difficulties in acquiring, testing, and deploying GPS and strainmeter systems. There are a number of manufacturers who provide high-precision, geodetic-quality GPS systems, and the GPS community has experience in specifying and acquiring equipment to fit the scientific demands of PBO. In addition, installation procedures for continuous GPS stations have been honed over the last decade in regional networks such as SCIGN, BARD, BAR-

Table II-2.1. Instrument deployment for PBO.

| Project Year | CGPS | Campaign | BSM | LSM |
|---|---|---|---|---|
| 1 | 50 | 50 | 2 | 0 |
| 2 | 200 | 50 | 15 | 0 |
| 3 | 250 | | 70 | 1 |
| 4 | 250 | | 70 | 2 |
| 5 | 125 | | 18 | 2 |
| **Total Sites** | **875** | **100** | **175** | **5** |

CGPS = permanent GPS, Campaign = portable GPS systems, BSM = Borehole strainmeter systems, LSM = laser strainmeters.

GEN, EBRY, PANGA, AKDA, and global networks installed by the UNAVCO facility (e.g., Figure II-2.3) such that a permanent GPS station can be installed in one to four days with a cost that deviates from the budget by only a few percent. However, there are only two or three research groups worldwide that provide geodetic quality strainmeters that fulfill the scientific objectives of PBO; each of their instruments is built on a custom order basis and the installation costs can vary by as much as 100% depending on difficulties encountered during drilling. Furthermore, borehole installations require specialized crews, and station installations can stretch for two to three weeks. The mini-PBO strainmeter experience in the San Francisco Bay Area provides an indication that the scope of strainmeter installations for PBO is achievable, but it will require significant planning and training, will require attention to drilling and borehole specifications, new methods for manufacturing the large number of strainmeters required, and well-documented installation techniques for training crews in geographically dispersed areas.

For the strainmeter component of PBO, a majority of the first year will be used to work with strainmeter developers in negotiating contracts to out source manufacture of the instruments, and to develop quality control standards and streamlined installation procedures. Two dedicated Strainmeter Engineering positions, one for northern and one for southern California will spearhead this work. These and more general issues associated with *Site Selection, Reconnaissance, and Permitting* are addressed in Section II-2.3 and *Site Installation* is discussed in Section II-2.4. Section II-2.5 details a strategy for *Major Equipment Purchases* and Section II-2.6 addresses *System Fabrication, Testing, and Deployment*.

GPS instruments and strainmeters capture deformation on sub-weekly to decadal time scales. For many fault systems this temporal resolution is insufficient to characterize the long-term strain history. For this reason, PBO includes a geologic and paleoseismologic component called Geo-PBO. Geo-PBO will provide aerial and satellite image data, archiving, and image processing tools and geochronologic dating facilities that will provide facility-based support to investigators to examining strain fields at longer time scales. More information on *Geo-PBO* can be found in Section II-2.9.

Figure II-2.3. Installation of station CRBT in the SCIGN network.

The *PBO Budget and Budget Justification* is found in Section II-2.11 and the MREFC costs are summarized in Table II-2.2. Note that Year 1-10 operations and maintenance costs will be submitted under a separate proposal. Major budget line items include GPS and strainmeter equipment and installation costs, campaign GPS instruments, funds to cover GEO PBO activities, and a 5% project contingency fee. Money is allocated for two PBO Standing Committee meetings per year and three Advisory Committee meetings in year one decreasing to two per year in Years 2-4.

To build and run an observatory with the complexity and geographic extent of PBO requires a dedicated staff for operations, data management and archiving, and generating data products. Staffing is accomplished by subawards to contractors, new positions created under UNAVCO, Inc., and adding staff at the UNAVCO GPS Facility, Scripps

Table II-2.2. PBO yearly and total five-year budget summary

| PBO MRE | Average Installation Cost/Station | 2003 | 2004 | 2005 | 2006 | 2007 | Five Year Total Cost |
|---|---|---|---|---|---|---|---|
| Campaign GPS | 10,000 | $500,000 | $500,000 | $- | $- | $- | $1,000,000 |
| Standard Strainmeter Equip & Installation | 134,920 | $269,840 | $2,023,800 | $9,444,400 | $9,444,400 | $2,428,560 | $23,611,000 |
| Long-Base Laser Strainmeter Equip & Install | 489,450 | $489,450 | $978,900 | $978,900 | $- | $- | $2,447,250 |
| Continuous GPS Equip & Installation | 37,863 | $1,893,150 | $7,572,600 | $9,465,750 | $9,465,750 | $4,732,875 | $33,130,125 |
| GeoPBO | n.a. | $1,000,000 | $1,000,000 | $1,000,000 | $1,000,000 | $1,000,000 | $5,000,000 |
| 5 % contingency | n.a. | $1,000,000 | $1,000,000 | $1,000,000 | $1,000,000 | $1,000,000 | $5,000,000 |
| Community Meetings | | | | | | | |
| PBO Standing Committee | | $19,200 | $19,776 | $20,369 | $21,082 | $21,925 | $102,353 |
| PBO Advisory Committees | | $126,000 | $86,520 | $89,116 | $46,340 | $- | $347,976 |
| Total Salaries & Benefits Specific to PBO* | | $3,555,529 | $4,132,175 | $4,237,584 | $4,364,712 | $4,495,653 | $20,785,653 |
| Total Non-Salary Program Support Specific to PBO* | | $1,187,560 | $1,609,969 | $1,462,063 | $1,443,901 | $1,431,489 | $7,134,982 |
| UNAVCO, Inc. Corporate Support (30% of selected HQ costs) | | $235,518 | $257,553 | $265,115 | $276,215 | $281,260 | $1,315,662 |
| **PBO TOTAL** | | **$10,276,247** | **$19,181,293** | **$27,963,297** | **$27,062,400** | **$15,391,763** | **$99,875,000** |
| **Management Fee** | | **$25,000** | **$25,000** | **$25,000** | **$25,000** | **$25,000** | **$125,000** |
| **PBO BUDGET WITH FEE** | | **$10,301,247** | **$19,206,293** | **$27,988,297** | **$27,087,400** | **$15,416,763** | **$100,000,000** |

Orbit and Permanent Array Center (SOPAC), and the UC Berkeley Seismological Laboratory. A total of 55 full- and part-time positions are proposed for PBO (Figure II-2.4). Of these, eight positions will be subawards, 38 positions will be new UNAVCO, Inc. employees (three of which will reside at UNAVCO, Inc. headquarters), six employees will be added to the UNAVCO Facility, and one employee each will be added to SOPAC and U.C. Berkeley Seismological Laboratory. A cost of living adjustment of 3% per annum was included in the budget calculations. A fringe benefit rate of 40% is assumed for all personnel.

A more detailed discussion of the budget can be found in Section II-2.11 and in the on-line documentation. Finally and most importantly, to achieve the science goals set out by the EarthScope working groups, the SAFOD, PBO, and USArray observational facilities will provide common and consistent access for individual and integrated data and data products for the scientific and education and outreach communities, reduce installation costs and minimize duplication by integrating projects where it makes sense, and create unified data/data products, access tools, and common display tools. To this end, areas of potential collaboration among the projects components are addressed throughout the following sections and a summary of coordination activities can be on the EarthScope web site (www.EarthScope.org).

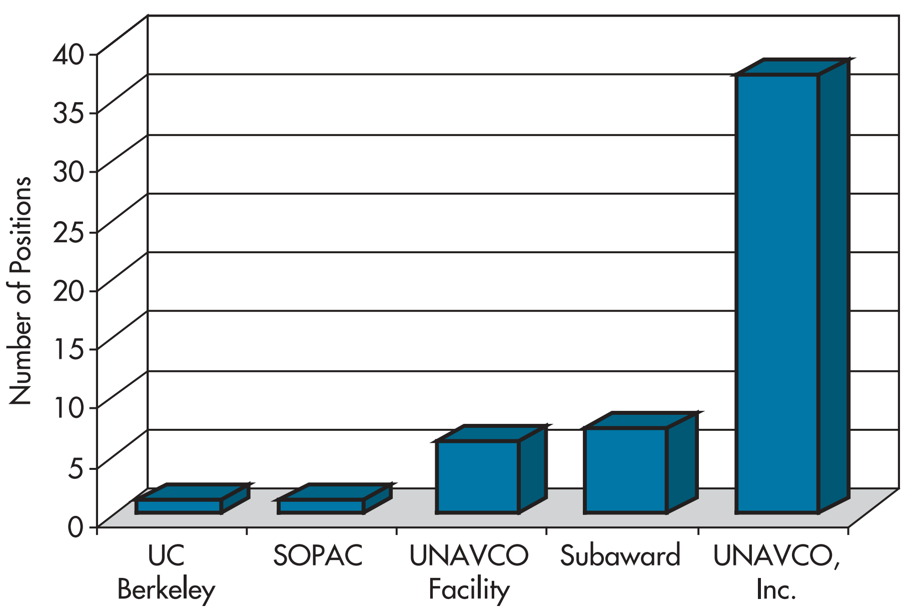



Figure II-2.4. Proposed PBO staffing levels by organization.

# 2.2. Management

## Background

Successful management of PBO requires an effective administrative structure and chain of responsibility and authority that can accomplish the project on schedule and within budget, and can do this in a manner that is accountable to the sponsors and the scientific community.

To achieve these goals, PBO will operate as a program under UNAVCO, Inc., a non-profit membership-governed organization that supports research applications of high-precision geodetic and strain techniques such as the GPS. The UNAVCO, Inc. President will oversee a PBO Director who has primary supervisory, budgetary, management, and reporting responsibility for all components of the PBO effort. The PBO Director will oversee two key personnel, the Operations Manager who will handle operational aspects of the PBO network and the Data Products Manager who will oversee data flow, data processing, data products, and data archiving activities (Figure II-2.5). A PBO Standing Committee, composed of scientists who will use PBO products, is charged with representing the scientific community in the implementation and management of the overall PBO Facility including data quality, data types, data products, and the accessibility of data and derivative products to the community. The PBO Standing Committee is appointed by and reports to the UNAVCO, Inc. President. The Science Advisory Committees consists of five advisory panels composed of regional scientists and existing network operators. These committees will provide for science input on all topics related to building PBO with special emphasis on siting and prioritization of station installations. If this proposal is successful, The UNAVCO, Inc. President will select interested members of the community to populate the committees. Committee members serve without compensation. However, the budget does include travel and meeting expenses for committee members.

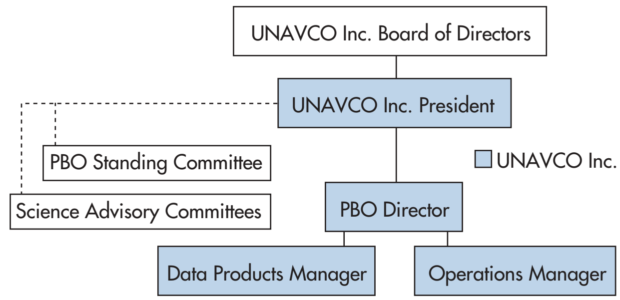



Figure II-2.5. PBO senior management structure under UNAVCO, Inc. Job titles in blue indicate UNAVCO, Inc. Employees. PBO Standing Committee and Science Advisory duties are explained in the text.

### The Plate Boundary Observatory (PBO) Science Advisory Committees

The PBO Science Advisory Committees are advisory committee of UNAVCO, Inc., appointed by and reporting to the UNAVCO, Inc. President. The role of the committee is to bring a regional scientific focus to the PBO project and to assist in assembling location maps of proposed stations and prioritize station installations to maximize the scientific return. The committees represent different tectonic styles including:

- Subduction: responsible for Pacific Northwest, Alaska, and Canada
- Transform: responsible for California and Mexico
- Intraplate: Basin and Range, Rocky Mountain, and Backbone
- Volcanic: responsible for Cascade, Alaska, Yellowstone, Long Valley volcanoes
- GEO-PBO: responsible for geologic and paleoseismic investigations

The committees will be encouraged to recommend areas where campaign GPS receivers could be used to densify measurements around cluster sites.

### The Plate Boundary Observatory (PBO) Standing Committees

The PBO Standing Committee is an advisory committee of UNAVCO, Inc., appointed by and reporting to the UNAVCO, Inc. President. The role of the committee is to represent the scientific community in the implementation and management of the PBO facility. The charge to the committee includes providing advice to the PBO Director and UNAVCO, Inc. President on matters that affect the accomplishment of the research goals of PBO as originally outlined in the PBO White Paper and EarthScope Project Plan and as evolve over the life of the PBO facility.

The current membership of the committee includes:

- Frank Webb, NASA/Jet Propulsion Laboratory - Chair
- John Bevin, Institute of Geological & Nuclear Sciences Limited (GNS)
- William Holt, SUNY at Stony Brook
- Susan Owen, University of Southern California
- Paul Segall, Stanford University
- Paul Silver, Carnegie Institute of Washington
- Mark Simons, California Institute of Technology

The first responsibility of the committee has been to review and advise on the technical and cost feasibility of the PBO proposal, with emphasis on ensuring accomplishment of the data and observational needs of the PBO research community. The committee will play a pivotal oversight and advice role throughout the life of the PBO facility.

## Operations

The Operations Manager, Regional Engineers, and Strainmeter Engineers will be responsible for permitting (including coordination with USArray), installation and maintenance of instruments, and documentation of station characteristics. They will also be responsible for GPS, strain, and other sensor installation, station documentation including station metadata (critical station information such as site ID and antenna height), and maintenance of all instrumentation in the PBO project area (Figure II-2.6 and II-2.7). The Operations Manager will work closely with the PBO Standing Committee to make sure that implementation of PBO continues to meet the science objectives and work with members of the Advisory Committees to ensure that stations are installed in the correct scientific order. A key component of this job will be coordinating the efforts between existing networks and new backbone and cluster installations. To achieve this, the Operations Manager will oversee engineers at six Regional PBO sub-network offices to coordinate operations of the Northern California, Southern California, Basin & Range, Pacific Northwest, Rocky Mountain, and Alaska regions (Figure II-2.6). Basin & Range, Pacific Northwest, Rocky Mountain, and Alaska Regional Engineers will have a staff of one installation and maintenance Engineer and one technician. Northern California and Southern California Regional Engineers, due to the larger number of installations in their regions, will supervise a dedicated strainmeter engineer, a GPS installation engineer, and two technicians. Depending on the PBO deployment schedule, fieldwork constraints in Alaska, and PBO budget constraints, regional subnetwork offices may not be immediately staffed, and resources and personnel will be shared between offices under direction of the PBO Director.

To ensure the science goals of PBO remain paramount in the operation of the facility, the PBO Operation Manager and Regional Engineers will work


Figure II-2.6. Operational division of PBO regions: Alaska, Pacific Northwest, Northern California, Southern California, Basin and Range, and Rocky Mountains.

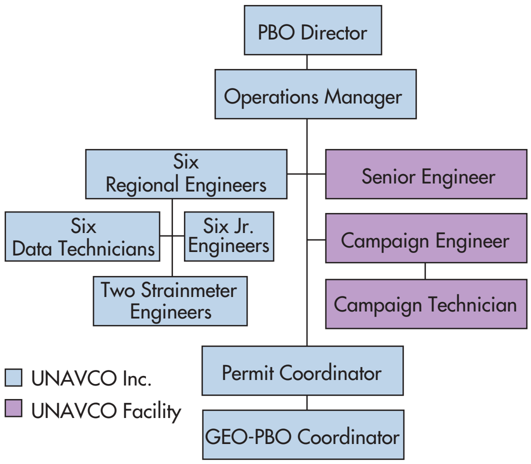



Figure II-2.7. Operations management structure under the PBO Director. Job titles in blue indicate UNAVCO, Inc. Employees. Job titles in purple represent UNAVCO Facility positions.

closely with Science Advisory Committees during the reconnaissance, site selection, and permitting phases of PBO. In addition, PBO personnel will rely heavily on expertise that exists at the UNAVCO Boulder Facility and at existing regional GPS and strainmeter networks, and capitalize on this experience during the siting, reconnaissance, and permitting of sites within each region. Although the responsibility of doing these tasks remains with PBO, the PBO Facility must interact, use, and build upon the existing expertise developed at NSF expense.

The Geo-PBO coordinator will monitor and manage subcontracts with institutions that provide radiocarbon and cosmogenic nuclide sample preparation and dating analysis. In addition the Geo-PBO coordinator will work with subcontractors on the specification and delivery of a distributed image archive for storing and accessing Geo-PBO raw, composite and modified images

A senior engineer position will be allocated to the UNAVCO Facility in Boulder, Colorado. This position will be responsible for training, technology transfer, and rapid field assistance in any region at the direction of the PBO director. Field engineers (current employees) from the UNAVCO Facility and regional contract staff will be used on an as-available/needed basis for installation, technical support, and maintenance.

Campaign support will consist of a Campaign Support Engineer and a Technician to oversee campaign equipment scheduling, maintenance, and shipping. Campaign field support will be handled using UNAVCO Facility engineers requested through science proposals evaluated by panels with rotating membership.

## Data and Data Products

The Data Products Manager will be responsible for data flow, data processing, data archiving, daily network state of health reports and maps, and will work with EarthScope Education and Outreach staff on the specification of an EarthScope data/data products display interface. The Data Products Manager will be a UNAVCO, Inc. employee and reside at UNAVCO, Inc. headquarters. The Data Products Manager will work closely with the PBO Director and the PBO Standing Committee to ensure that the data products are meeting the science objectives of PBO. The Data Products Manager will oversee two critical aspects of PBO —raw data and data products (Figure II-2.8). A PBO Archivist will monitor raw data flow including strainmeter and GPS data, station metadata, and ancillary data (tilt, met). The Archivist will monitor the transport of raw data from regional centers to solution centers and GSAC archives. The UNAVCO Facility and SOPAC will archive GPS data and the UC Berkeley Seismological Laboratory (with a data mirror to the IRIS DMC) will archive strainmeter data (see Section II-2.7 on *Data Management and Archiving*). The UNAVCO and SOPAC facilities are the primary community GPS archives and the U.C. Berkeley Seismological Laboratory currently archives all USGS strainmeter data. The PBO Archivist will be a UNAVCO, Inc. position and will report directly to the Data Products Manager.

A Solution Coordinator will manage, quality check, and combine data products produced by PBO Solution Centers. The PBO Solution Coordinator will oversee production of the data products such as time series of estimated site positions (GPS) or daily strain time series (strainmeters), average site velocities (GPS), time series products (GPS and strainmeters), and ancillary data types and parameter estimates (GPS and strainmeters; see Section II-2.8 on *PBO Data Analysis and Products*) from two analysis centers. The Solution Coordinator will oversee GPS data products generated at Solution Centers and strain products generated at laser and borehole analysis centers. Subcontracts for GPS and Strain Analysis Centers will be awarded based on competitive bid. The PBO Director will appoint the Solution Coordinator.

In summary, we feel this PBO management structure will provide accountability to sponsors, EarthScope partners, and the scientific community, will achieve the scientific mandate outlined for PBO, and will capitalize on the experience and knowledge provided by existing investigators and NSF-funded facilities.

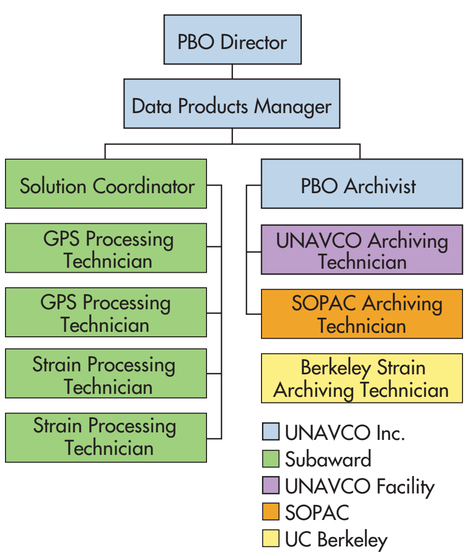



Figure II-2.8. Data Products management structure under the PBO Director.

# 2.3. Site Selection, Reconnaissance, and Permitting

## Background

The strainmeter and GPS site selection, reconnaissance, and permitting activities for PBO will be the responsibility of UNAVCO, Inc. Regional Engineers overseen by the Operations Manager and the PBO Director. In turn the PBO Director and Operations Manager will work closely with Science Advisory Committees to make sure the science objectives of PBO are achieved and sites are installed according to scientific priority. For both GPS and strainmeters, the station installation cycle involves preliminary siting of stations, a thorough site reconnaissance, and initiation and acquisition of a land use permit. Table II-2.3 shows the resources UNAVCO, Inc. will marshal to complete these tasks.

## Site Selection Procedure for GPS and Strainmeter Installations

Site selection process for PBO will be driven by the goal of maximizing the scientific return of each station, maximizing the dependability of the station, and minimizing the overall cost of the installation. To accomplish this, Science Advisory Committees will meet as a pre-EarthScope activity in March of 2003 to produce regional site location maps, often called "dots maps," of station targets that satisfy the science goals of the network.

The site selection process will start by using station location maps and PBO mini-proposals to produce a target installation map. Based on the number of stations allocated, scientific target and priority, geography, data communications layout, known permitting issues, logistical considerations, coordination with other networks (see below) and pre-PBO funded network sensitivity analysis currently underway at Stanford as a pre-EarthScope effort. The network sensitivity analysis will first evaluate the capabilities of the proposed strainmeter and GPS networks and determine the detection threshold for a number of processes such as silent earthquakes on the Cascadia subduction and the San Andreas fault, dike propagation, and earthquake after slip. The result of the work by the Science Advisory

Table II-2.3. Resources available for site selection, reconnaissance, and permitting activities.

| Activity | Resource |
|---|---|
| Preliminary station location | Science Advisory Committees |
| | Regional Network Operators |
| Station Reconnaissance | UNAVCO, Inc. Regional Engineers |
| | USArray Personnel |
| | Contract Personnel |
| Station Permitting | UNAVCO, Inc. Permitting Coordinator |
| | Permit and Land Use Consulting Firm |
| | Regional Seismic/GPS network operators |
| | UNAVCO, Inc. Regional Engineers |

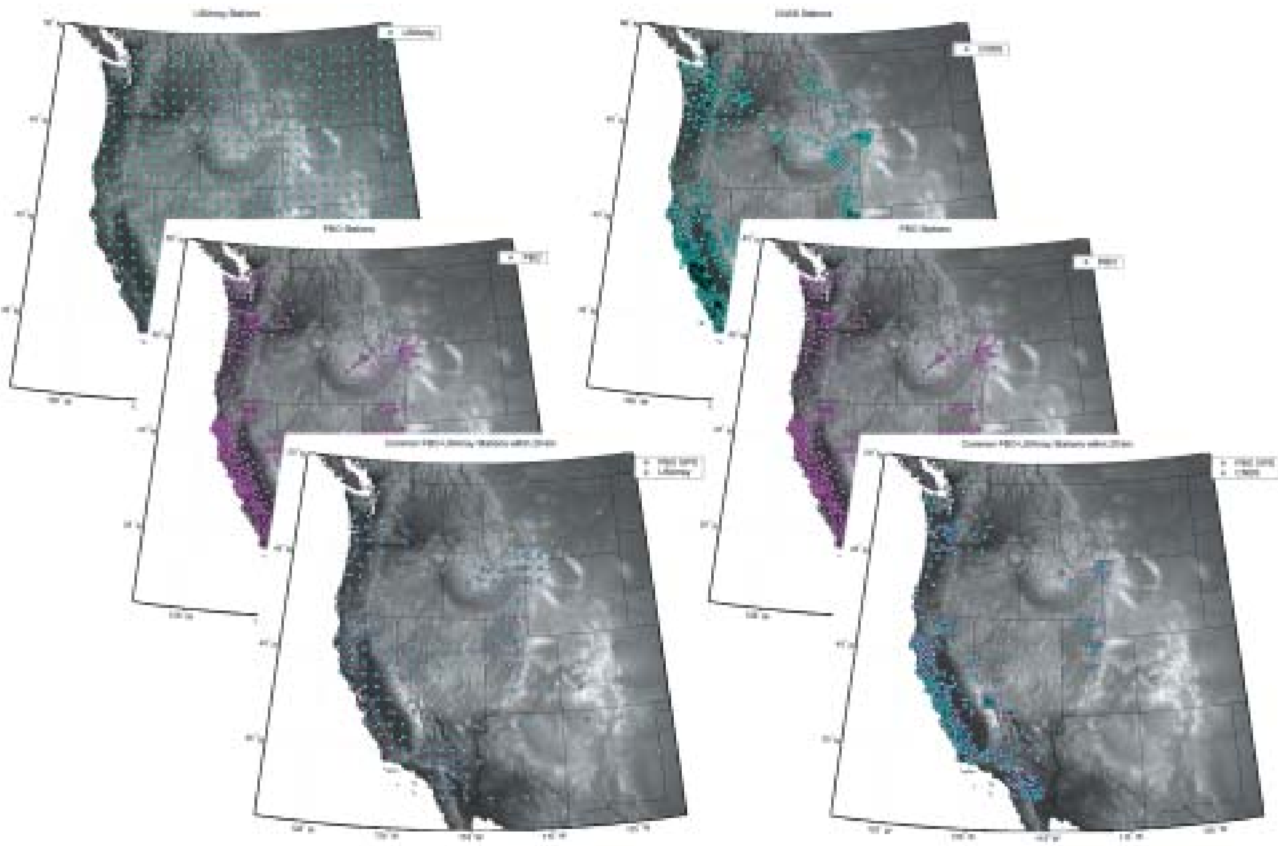


Figure II-2.9. Left figure shows USArray (upper), PBO (middle), and 180 stations with in 20 km of each other (bottom) that will be evaluated for collocation. Right figure shows ANSS (upper), PBO (middle) and 480 stations within 20 km of each other (bottom) that could be collocated.

Committees will be a set of prioritized yearly installation dots maps that can be used for site reconnaissance. The maps will be submitted to the UNAVCO Inc. President for approval. Once each is approved, the Regional Engineer can begin the site reconnaissance.

A major goal of PBO is to constrain transient deformation at seismogenic depths. While surface geodesy places some constraints on this, seismic techniques, based on either temporal variations in seismicity, or in the properties of the medium itself, constitute a valuable complement to the surface instruments. This is why there are approximately 200 PBO 3-component borehole seismometers that are collocated with the borehole strainmeters. We would very much like to augment the seismic component of PBO, by collocating seismometers with the GPS receivers that are in seismogenic areas. Two opportunities exist for doing this: collocating stations with the USArray transportable array and collocating stations with existing seismometers in the Advanced National Seismic System (ANSS) (Figure II-2.9).

The PBO observational array extends across the western United States and Alaska and will be installed over a five-year period. The USArray 400 instrument transportable array will cover the entire United States (except Hawaii) and take ten years to complete. In years 1-5, USArray will focus on the western United States, starting in California and working to the eastern extent of the PBO. The time and geographic phasing of USArray provides a unique opportunity to collocate, at least for the duration of the USArray observations, GPS sensors and broadband seismometers. At least 180 planned PBO sites are located within 20 km of USArray transportable array sites and are suitable for joint siting (Figure II-2.9). In addition, PBO will install 151 systems in Years 1-5 in Alaska so that USArray can benefit from reconnaissance and siting efforts when they arrive in Years 8-10. Both USArray and PBO are planning for joint reconnaissance and siting teams to evaluate these and other sites for instrument collocation. Finally, investigators will have access to an additional 200 broadband and 200 short period instruments from the USArray Flexible Array that could be collocated at GPS sites.

Another exciting possibility is the collocation of PBO permanent GPS receivers along with existing regional seismometers in the Advanced National Seismic System. These sites are already permitted and have power and communications issues resolved. Although the individual networks are populated with a variety of seismic instruments including short, long period, and strong motion sensors, there are 480 locations where GPS and seismic instruments could be collocated (right bottom of Figure II-2.9). Members of the PBO Standing Committee and the UNAVCO, Inc. Board of Directors are currently opening discussions with the USGS and individual network operators on the feasibility of utilizing ANSS sites for permanent GPS installations.

## Site Reconnaissance

Site reconnaissance involves the transition from a mapbased image to the reality of a ground-based network. Stated another way, it is moving from a dot on a map with a 2-20 km uncertainty to an exact location on the ground for an installation. The PBO Operations Manager will specify criteria to be used for selecting GPS and combined GPS - strainmeter sites. For GPS the primary criteria for site selection is 360° sky view down to 5° elevation, competent bedrock for a monument, availability of power and data communications, and site security. Strainmeter sites require suitable access for drill rigs, competent bedrock down to the target drilling depth (200 m), availability of power and data communications, and site security. Satisfying all these criteria under the constraints of a dots map is often impossible and alternative sites must be relocated while the engineer is in the field. The Regional Engineers will publish reconnaissance reports and discuss any significant deviations from the dots maps with the PBO Director and Operations Manager who will in turn inform the Advisory Committees on changes.

Prior to going into the field, Regional Engineers will coordinate with USArray operational personnel and local and regional agencies and scientists to optimize site visits, discuss logistics, and siting and permitting options. Regional Engineers will be responsible for performing a thorough, well documented site reconnaissance. The Regional Engineer will identify and coordinate with existing network operators, local scientists, local network engineers, and interested city, county, and governmental organizations who can assist in location, permitting and permission issues. The engineer will then visit each proposed site location, determine detailed on-site issues including land ownership, data communications, power, security, and maintenance issues. The engineer will provide a reconnaissance report for each site visit with recommendations on acceptance/rejection of the proposed site, and detailed information regarding permitting, installation, power, data communications, access, security, and maintenance issues. Strainmeter site reconnaissance will require finding a minimum of two potential drill sites within the permit area, and because they will house GPS antennas, the sites must have an unobstructed sky view. During reconnaissance, if a site is clearly unacceptable, the engineer can visit alternative sites in the nearby area and make recommendations accordingly. The Regional Engineer and Operations Manager will review reconnaissance reports and recommend a more detailed site visit, accept and move to the permitting process for the station, or reject and reselect another site.

## Permitting

Station permitting and the permit approval process dominate the time and uncertainty in predicting the rate of station construction, limit the ability of the stations to be scheduled for construction, and thus control the eventual rate of network deployment. PBO will take a four-phased approach to obtaining 10-year (or greater) site installation and land use permits. First, we will attempt to negotiate an agreement between EarthScope and the Departments of Interior and Agriculture so that regional offices are aware, sympathetic, and willing to expedite the permit process for the EarthScope initiative. Second, we will hire a national consulting firm that specializes in acquiring land use permits to obtain permits on BLM, Forest Service, National Park Service, county, state, and municipal lands. Third, PBO Regional Engineers will work with regional investigators who have tremendous experience in land use permitting in their local areas to gain permits for additional sites. Fourth, we will look for opportunities to collocate stations on already permitted lands or jointly permit sites with other agencies, for example USArray sites and sites in the existing national seismic arrays. A PBO Site Permit Coordinator will integrate the entire process.

Once a site is moved to the permitting phase, the PBO Site Permit Coordinator in consultation with the Regional Engineer will initiate the permit process. Based on the landowner the following action will be taken:

- If the site is owned by a State, County, City or Government agency that has provided a blanket approval or has a history of a rapid approval/denial process then the Regional Engineer or designated consultant will apply for a permit using criteria established between UNAVCO, Inc. and that agency.

- If a state, county, city or government agency, BLM, Forest Service, or Park Service owns the site the permitting contractor will negotiate the Land Use Agreement.

- If the site is privately owned and the landowner has no permit restrictions the Regional Engineer or designated consultant will ask that the owner sign a PBO Land Use Agreement.

- If the site is privately owned and the landowner has permit restrictions the Regional Engineer or designated consultant will ascertain what special conditions the landowner requires including lease payments, get approval from PBO Director and add an amendment to standard PBO Land Use Agreement.

Legal council for UNAVCO, Inc., in consultation the PBO Site Permit Coordinator and the designated permitting consultant, will develop the PBO Land Use Agreement and standard permit forms. The PBO Site Permit Coordinator will provide a monthly permitting report to the Operations Manager and PBO director who will advise the PBO Standing Committee (or designated subcommittee) of permitting and site selection status. Once permits are obtained, a pre-installation report is compiled with recommendations on monument type, communications methodology, power infrastructure, and security requirements at the site.

# 2.4. Site Installation

Once GPS and strainmeter sites are permitted, station installation involves the following steps:

1. Identifying and scheduling installation resources (drill rigs, equipment kits, installation crews and contractors);
2. Identifying and ordering installation equipment and major infrastructure materials (GPS receivers, strainmeters, seismometers, tiltmeters);
3. Coordinating installations with other EarthScope programs and local agencies;
4. Scheduling the installations;
5. Conducting the installations;
6. Transitioning the site to an operational status.

The PBO Operations Manager and PBO Director will provide overall project coordination with Regional Engineers who will be responsible for all phases of the site installation process and manage installation contractors for the strainmeter and GPS installation efforts. Regional Engineers will work to a station installation schedule published by the PBO Director that is based on priorities recommended by the Science Advisory Committees, funding availability, equipment and personnel availability, station permitting, and logistical constrains such as the short field season in Alaska. Online database utilities will be used to track the status of station installations for community wide visibility and for creating detailed installation reports.

GPS and strainmeter installations are divided into planning, below ground, above ground, break-in, and operational phases. Although the resources and techniques needed to accomplish GPS and strainmeter installations are different, the installation steps are similar. Within a region, two or three groups of contractors of varying skill level will work in parallel to optimize the station installation process (Figure II-2.10). For example, an unskilled crew could stage and prep a site for installation and then move to the next site. A highly skilled crew of drillers and welders would visit the site and do the below ground installation and move on to the next site. Finally, a crew skilled in data communications and power infrastructure would visit the site to do the above ground installation and commission the station. The Regional Engineer manages the entire process.

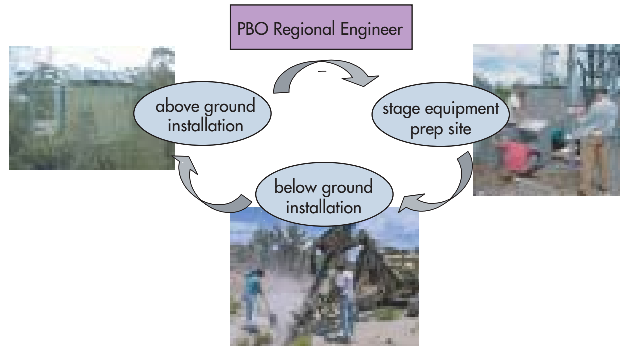



Figure II-2.10. Schematic diagram showing different phases of the station installation process. As each crew is finished they move to the next station.

## Planning Phase

Planning an installation involves the identification and scheduling of installation resources such as PBO and contractor personnel and equipment, and identifying and ordering installation equipment and major infrastructure materials from the equipment depots (see Sections II-2.5 and II-2.6 on *Major Equipment Purchases* and *System Fabrication, Testing, and Deployment*).

Equipment ordering will be initiated by the Regional Engineer using an online equipment request form that is tied to an up-to-date equipment inventory of materials at the equipment depot. This request will trigger the depot technicians to locate, inventory, package, and ship standard, pre-tested equipment bundles from the equipment depot. The PBO Operations Manager will monitor equipment inventories and shortages of critical installation components and rectify shortages and quality issues in a prompt fashion. In parallel, the Regional Engineer will schedule the installation with the station installation contractor, drillers, and other installation crews. As the equipment is received from the depot, the Regional Engineer will inventory the equipment, provide final operational checks, and stage the installation equipment at the site.

## Below Ground Installation Phase

The below ground installation phase will likely be the most complicated due to the level of coordination needed between drillers and installation staff. For GPS stations, the type of substrate will dictate the type of monument used, which in turn will determine the complexity of the installation. For sites located in unconsolidated materials and areas with readily accessible bedrock the Wyatt-Agnew designed deep drill braced monument (DDBM) will be used (Figure II-2.11). This monument requires a skilled installation crew, a truck mounted, multi-directional air impact drill capable of going

Figure II-2.11. A deep drilled (40-45 ft) monument at station SCIA in the SCIGN network (left) and a short drilled braced (6-10 ft) monument installed at station PUPU for the post-Nisqually earthquake response (right).

to depths of 40-45 feet, and a grout pump to fill the holes and secure the legs. For bedrock sites with access problems the SCIGN short drill braced monuments (SDBM) will be used. The drilling and welding equipment needed for the SDBM can be carried in standard field vehicles or helicopters making it ideal for remote installations. Detailed installation procedures are available for each of these monument types and a time interval of one to two days will be allowed for drilling and monumenting activities. Once monuments are installed, drillers will excavate holes for vertical supports for system enclosures and solar panels, pads for USArray strainmeter enclosures, and drill holes for reference marks. There are a number of west-coast commercial contractors with experience in the installation of both the short and deep drill braced monuments. New contractors will be sought for installations in Alaska and the Rocky Mountain regions of PBO.

Borehole strainmeter installations require a skilled drilling crew and a rig capable of drilling a cased hole to 100-200 m depth. For borehole installations the procedure is to drill an 8-inch diameter hole to 10-20 m depth; below this the strata are logged to verify the existence of solid rock. If the rock is high quality, the hole is drilled to 15 m above the target depth, cased, and cemented. The bottom is re-drilled to create an uncased section in which the strainmeter is installed (Figure II-2.12). A time interval of 1-2 weeks will be scheduled for this activity. Once the hole is drilled to the proper depth, an expansive grout is pumped into the hole and the strainmeter is lowered into the grout and tested. After the strainmeter is installed, the hole can be cemented; if other sensors are installed this must be done in repeated steps of cementing up to a target depth followed by installing and testing each sensor, and further cementing above the sensor. A time interval of two to four days, depending on the number of sensors installed, should be allocated for sensor installation. For PBO installations the strainmeter

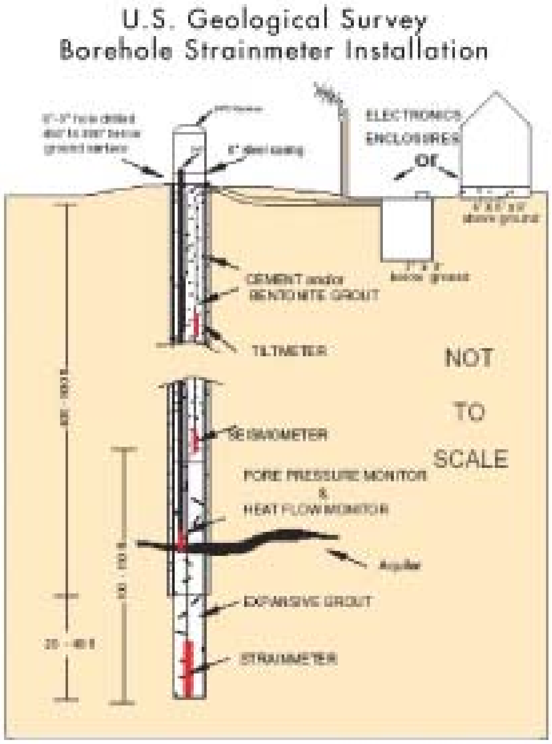



Figure II-3.12. Schematic of the USGS, Berkeley, and Carnegie strainmeter and GPS installation. From USGS Mini-Plate Boundary Observatory Fact Sheet

borehole casing will be used as a monument for a GPS antenna resulting in an overall savings on GPS monumentation, assuming sites with a 360° unobstructed view of the sky are available. For drilling activities we have opened discussions with a consortium called Drilling, Observation and Sampling of the Earth's Continental Crust, Inc. (DOSECC) to contract and manage the drilling operations for PBO. DOSECC provides the benefit of having a long history of working directly with NSF and USGS investigators on scientific drilling operations including the installation of strainmeters in Hawaii and on Montserrat.

### DOSECC: Drilling, Observation and Sampling of the Earth's Continental Crust, Inc.

DOSECC (www.dosecc.org) is a consortium of universities, national laboratories and a state geological survey dedicated to providing a bridge between earth science and drilling technology primarily for NSF funded investigations. DOSECC does this through contracts with experienced drilling engineers who are able to work with investigators to plan and develop realistic budgets for drilling operations and managing drilling projects.

## Above Ground Installation Phase

The above ground installation phase includes the installation of power, communications, lightning protection, environmental sensors, and security; performing site remediation; preparing the site installation report; and documenting station metadata. For GPS site installations this requires installing a GPS receiver, antenna leveling mount and GPS antenna, radome if required, and meteorological sensors for backbone stations. Contractors will perform GPS and strainmeter installations and Regional Engineers will manage the process. The GPS antenna type will be decided in a community based technology meeting but will most likely be a choke ring design with a Dorne Margolin antenna element. Antenna mounts and domes will be based on current community designs such as those developed for SCIGN. USArray and PBO will specify common DC and AC power systems, data communications systems (e.g., 802.11b, VSAT, radio modem), enclosures and security systems to enable common operations and maintenance activities. The ability of USArray and PBO staff to interchangeably support EarthScope infrastructure will have a dramatically positive impact on the long-term support to the project. Installations in Alaska have specialized power and enclosure needs and the Regional Engineer will work closely with the USGS and the University of Alaska that region. Specific data communications options are detailed in *Major Equipment Purchases*, Section II-2.5.

## Pre-operational Phase

GPS and strainmeter stations will operate for two weeks before being declared operational. During this time the on-line station documentation and metadata forms are completed, the data quality checked, initial solutions are performed, and data flow issues resolved. The Regional Engineer will work closely with the Data Products manager to ensure the station telemetry is reliable and robust and that strainmeter data are free of unusual artifacts due to grout curing. Once the station has passed the break-in period it will be declared operational.

# 2.5. Major Equipment Purchases

## Background

The GPS component of the PBO will be a homogeneous network consisting of a common receiver and antenna type, a suite of standardized monument types to be used based on local geology conditions and access, a suite of standardized data communications options depending on site-specific conditions, and a standardized power system. These component systems will be procured through a competitive process based on a detailed performance specification to be developed by the PBO Director in consultation with the community and PBO Standing Committee. In the event this competitive process suggests the need for a phased approach to the purchase of certain components such as GPS receivers, several multi-year purchases may be required to accommodate future developments. The fabrication of these components into GPS station systems will be out-sourced based on a competitive process. The UNAVCO Facility will be responsible for receipt of systems from the fabrication vendor, final system testing, and shipping to meet the needs of either backbone or regional network installation. One of the lessons learned from the SCIGN network installation was that it is critical to systematically test systems prior to field deployment. In the SCIGN network both GPS antennas and receivers experienced technical problems requiring replacement and refurbishment after they were installed. As a result of this experience, PBO will not rely on manufacturers to do final systems checks prior to deployment. Figure II-2.13 shows the functional relationship among the component vendors, the fabrication vendor, the UNAVCO Facility, and regional networks.

## GPS Systems

The UNAVCO community has extensive experience in the selection of GPS systems for installation in large regional networks. The process for such selection has been validated through past large scale purchases including the community Academic Research Infrastructure (ARI) procurement of over 250 systems in the mid-1990's, the SCIGN network of 250 systems in the late 1990's, and the Suomi-Net Major Research Infrastructure (MRI) purchase of over 100 systems in 2000. A GPS system specification will be developed by the PBO Director based on past community experience and new receiver/antenna developments which will be used by UNAVCO, Inc. to issue a competitive Request for Proposals (RFP) to the major commercial GPS vendors that develop and manufacture high-end, dual frequency receivers and geodetic quality antennas. The following are the primary requirements of the GPS receiver and antenna system:

- Dual frequency, L1 and L2 pseudorange; L1 and L2 phase observables; carrier phase precision <2 mm L1 and L2 at 30 sec (or lower) sampling; pseudorange precision <30 cm on L1 and L2 at 30 sec. (or lower) sampling;

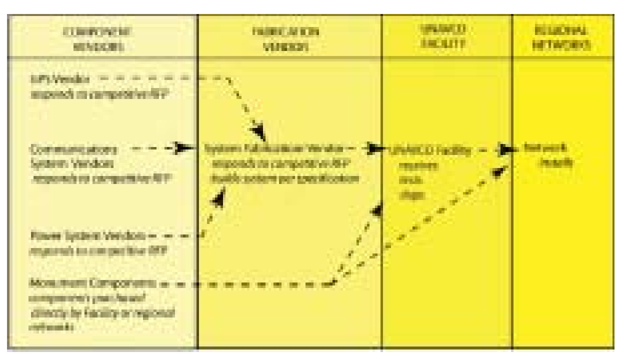


Figure II-2.13. Functional Relationship between GPS Component and System Fabrication Vendors and the UNAVCO Facility

- 12 channels L1, 12 channels L2; full phase and pseudorange data must be tracked, recorded and streamed from a minimum of 12 satellites simultaneously;
- Must stream GPS observables at a minimum of 5 Hz;
- L1, L2 SNR in dB HZ referenced to 1 Hz bandwidth SNR (amplitude) discretization should be better than 0.5% of full scale;
- Separate L1/L2 antenna with ground plane with well defined and documented phase (and gain) pattern allowing mixing with other standard antennas with negligible error;
- Low power < 4 W;
- Direct Ethernet connectivity;
- Support for BINEX GPS data streaming and logging;
- Backward compatibility with anticipated future modifications/enhancements to the GPS space segment including new civilian frequencies.

The UNAVCO Facility will conduct extensive testing of GPS vendor equipment supplied as part of the RFP. The Facility will provide an analysis of performance/cost benefits of different receiver/antenna types. The final choice for major equipment vendors will be made by the PBO Director in consultation with the PBO Standing Committee (or designated subcommittee) and based on test results, functionality, and price. Full-scale production of PBO GPS systems will commence only upon successful First Article testing of the winning vendor by the UNAVCO Facility. GPS receiver purchases will be phased on an annual basis consistent with the planned installation schedule. The goal is to have the same equipment at all PBO sites. If a vendor makes modifications or upgrades to the equipment during the installation of PBO (e.g. implementation of C/A code on L2), we will evaluate the modification for backward compatibility and insure the additional functionality is worth the loss of homogeneity. The issue of maintaining a homogeneous network from a form and function perspective, however, will remain paramount.

As part of USArray, 16 geodetic quality GPS receivers will be collocated at Advanced National Seismic System (ANSS)/Global Seismic Network (GSN) sites. UNAVCO, Inc. will advise USArray on the recommended receiver and antenna, as well as specifications for monumentation and infrastructure.

The purchase of the 100 portable Campaign GPS receivers for PBO will begin with the development of a detailed equipment specification as part of a Request For Proposal (RFP) that will be sent to the major geodetic GPS equipment manufacturers. Ten of the 100 systems will be purchased with real-time kinematic capability requiring additional radio and data logging equipment. Real-time kinematic systems will be used to rapidly map fault traces and profile fault escarpments and collect precise position information for GIS based geologic mapping. The RFP will require GPS vendors to provide a proposal detailing how their system meets the specification and provide a cost structure for quantity discounts. The UNAVCO Facility will test all equipment to ensure data quality and receiver portability/functionality requirements are met with an emphasis on data quality, minimal loss of data, power consumption, ease of use, and lifetime cost of operations and maintenance. A report and recommendation for purchase will be made by the Facility to the PBO Director. The winning vendor will be required to submit a First Article to the Facility for acceptance testing before large-scale shipment commences. Upon receipt of production quantities of equipment, the Facility will implement an internal test and acceptance plan to check everything from inventory lists of materials to individual receiver/antenna performance.

## Strainmeter Systems

The number of borehole strainmeters to be installed as part of the PBO is about four times the number that have been installed in the United States in the past 20 years. In addition, there is a limited pool of geodetic quality strainmeter manufacturers and each installation is customized. The PBO Strainmeter Working Group evaluated current strainmeter technology and recommended using a mix of Sacks-Evertsen dilatometers and Gladwin Tensor Strain instruments (Figure II-2.14) for borehole installations, and the SIO/IGPP instrument for long-baseline laser strainmeter installations. The working group recommended an initial purchase of 50 borehole systems split evenly between the Sacks-Evertsen dilatometers for volcano deployments and Gladwin Tensor Strain instruments for deployment in non-volcanic regions. The Working Group also recommended that a small number of the newer SES3 (Sacks-Evertsen-Sakata 3-component strainmeter) are purchased and tested relative to the Gladwin Tensor Strain instrument. Subsequent strainmeter purchases will depend on the quality and performance of systems purchased in previous years. Laser strainmeters manufactured by SIO/IGPP will be placed at sites that are densely instrumented with borehole strainmeters and GPS (e.g., Parkfield, Landers-Hector Mine region, and Durmid Hill).

Figure II-22.14. Installation of a Gladwin Tensor Strainmeter instrument.

All strainmeter systems considered for deployment in PBO are made by small university or government research groups. For the quantities of borehole systems required for PBO and to realize cost savings based on larger volumes, fabrication and quality assurance testing must be contracted to outside manufacturers. However, the manufacturers must be carefully supervised at each stage in the production process by instrument designers to ensure documented strainmeter design criteria are met. For strainmeter installations we have budgeted a small sum to fund instrument designers to produce technical plans, fabrication, assembly, and quality control documentation for hand off to contracted manufacturers.

The PBO will have a large seismic component including 175 seismometers installed along with strainmeters in borehole installations. USArray will advise PBO on the preferred instrument to maximize return to the scientific strainmeter, seismic, and geodetic communities. The minimum specification will include a 3-component, 1-Hz, borehole seismometer with simple moving coil sensors (e.g., an L4). If budget permits, the 1 Hz system can be upgraded to a 3-component broadband sensor (e.g., Guralp CMG3T). Broadband instruments require tighter borehole casing specifications, thus adding a significant cost to the project. Since borehole strainmeters will be deployed in clusters of ~5 instruments, the option exists to upgrade one of the 5 boreholes to a broadband instrument thereby minimizing the upgrade cost.

## Data Communications Systems

As with GPS receivers, the UNAVCO community has considerable experience in the evaluation and implementation of a wide range of data communications options. First-hand experience has also shown the benefits of quasi-real time data communications in terms of station maintenance and troubleshooting, and overall data availability and quality, as well as the streamlining of downstream data quality control and processing. Other issues come into play such as integrating GPS, strainmeter, and seismic data at collocated sites. Given the considerable geographic extent and variable conditions under which PBO systems will be installed, a tiered approach for data communications will be required, as follows:

1. Direct Internet connectivity will be the preferred choice of data communications at each station;
2. If a suitable Internet connection is not available within proximity to the station, radio modems/ radio repeaters will be used to transfer data to an Internet node;
3. If the distance to an Internet node exceeds the distance capability of radio modems, then a commercial satellite-based Internet connection (e.g., Starband or DIRECWAY/Hughes) will be used;
4. If a satellite-based Internet connection is not an option based on local conditions, a Very Small Aperture Terminal (VSAT) system will be used; VSAT may also be used as a local hub for small-scale sub-networks such as on volcanoes; a VSAT download Hub is available at the UNAVCO Facility in Boulder and others may be established based on need and specific satellite footprint, e.g., for Alaska;
5. If none of the above options are viable, a cell phone modem connection will be used;
6. If none of the above options for quasi-real time data communications are viable, periodic manual downloads will be performed by network staff.

The various data communications options identified above which require specific hardware will be procured on a competitive basis at the component level by UNAVCO, Inc. and shipped direct from the source to the fabrication vendor for assembly into integrated stations. The specific choice of data communications option will be made on a station-by-station basis by the Regional Engineers and communicated to the UNAVCO Facility, which will bundle system specifications for assembly by the fabrication vendor.

## Power Systems

DC power is preferred for running PBO stations because of community experience with the standalone nature and reliability of DC power. Most GPS sites run on < 12 W and strainmeters consume < 30 W of DC power. Combinations of solar panels and batteries, with high-quality voltage regulators and critical lightning isolation have been shown to be both reliable and cost effective in both types of installations. The PBO Director will develop the specification for the power systems and the system components purchased by competitive RFP by UNAVCO, Inc. Power components will be shipped directly to the fabrication vendor for assembly into GPS stations.

## Monuments

The GPS research community has converged on two GPS monuments for PBO with a site-specific decision to be based on accessibility. The monument of choice for both unconsolidated materials and bedrock installations is the deep drilled braced monument (e.g., Figure II-2.11). This design minimizes the probability of monument motion but is the most expensive option in terms of both material and personnel time for installation, and requires access by a full-sized drill rig. In cases where access by a drill rig is not possible (e.g., National Parks), a short drilled braced monument developed by SCIGN with the legs drilled using a large electronic hand drill has been found effective in the SCIGN network and at several geodetic quality SuomiNet stations. Other cases, for example permafrost installations in Alaska and areas with no bedrock and where limited accessibility exist, the type of monument installed will be evaluated on a case-by-case

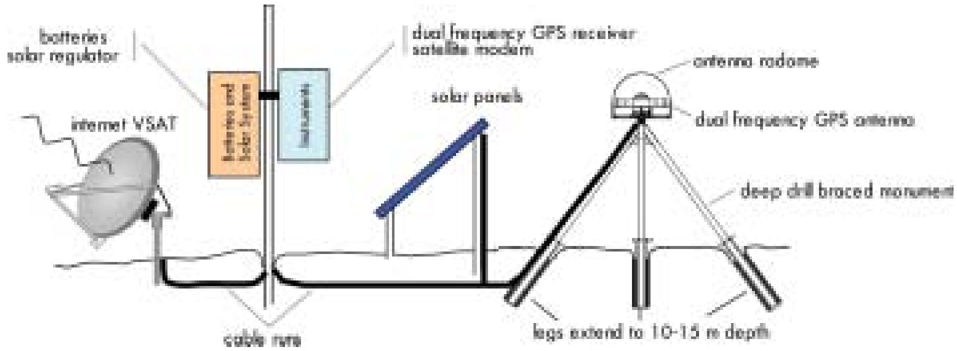



Figure II-2.15. Schematic diagram of a typical PBO permanent GPS installation with satellite Internet option.

basis. The final decision on which option to use will be made by the respective Regional Engineer in consultation with the PBO Director and Operations Manager on a site-specific basis depending on science, budget, and logistics considerations.

## Installation Options

A standard permanent GPS installation hosts a high quality, deeply anchored monument, a dual frequency GPS antenna and receiver, data communications and power infrastructure, and secure system enclosures. Figure II-2.15 shows a typical DC-based installation with satellite modem communications similar to a prototype PBO site on Guadalupe Island off the coast of Baja. Other communications options include direct connection to the Internet, or a radio or microwave modem relay to download computer.

Combined GPS, borehole strainmeter, and seismometer installations will likely be the most complex in terms of below ground drilling, data communications, and power. For these installations, solar systems capable of generating ~30 W of power and communications systems capable of full-time 56 kbps transmission are required (Figure II-2.16).

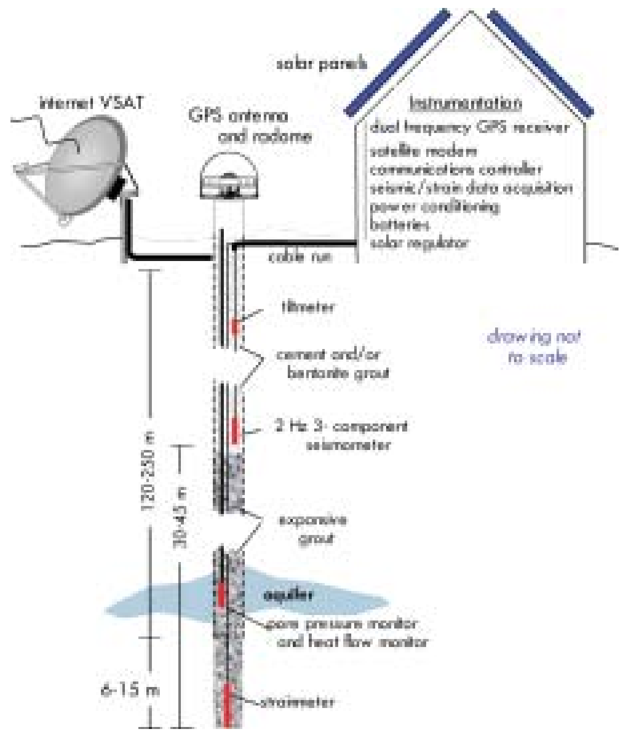



Figure II-2.16. Schematic diagram of a combined permanent GPS, strainmeter, and seismometer installation. This type of installation also includes a borehole tiltmeter, a pore pressure transducer, heat flow monitor and barometric pressure sensor.

# 2.6. System Fabrication, Testing, and Deployment

## Background

As discussed in the previous section, UNAVCO, Inc. will handle the purchase of PBO hardware with component vendors shipping system parts directly to the fabrication vendor who will assemble the GPS and strainmeter stations. The completed stations will then be shipped to the UNAVCO Facility for final inventory, testing, and eventual shipment to regional networks for installation. The fabrication vendor will be chosen in part based on proximity to the Boulder Facility location. Strainmeter systems will ship directly from the manufacturer to the Boulder Facility or regional network offices. The details of how this process will work are provided below.

## System Fabrication

The GPS component of PBO will have four major subsystems including GPS receiver and antenna, data communications, power, and monuments. All of these subsystems will be procured directly from vendors based on a competitive RFP process as previously discussed. The receiver/antenna, communications and power subsystems will be shipped in accordance with a pre-determined weekly schedule from the manufacturers' location directly to the fabrication vendor. The UNAVCO Facility will be responsible for maintaining the master schedule for subsystem shipments, system fabrication, receipt of finished systems at the Facility, and shipments to the regional networks for installation. Figure II-2.17 shows the flow of planning information between the vendors, fabrication vendor, Facility and regional networks.

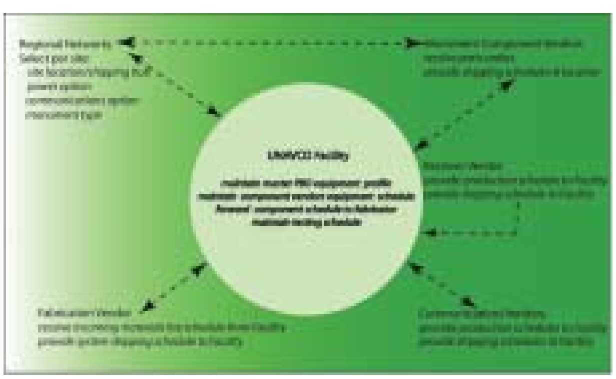


Figure II-2.17. Flow of planning information between the PBO component vendors, fabrication vendor, UNAVCO Facility and regional networks

The UNAVCO Facility will have the prime responsibility as the information clearinghouse for the site-specific hardware requirements for all the regional networks as well as the backbone network. UNAVCO will ensure the flow of planning information and materials between the subsystem vendors and fabrication vendor and oversee the shipment of finished systems to individual sites or regional shipping hubs as specified by the regional networks. This process will insure adequate communication between all parties and eliminate confusion regarding the flow of equipment within the network.

For borehole strainmeter instruments an external subcomponent manufacturer will be used with supervision of final fabrication and quality assurance provided by strainmeter designers. Instrument manufacturers are required to produce at least two production prototype instruments using the same methods planned for the production run. Pre-production units will be tested by the UNAVCO Facility prior to authorization of a production run. A minimum lead time of six months will be allowed for production of the first fully tested borehole systems following authorization of the program. This minimum time assumes the existence of a fully defined production prototype as of the date the PBO program is funded. Potential instrument providers must be prepared to formally guarantee production rates of at least thirty instruments per year to required standards in the second year, and up to 50 units per year thereafter. It is desirable for instrument production rate to be at least 50% higher than deployment rates to maximize test time and ensure that no field deployment opportunities are lost.

## System Testing

The finished GPS and strainmeter systems will be shipped from the fabrication vendor to the UNAVCO Facility in accordance with a published weekly schedule. The systems will be inventoried at the system level as well as at the individual component part number level. The Facility will develop appropriate testing facilities to ensure equipment testing and burn-in are accomplished to meet the installation schedule developed by the regional networks. Automated test stations with PC-controlled data collection will be built to ensure all critical system functions are exercised and that the systems are burned in sufficiently to avoid shipping broken systems into the field. Configuration records including everything from part numbers to GPS data records will be maintained in an already developed UNAVCO Facility equipment relational database for each system as part of the overall configuration management process for the network. This database will allow entry of hardware changes from the field as maintenance and repair activities are conducted over the life of the network. Prototype and production run strainmeter systems will be tested at the UNAVCO Facility based on USGS and manufacturer test criteria.

## System Deployment

Once successfully inventoried, tested and burned-in, GPS and strainmeter systems will be shipped to specific regional network sites or local shipping hubs as directed by the Regional Engineer. The individual components for monuments will either be shipped along with the systems, or the regional networks will have the option of acquiring materials locally. For example, independent drill rig crews operating on a regional basis could install drilled braced monuments. The UNAVCO Facility will maintain vehicles for local movement of components and systems. The Facility will have the flexibility to expedite delivery of systems on a rush basis to remote locations over the western US when commercial shippers cannot respond adequately.

# 2.7. Data Management and Archiving

## Background

The PBO Data Products Manager will oversee the reliable transfer of GPS and strain data from the regional networks to PBO supported long-term archives. All campaign and continuous GPS and strainmeter data will be made immediately available to the PBO community via the archives and the PBO web site. PBO data management will be streamlined by: (1) taking advantage of the GPS community's long history of successful data transmission and archiving, (2) by having a network of two to three standardized field equipment packages, (3) by having a single point of collection and dissemination of station metadata, and (4) using new data distribution tools and interfaces. The proposed model for data flow in PBO shows data flowing from Data Providers (primarily Data Technicians at Regional Centers) through a data transport layer to Processing Centers, Archives, and end users (Figure II-2.18). Data management of the 200+ continuous sites currently managed by UNAVCO involves a complex data management strategy due to a wide range of individual site equipment and communications configurations. PBO continuous sites, in contrast, will be treated as a single project, with uniform site and communications configurations. This will allow for a high degree of efficiency in data management. Retaining metadata in a database rather than transmitting metadata with the file will simplify metadata management.

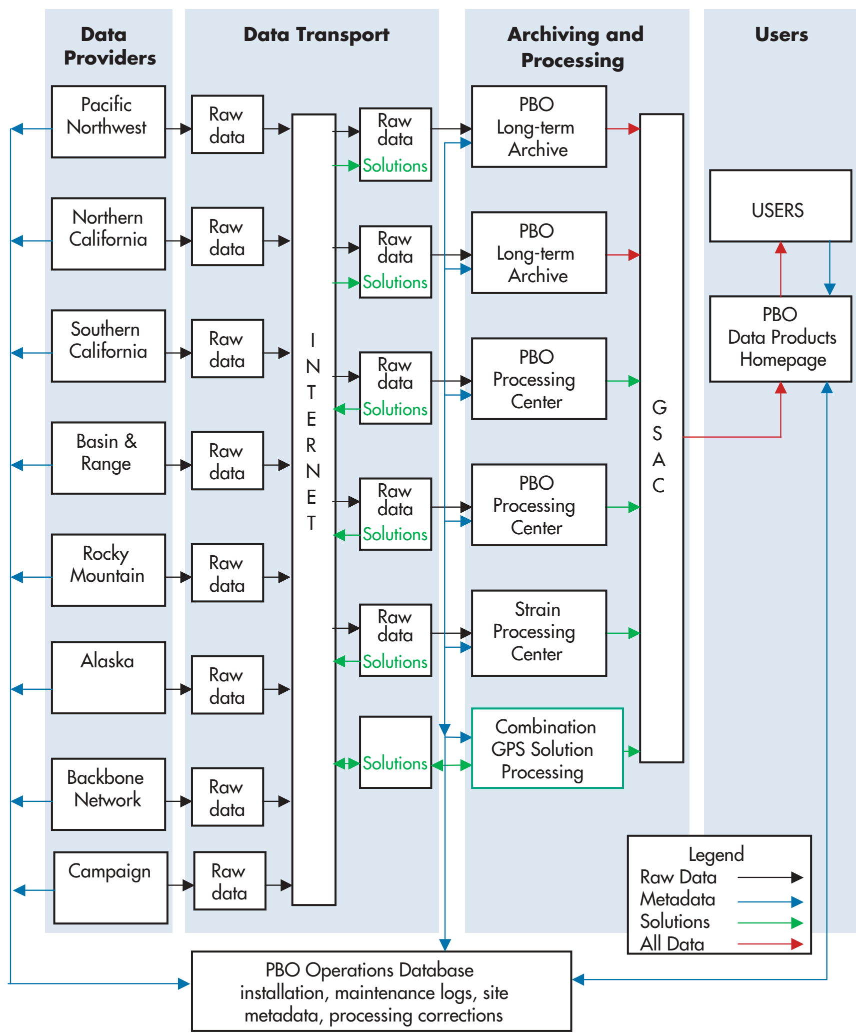



Figure II-2.18. Plate Boundary Observatory Data Management and Archiving Schematic.

## Regional Data Communications

In the proposed data management model, the primary job of the Regional Data Technicians is to download data from regional GPS and strainmeter stations. Each region will manage on the order of 100 or more GPS stations and 10 or more strainmeters. Data Technicians will be responsible for data links from individual stations to the regional data hub. The technicians will place the raw data into a pick-up directory and an automated Internet data distribution system, for example UNIDATA's Internet Data Distribution "IDD" project's Local Data Manager "LDM" software, grabs the data and delivers it to Processing Centers and Archives.

### Local Data Manager (LDM)

The Unidata Local Data Manager (LDM) is a collection of cooperating programs that select, capture, manage, and distribute scientific data products. The system is designed for event-driven data distribution, and is currently used in the Unidata Internet Data Distribution (IDD) project. The LDM system includes network client and server programs and their shared protocols. An important characteristic of the LDM is its support for flexible and site-specific configuration. Geodetic Customers for LDM include a number of stations in the EBRY network, stations belonging to the NOAA Forecast Systems Laboratory, and all the SuomiNet GPS stations. The Unidata LDM software is used by more than 150 universities/cooperating agencies and is freely available via anonymous ftp.

## Data Transport Model

Data transport for PBO requires a secure, automated, and freely available Internet data distribution system for data and product file transfer. The chosen system should have the ability to do multiple file retries, work over noisy data links, and provide automated file purging. For example, LDM was adopted by the Atmospheric GPS project SUOMINET for automated transfer of raw GPS data (e.g. BINEX format) from 50 universities across the world. SuomiNet raw data are placed in a data queue on a local computer connected to the Internet. LDM picks up the data and delivers it to archiving and processing centers then distributes the resulting products back to project investigators.

In PBO, 13 full time LDM nodes, including regional download hubs and PBO processing facilities, would be established for automated transfer of raw GPS, strain data, and derived products. Additional nodes can be created to capture campaign data from individual investigators if needed. The data injected from each region are simultaneously deposited at each of the archive and processing centers (Figure II-2.18). In this model, additional processing centers can also subscribe to data and then LDM will deposit data directly in their local LDM queues. LDM is then used to transport solutions from processing centers to the machine used to display PBO results and products. This model has the security benefit that traditional ftp access for outside users is provided only from the archive centers, and optionally from the processing centers. Also, the users of the raw data (archives, solution centers, independent processors) get the data at the same time and independently of each other. For example, a processing center need not depend on an archive center for the data.

## PBO Archives

The UNAVCO Community currently supports two long-term archives, one at the UNAVCO Facility and another at the Scripps Orbit and Permanent Array Center (SOPAC). These two groups will receive funding to preserve and redistribute the entire PBO GPS raw data set and derived products (coordinates, velocities, strain rates, etc.). These archive centers will mirror the data and solution products and will be linked and accessible via the GSAC system. For GPS data, the raw data file name will contain key information such as 4-char ID, monument id number, download node name, date and time. This information can be used to extract additional site metadata from the PBO database ensuring up-to-date and accurate information about the site. By using a product like LDM, both archives (and for that matter the analysis centers as well) simultaneously receive identical data from all the regional networks, which greatly simplifies the task of mirroring data. Since the unmodified raw GPS data are the file type transferred throughout the system, and metadata are only obtained from a single common database, there is no modification of the data or metadata along the way and thus sources of error are reduced. The data will flow straight from the source into the archives and processing centers. Strainmeter data will undergo quality control processing at the northern and southern California regional centers and will be archived in SEED format at the U.C. Berkeley Seismological Laboratory with a copy of the data residing at the IRIS Data Management Center (DMC) located in Seattle.

The PBO archivist will monitor the archive content via the GSAC. Simple scripts can be created to automatically verify correct mirroring of the raw and solution data using GSAC tables produced at each archive and processing center. The archives can provide traditional RINEX and log files using the raw data and metadata obtained from the PBO database.

# 2.8. Data Analysis and Products

The GPS research community has many years of experience with operation of a community-based data and data products infrastructure through the International GPS Service (IGS). The IGS has as its goal the worldwide distribution of data and data products required for determining precise GPS satellite orbit solutions and geophysical results. This process is made possible by the efforts of independent but coordinated data analysis centers whose products are combined into official IGS products through a rigorous community-determined process. This model has the benefit of producing redundant solutions that can help to identify network or analysis problems and it allows a combined "best" solution for geodynamic modeling. The IGS model will also easily accommodate other data types such as borehole and laser strainmeters as discussed below.

The IGS was formally established in 1993 and provides raw GPS tracking data and data products such as precise orbits, clock solutions, troposphere delays, ionosphere maps, and station positions, all in support of geodetic and geophysical research. These products are produced by Individual Analysis Centers (IAC) with an official combined product produced by an independent Analysis Center Coordinator (ACC). The ACC is appointed by the IGS Board and has full oversight and responsibility for all products. All IGS products and data are available on the Internet via anonymous ftp. Weekly reports are generated and archived that discuss the quality and latency of the products. Annual reports are also generated by both the Analysis Centers and the ACC.

## The PBO Data Products Model

The key characteristics of the PBO data and data products model include:

- Open and immediate availability of raw data for the entire network, including both permanent station GPS and strainmeter and campaign GPS data;
- Specialized datasets available upon request, e.g., higher data rates for experiments;
- Well-documented and web-accessible site/equipment descriptions and metadata;
- Multiple individual analysis centers (IAC) using different analysis software;
- Independent Analysis Center Coordinator (ACC);
- Redundant quality control assessments by the IAC and ACC;
- Open availability of a suite of high quality official data products.

There is clear community consensus that more than one analysis center is needed in order to provide verifiable data products. A total of four analysis centers will be supported through PBO, two each for GPS and strainmeter data. Each center will reduce either raw GPS or laser and borehole strainmeter data to final products. Subawards for the analysis centers will be made based on a competitive bid process that emphasizes established processing and analysis capability and degree of institutional cost sharing. An independent PBO Solution Coordinator will oversee production of a suite of PBO Facility data products (detailed below) and the combination of products into official PBO products. The PBO Director will appoint the Solution Coordinator based on a competitive job search. For campaign data we propose that each GPS Analysis Center will accommodate routine processing of campaign data including the generation of campaign solution SINEX files.

## Requirements for a PBO Analysis Center

The PBO Director will solicit proposals from the geodetic community for two PBO Analysis Centers (PBO-AC). A fundamental requirement for GPS data processing will be that at least two different software packages are used in the production of products, for example Bernese, GIPSY, and/or GAMIT. Each software package approaches the analysis problem differently and thus reconciling differences in the solutions leads to the ultimate accuracy of GPS. In addition to the proven ability to analyze GPS data, any organization selected to function as a PBO Analysis Center must also be able to isolate modeling errors, improve analysis strategies, and estimate precise ephemerides, all of which require a sophisticated understanding of the data and analysis software.

Each Analysis Center will provide daily solutions to the Analysis Center Coordinator in a predetermined format (e.g., SINEX) for GPS or reduced time series for strain. With a single raw data type from PBO GPS receivers (e.g., BINEX), Analysis Centers can directly read the raw data file, eliminating the need to translate to RINEX, while obtaining up-to-date station metadata directly from the PBO operations database. Each Analysis Center will also be required to provide feedback and corrections to the station metadata database if errors are detected during the analysis process, e.g., processing results showing a position jump possibly indicating a non-geophysical displacement of a monument or movement of an antenna. Analysis Centers will be required to accommodate and process specialized data sets, such as high rate GPS or strainmeter data on request.

Analysis Centers will provide annual reports outlining their analysis strategies (and any changes therein), and detailing accuracy statistics for all stations within their purview. Any changes in analysis strategies must be announced to and approved by the Analysis Center Coordinator to ensure the coherency of the data and data products from that Center. All Analysis Center summaries and reports will be posted on the PBO web site.

## Requirements for the PBO Analysis Center Coordinator

The PBO Director will appoint an Analysis Center Coordinator (ACC) to produce the official PBO products in a timely manner and to constantly assess the quality of the official PBO products. A secondary but important role will be to use the official PBO products to flag possible transient motion associated with specific GPS and/or strainmeter stations so that the community can respond with additional instrumentation or analysis. The ACC will be a full-time position with the incumbent having a strong geodetic background with a detailed understanding of strainmeter error correction, GPS analysis strategies, and the application of reference frame constraints to GPS solutions. The ACC and the PBO Director will provide a yearly report to the PBO Standing Committee so the official PBO products can be assessed for accuracy and scientific relevance. Appropriate data sets will be submitted as contributions to projects such as the UNAVCO community GPS Velocity Project (http://icarus.unavco.ucar.edu/science_support/crustal_motion/dxdt/gpsvel/) and the International Earth Rotation Service (IERS).

## PBO Products

The most fundamental PBO product will be daily RINEX data files, GPS Cartesian position estimates, and a reduced strainmeter time series. Each GPS Analysis Center will produce a network solution on a daily basis including station positions and variances, most likely in SINEX format, and a simplified solution time series such as JPL's XML time series files. The Analysis Center Coordinator will then combine the two Analysis Center solutions to produce an official daily PBO SINEX file. The reference frame will be determined by the ACC in consultation with the PBO Director. Each GPS Analysis Center will provide automated PBO campaign data processing to ensure that data are processed in a consistent and efficient manner. Derivative products will include GPS tropospheric water vapor, precise orbits, and ionospheric total electron content estimates.

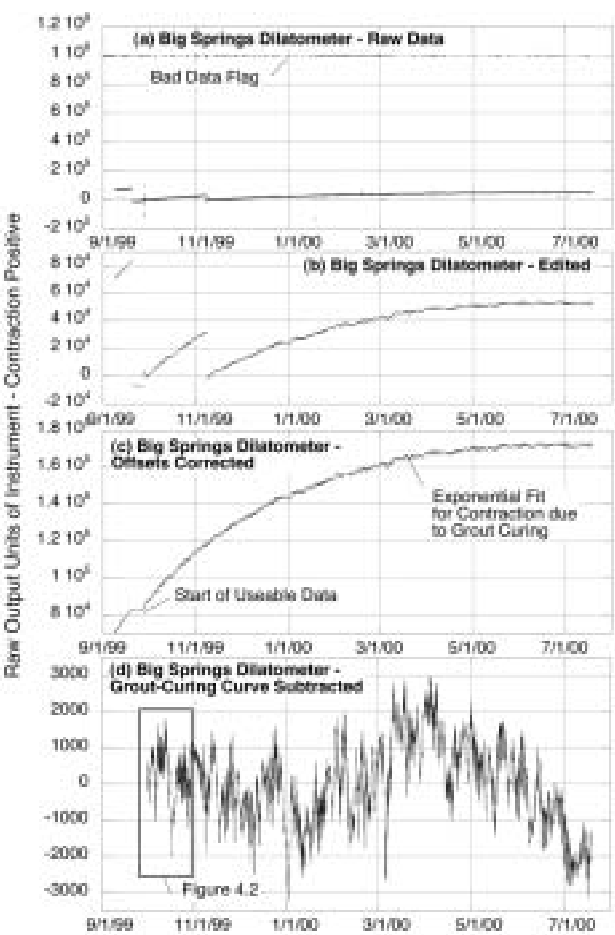



Figure II-2.19. Top graph shows raw borehole strainmeter data. Progressive graphs show removal of bad data and an exponential curve induced in the data due to grout cure effects.

For strainmeter data, a daily time series will be produced that applies corrections for solid earth tides, barometric pressure corrections, and any exponential trends resulting from grout curing and known seasonal signals (Figure II-2.19). For laser strainmeters the data product will be an edited time series with bad data points removed, spurious offsets removed (strain measurement, and end-monument corrections from the anchors) and end-monument motions, laser frequency, and vacuum level corrections applied to the series (Figure II-2.20). The Analysis Center Coordinator will produce a PBO station velocity and strain map that will be updated on a regular basis. Some level of geophysical modeling of the PBO data may also take place to guarantee the quality and sufficiency of the data to meet PBO research goals. Otherwise, geophysical modeling and development of model products will be a component of the associated EarthScope research program.

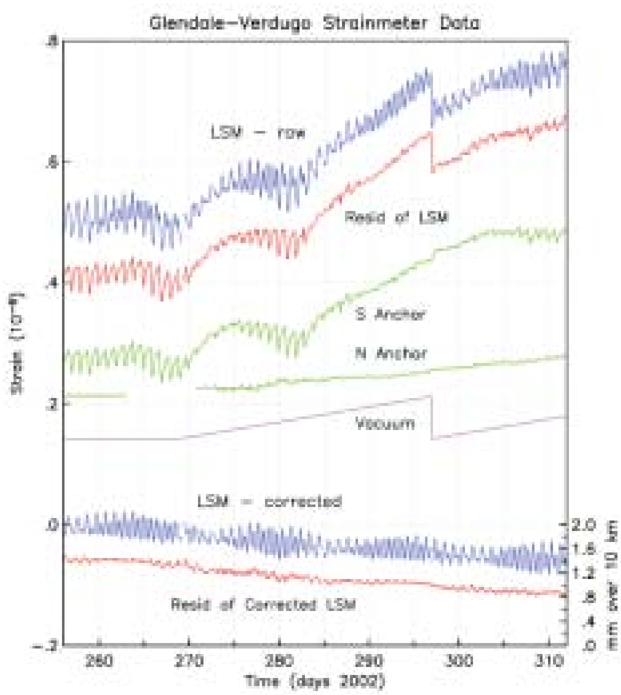



Figure II-2.20. Laser strainmeter record from SCIGN. Blue: the uncorrected strain between the strainmeter ends. Red: residual strain with tidal signal removed. Green: corrections from the optical anchors at the south and north ends. Pink: correction for changes in the vacuum. Bottom Blue and Red: fully corrected strain and residual strain.

# 2.9. Geo-PBO

## Introduction

Fault systems are persistent through time, often with a life cycle lasting on the order of 1 to 10 Myr with repeat times of major earthquakes (durations of the seismic cycle) on the order of hundreds to thousands of years. Hence, any attempt to understand tectonic systems must include observations over this wide range of time scales. The geodetic component of the PBO will provide a backbone of GPS sites, targeted clusters of GPS sites, and borehole and laser strainmeter arrays that will define the strain field of the upper continental crust on the decadal time scale, including transient modes of deformation. Geo-PBO will provide image data and dating facilities that will allow investigators to examine the strain field at longer time scales (Figure II-2.21). The PBO Facility will support paleoseismic and geologic investigations funded through the PBO science proposal process. A science based community workshop (see: http://www.unavco.org/research_science/publications/proposals/pbo/geo_pbo_wp.pdf) recommended that the PBO Facility provide the following support and infrastructure:

- Support for the purchase of aerial imagery such as ASTER (Advanced Space-borne Thermal Emission and Reflection), SPOT, Light Detection and Ranging (LIDAR), and Advanced Laser Swath Mapping (ALSM) to identify and characterize active tectonic structures across the PBO region.
- Specification and development of an image data archive and retrieval system that will make acquired images easily accessible to the entire EarthScope community.
- Support for new and existing NSF-funded radiocarbon and cosmogenic nuclide chemical preparation facilities.

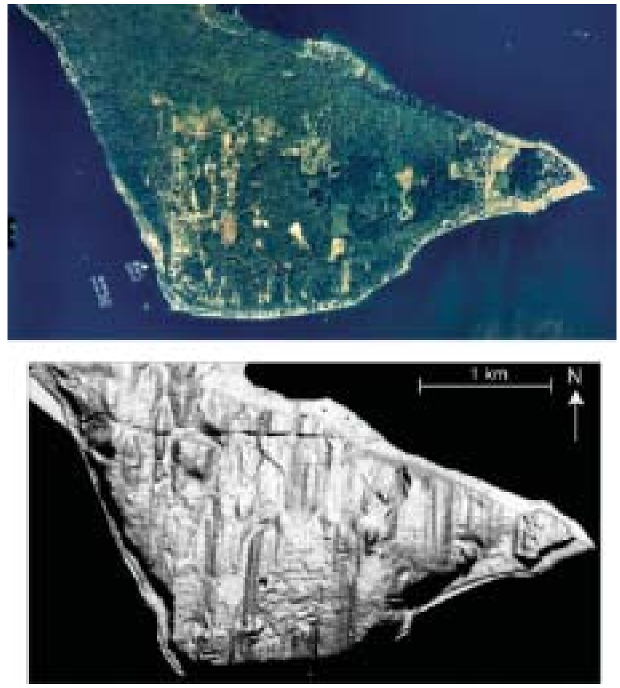



Figure II-2.21. Aerial photograph (top) and LIDAR (bottom) image of the Toe Jam Hill fault scarp. Paleoseismic investigations confirmed that the scarp records at least one large earthquake since the last ice age. Note the fossil beach terrace that surrounds this part of Bainbridge Island: it was uplifted about 7 meters in a single large earthquake about 1,100 years. From http://geohazards.cr.usgs.gov/pacnw/paleo/bainisl/sfhistory.html

## Aerial and Satellite Imagery

In years 2-5 of the PBO project, PBO will support the acquisition of $2.3 million dollars worth of imagery, a combination of aerial imagery (photography, LIDAR) and satellite imagery (SPOT, ASTER, IKONOS, QuickBird). The Geo-PBO Advisory committee will provide guidance on the location and type of imagery required. To archive, process, and display the images, we propose to purchase commercial products that can be combined to produce an Internet-based image-processing capability for the EarthScope community. The components of the system include: a physical disk archive and server system with software to catalog purchased and analyzed images; a data processing server and software to manipulate (subset, enhance) images; and a simple and inexpensive interface so users can select, manipulate, and send new images to the archive for storage (Figure II-2.22). Development of the image archive will require approximately 750 person-hours to create the links between the various software packages and a simple user interface. Image acquisition activities will be closely coordinated with sponsors at NASA to capitalize on existing imagery, software and processing utilities including large volume satellite data purchases. Another example of potential collaboration with NASA is the use of existing software such as RODIN, an image data archive and retrieval system developed as part of NASA's NEpster system which give users internet access to distributed image archive systems including Goddard's Distributed Active Archive Center (DAAC). RODIN was developed for NASA Goddard by the GST Corporation (http://www.gst.com/) and could be easily modified to accommodate Geo-PBO image archiving needs.

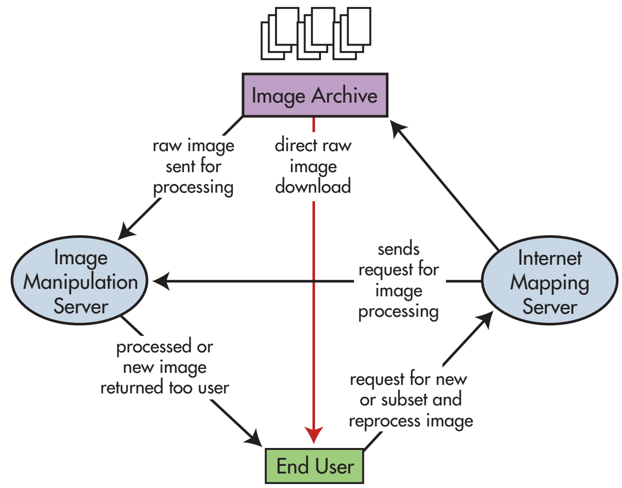



Figure II-2.22. Proposed image archive and processing scheme for PBO. End users access and process images through a web interface. All processing activity occurs on an image manipulation server. Processed images can be returned to the archive for long term storage.

## Geochronology

The Geo-PBO workshop also identified a need for enhanced dating facilities. EarthScope science proposals for trenching activities and other quaternary geologic studies will gen-erate as many as 2000 datable samples/year. To handle this volume of material, we propose to enhance existing dating infrastructure. Dating samples is a two-stage process; first the samples are reduced to accelerator targets using wet chemical techniques, then accelerator mass spectrometry (AMS) is used to measure time dependent accumulations of radionuclides such as isotopes of beryllium, carbon, aluminum, chlorine, calcium, and iodine that occur in sampled material. There are sufficient AMS facilities to handle the throughput of samples required by PBO. However, sample preparation (especially for cosmogenic nuclides), is time and labor intensive, and will be a significant bottleneck for PBO. We propose to augment the staff at one existing radiocarbon preparation facility such as National Ocean Sciences Accelerator Mass Spectrometry Facility (NOSAMS), Purdue Rare Isotope Measurement Laboratory (PRIME), Lawrence Livermore National Laboratory Center for Accelerator Mass Spectrometry (CAMS), University of Arizona Accelerator Mass Spectrometry Laboratory (AMS), or the University of Colorado INSTARR Nuclear Structure Research Laboratory (NSRL) at a level of $450 k over a three-year period. For cosmogenic isotope preparation we proposed to create one new lab ($1.12 M over five years) and augment one existing lab ($450 k over a three-year period). The Geo-PBO Advisory committee will advise on the selection of laboratories for staff augmentation and the establishment of new laboratories.

A UNAVCO Inc. Geo-PBO coordinator will oversee and manage subcontracts to geochronology facilities, establish and maintain the servers for the image archive and processing, and specify and monitor the development of the user interface and provide training to PBO investigators on how to use the system.

In summary, Geo-PBO will provide an archive of fault image data. These images will be used in EarthScope funded geologic studies to extend faulting records beyond the decade time scales available from the geodetic side of PBO. And Geo-PBO will greatly increase the capacity for dating samples that are acquired during these investigations.

# 2.10. Utilizing the PBO

The primary activity of the PBO will be to provide data and data products so that interested scientists can study the plate boundary zone without the burden of managing a large network. A broad spectrum of users will benefit from PBO including researchers interested in using raw data and those who use higher level products to develop and test geophysical models. In addition the PBO will service educators through Education and Outreach activities, local surveyors through base station data and velocity estimates of benchmarks, and researchers interested in ancillary products such as GPS derived tropospheric water vapor, precise orbits, and ionospheric total electron content estimates.

The main portal into the PBO will be through a World Wide Web interface with data, data products, and station metadata available via a web interface and anonymous ftp. These tools will be closely coordinated between PBO and the larger EarthScope Education and Outreach effort. The Data Products Manager will maintain the web interface and content with help from the operational staff. Some mission critical information such as station installation documentation that contains sensitive contact details and data routing information such IP addresses will not be publicly available. Proposed items for the web include:

- General info on PBO—with links to related projects such as USArray and SAFOD
- Network installation timeline
- Station permitting status reports
- Site installation documentation
- Graphical and text based network reports
- Site maintenance reports
- Station metadata and raw data
- Analysis center time series and combined time series
- Velocity and strain maps
- Links to ancillary products from PBO (clocks, orbits, Earth Orientation Parameters, troposphere, ionosphere)
- Links to modeling software and public domain PBO software
- Acknowledgements and contacts
- News pages
- Links to educational materials and resources
- Calendar of related workshops, seminars
- How to request support

The final bullet is critical for the success of PBO. It will be designed for investigators who have questions on how to get data or results, how to request special data sets, or how to schedule campaign GPS systems and engineering support through PBO. More importantly, new investigators and students interested in becoming involved in using the products of PBO should use the request form. The support request will be modeled on a similar page found on the UNAVCO Facility web site (https://www.unavco.net/project/forms/howtorequestsupport.html) (Figure II-2.23). When an investigator clicks on this link, they are presented with support options to select. Depending on the support required the information requested on the form changes. Once the form is completed it is sent to the relevant section of the UNAVCO Facility with


Figure II-2.23. Help request form found on the UNAVCO Facility web site.

a copy to Facility managers. For PBO for example, investigators could use a form similar to this to request campaign support, science proposal budgets, and specialized data sets or to ask general questions of PBO staff. This tool has proven to be an effective mechanism for receiving, tracking and cataloging investigator requests and provides the ability to quickly generate statistics on who is requesting support.

# 2.11. Budget and Budget Justification

## Introduction and Summary

The EarthScope Observatory will have two major NSF funding components including a five-year Major Research Equipment and Facilities Construction (MREFC) component that will build the core EarthScope Facilities, and a ten-year Operations and Maintenance (O&M) component funded through Research and Related Activities (R&RA) accounts.

The budget presented here is for the MREFC portion of EarthScope's Plate Boundary Observatory (PBO) (Table II-2.4). The budget for PBO operations and maintenance is covered in a separate proposal. Funding for the PBO component of Earthscope is proposed to flow through a cooperative agreement to UNAVCO, Inc. UNAVCO, Inc. currently operates on a direct cost basis, so corporate management and administrative costs associated with PBO are explicitly included in the budget at 30% of corporate staff and associated operating costs.

UNAVCO Inc. will hire 55 staff to install and establish initial operational capability for 1,050 Global Positioning System (GPS) and strainmeter instruments, provide data and data products to the EarthScope community, and provide management and administrative support to the project. PBO staff will operate from the UNAVCO Facility, the Scripps Orbit and Permanent Array Center (SOPAC) archive, the University of California, Berkeley Seismological Laboratory, and through subawards to major participating universities, with the majority of positions accounted for as UNAVCO Inc. staff.

Currently, in the western U.S. there is approximately one borehole strainmeter for every 20-30 continuously operating GPS stations. PBO will change that ratio to about one-to-four. Based on the large number of GPS stations previously installed in the western U.S., the installation costs are well known. Borehole strainmeter installation costs, on the other hand, can vary by more than 100% depending on the difficulty of drilling the borehole. To accommodate the large uncertainty in the strainmeter costs, strainmeter installations will be prioritized such that the highest priority groupings of stations are installed first. This will provide a way to control costs while ensuring the highest priority sites are completed successfully.

To account for regional differences in logistics and associated difficulties in installations, strainmeter and GPS installation costs were first calculated on a region-by-region and per-station basis. These numbers were then used to calculate a network-wide average installation cost. Annual costs were then calculated by multiplying the average costs by the number of systems to be installed on an annual basis (Table II-2.4). Table II-2.4 therefore provides a summary of the total PBO costs including equipment and installation, personnel and associated space, travel and office costs, support for the GeoPBO program, and activities of the PBO Standing and other advisory committees. Based on NSF guidance, a 5% project contingency fee is allocated to buffer against unexpected cost overruns. The budget justification that follows addresses these line items in more detail.

Table II-2.4. PBO Yearly and Total Five-Year Budget Summary

| **PBO MRE** | **Average Installation Cost/Station** | **2003** | **2004** | **2005** | **2006** | **2007** | **Five Year Total Cost** |
|---|---|---|---|---|---|---|---|
| Campaign GPS | 10,000 | $500,000 | $500,000 | $- | $- | $- | $1,000,000 |
| Standard Strainmeter Equip & Installation | 134,920 | $269,840 | $2,023,800 | $9,444,400 | $9,444,400 | $2,428,560 | $23,611,000 |
| Long-Base Laser Strainmeter Equip & Install | 489,450 | $489,450 | $978,900 | $978,900 | $- | $- | $2,447,250 |
| Continuous GPS Equip & Installation | 37,863 | $1,893,150 | $7,572,600 | $9,465,750 | $9,465,750 | $4,732,875 | $33,130,125 |
| GeoPBO | n.a. | $1,000,000 | $1,000,000 | $1,000,000 | $1,000,000 | $1,000,000 | $5,000,000 |
| 5 % contingency | n.a. | $1,000,000 | $1,000,000 | $1,000,000 | $1,000,000 | $1,000,000 | $5,000,000 |
| Community Meetings | | | | | | | |
| PBO Standing Committee | | $19,200 | $19,776 | $20,369 | $21,082 | $21,925 | $102,353 |
| PBO Advisory Committees | | $126,000 | $86,520 | $89,116 | $46,340 | $- | $347,976 |
| Total Salaries & Benefits Specific to PBO | | $3,555,529 | $4,132,175 | $4,237,584 | $4,364,712 | $4,495,653 | $20,785,653 |
| Total Non-Salary Program Support Specific to PBO | | $1,187,560 | $1,609,969 | $1,462,063 | $1,443,901 | $1,431,489 | $7,134,982 |
| UNAVCO, Inc. Corporate Support (30% of selected HQ costs) | | $235,518 | $257,553 | $265,115 | $276,215 | $281,260 | $1,315,662 |
| PBO TOTAL | | $10,276,247 | $19,181,293 | $27,963,297 | $27,062,400 | $15,391,763 | $99,875,000 |
| Management Fee | | $25,000 | $25,000 | $25,000 | $25,000 | $25,000 | $125,000 |
| **PBO BUDGET WITH FEE** | | **$10,301,247** | **$19,206,293** | **$27,988,297** | **$27,087,400** | **$15,416,763** | **$100,000,000** |
| **MRE PROJECTED BUDGET** | | **$15,096,407** | **$20,880,807** | **$22,907,537** | **$20,847,940** | **$20,267,309** | **$100,000,000** |
| **BUDGET SURPLUS (DEFICIT)** | | **$4,795,160** | **$1,674,514** | **$(5,080,760)** | **$(6,239,460)** | **$4,850,546** | **$(0)** |

Note: Detailed budgets for all PBO cost components can be found on the UNAVCO, Inc. website on www.unavco.org/research_science/publications/proposals/pbo/budget/PBO_Budget_Details.html

Table II-2.5. Equipment Deployment Schedule for PBO (Actual Installations)

| Project Year | CGPS | Campaign | BSM | LSM |
|---|---|---|---|---|
| 1 | 50 | 50 | 2 | 1 |
| 2 | 20 | 50 | 15 | 2 |
| 3 | 250 | | 70 | 2 |
| 4 | 250 | | 70 | 0 |
| 5 | 125 | | 18 | 0 |
| **Total Sites** | **875** | **100** | **175** | **5** |

CGPS = permanent GPS tectonic and volcanic cluster and backbone sites; Campaign = portable GPS systems; BSM = borehole strainmeter systems; LSM = laser strainmeters.

## Station Deployment Schedule

The deployment schedule shown in Table II-2.5 is based on the number of target stations specified in the EarthScope Project Plan, the estimated rate at which land-use permits can be acquired, and the number of GPS and strainmeter systems that can be installed given the proposed staffing levels. This schedule will evolve as the various PBO advisory committees meet and prioritize station installations based on science goals. Equipment purchases will be accelerated in the early years of the proposal and non-critical staff deferred to balance out the yearly budget allocations once they are specified. The initial 50 GPS installations in Year 1 reflect stations that will require little or no lead time for land-use permitting. Discussions with representatives within the proposed regions indicate there are at least 35 sites with current or pending permits that can be used by PBO. Rapid permitting is expected for at least 10-15 backbone sites targeted for private lands in the Rocky Mountain and Basin and Range regions. The limited number of strainmeter installations in Year 1 reflects the lead time required for strainmeter manufacturers to produce systems once orders are in place and provides time for strainmeter installation documentation and staff training. Remaining installations are ramped up in Years 2 through 4 and taper in Year 5, after which the installations will be complete. Laser strainmeter installations may be shifted into Years 1 through 3 based on budget opportunities, advisory committee recommendations, and availability of skilled staff to begin the installations.

## System Installations

For each region, station installation categories were defined so that reasonable average equipment and installation costs could be estimated. For example, in northern and southern California, the category types that were defined include strainmeter stations with GPS monuments on the borehole casing, GPS stations requiring deep-drill braced monuments, GPS stations requiring short-drill braced monuments, and backbone stations requiring meteorological packages. The cost of equipment and installation for each category of installation was then calculated and averaged to produce a regional average equipment and installation cost (Table II-2.6).

Costs for installation of stations in Alaska are the most complex due to extreme environmental conditions, remoteness, and distance between stations. Average station costs for Alaska are therefore developed in the discussion below as representative of the most extreme conditions related to installation operations. Other regions follow a similar but less complex cost rationale, the details of which can be found on the UNAVCO, Inc. web site.

### Detailed Budgets - Alaska

Station installations for the Alaska region are broken down into five categories:

• Helicopter required, remote, multiple GPS and strainmeter installations, primarily focused in the Aleutians.

• GPS sites accessible by road.

Table II-2.6. Average Strainmeter and GPS Costs per Region.

| MRE Costs | Number of Instruments | Network Cost | Average Cost Per Station |
|---|---|---|---|
| **Strainmeters** | | | |
| Alaska | 13 | $1,939,323 | $149,179 |
| Pacific Northwest | 8 | $1,071,179 | $133,897 |
| Northern California | 86 | $11,503,899 | $133,766 |
| Southern California | 64 | $8,560,313 | $133,755 |
| Rocky Mountain | 4 | $536,219 | $134,055 |
| Basin and Range | 0 | | |
| **Total MRE Strainmeters** | **175** | **$23,610,932** | **$134,920** |
| **GPS** | | | |
| Alaska | 151 | $7,210,415 | $47,751 |
| Pacific Northwest | 149 | $5,447,382 | $36,560 |
| Northern California | 261 | $9,062,641 | $34,723 |
| Southern California | 170 | $5,903,610 | $34,727 |
| Rocky Mountain | 54 | $2,188,623 | $40,530 |
| Basin and Range | 90 | $3,317,478 | $36,861 |
| **Total MRE GPS** | **875** | **$33,130,148** | **$37,863** |
| **Total for MRE Equipment** | **1050** | **$56,741,080** | **$54,039** |

• Single site helicopter GPS installations.
• Sites accessible by scheduled air, float plane, or boat service.
• Stations with unknown access.

The cost to install stations in each category differs primarily due to the type of monument and transportation costs. For example, this section discusses the costs for installations at remote sites that require helicopter support for access, and where a group of GPS instruments and strainmeters will be installed in a cluster. Budget details for the remaining classes of stations can be accessed via the UNAVCO, Inc. web site.

Instrument clusters requiring helicopter access are limited to tectonic and volcanic locations in the Gulf of Alaska/Bering Sea. To come up with an average station cost for these sites, a cluster of eight stations was assumed installed at the same time, thus sharing barge and helicopter costs (Table II-2.7). Staging for these sites occurs at a base station with air or sea support, for example Dutch Harbor for installations on Akutan and False Pass for stations on Unimak.

All GPS stations in this case use short drill braced monuments compatible with helicopter transport and augmented solar/enclosure systems developed at the USGS Alaska Volcano Observatory and the University of Alaska. For these sites, data com-

Table II-2.7. Detailed Gulf of Alaska/Bering Sea Region PBO Installation Costs.
(Assumes 6 networks of 8 stations for 48 total)

| Instrumentation | Cost per | Cost per 8 |
|---|---|---|
| Permanent GPS | | |
| GPS receiver | $5,200 | $41,600 |
| GPS antenna | $3,000 | $24,000 |
| Domes & Mounts | $1,000 | $8,000 |
| Data transmission (1) | $5,188 | $41,500 |
| Met Station (backbone only) | | |
| Power and enclosures (2) | $7,500 | $60,000 |
| Security | | |
| Cables | $1,000 | $8,000 |
| **Subtotal** | **$22,888** | **$183,100** |
| **Installation** | | |
| Permanent GPS | | |
| Reconnaissance | $2,000 | $16,000 |
| Permitting (3) | | |
| Monumentation (4) | $2,000 | $16,000 |
| Installation | | |
| Travel (5) | $563 | $4,500 |
| per diem (6) | $1,875 | $15,000 |
| Shipping (overland) | $2,000 | $16,000 |
| Helicopter (7) | $8,047 | $64,375 |
| Fuel and transport (8) | $1,500 | $12,000 |
| Shipping (barge) | $625 | $5,000 |
| **Subtotal** | **$18,609** | **$148,875** |
| **Total Per Station Install Cost** | **$41,497** | |

(1) Assume 1 VSAT remote (25k) for 8 station radio network and 3 repeater radios at $1.5k each per network.
(2) Alaska installations require enhanced enclosures ($3k) and ~ 3 times the number of batteries.
(3) Assume no permitting costs (personal communication from Jeff Freymueller).
(4) Assume all short drill braced monuments
(5) Assume $1500 each for 3 persons.
(6) Assume 25 days to install 8 stations with $200/day per diem for 3 people.
(7) Assume helicopter $1600/day for 25 days. Assume 3 hrs per day flight time at $325/hour.
(8) Assume 2 barrels fuel per day for 25 days @ $200/barrel. Assume $2k fuel transport costs.

munications will use Time Delay Multiple Access (TDMA)-based radio modems at each site broadcasting to a remote Very Small Aperture Terminal (VSAT) satellite terminal handling both GPS and strainmeter data sets. A PBO-funded VSAT hub station, located at the University of Alaska, will receive data from the remote stations and forward it to data processing centers and archives. Each installation assumes three people are required, equipment is delivered to the staging location by barge, and personnel fly by contract or commercial air carrier into the local airport. From there, helicopters are used to perform station installations, assuming eight GPS stations can be installed in a 25-day period taking into account no-fly days. Helicopter costs are based on rates charged in the summer of 2002 and include a daily cost of $1600/day and three hours of flight time per day at $325/hour. Helicopter costs are increased to $2400/day for the heavy lift requirements for strainmeter installations. Helicopter costs, fuel, barge and transport costs are based on GPS station installations on Akutan and Unimak islands in the summer of 2002 (J. Freymueller, personal communications, 2002). Maintenance of the stations will require one group-site visit per year and savings can be obtained by visiting strainmeter and GPS stations simultaneously. Maintenance costs are included in a companion O&M proposal. Table II-2.8 summarizes total Alaska installation costs by category of installation and year, including one-time costs such as the Alaska VSAT hub.

A similar budget development process is repeated for the remaining installation categories in Alaska and installations in northern and southern California, Basin and Range, Pacific Northwest, and Rocky Mountain regions. These and other budget details can be found at the UNAVCO Inc. web site.

Table II-2.8. Five-year Summarized Cost for All Alaska Stations.

| Cost Breakdown | | # Stations | MRE |
|---|---|---|---|
| Alaska Strainmeter | | 13 | $1,928,875 |
| Alaska Volcano Clusters SDBM | | 48 | $1,991,850 |
| Alaska Road Access DDBM | | 13 | $694,936 |
| Single Install Helicopter Access SDBM | | 13 | $596,230 |
| Single Scheduled Air Access SDBM | | 13 | $511,379 |
| Single Remote Boat Access SDBM | | 8 | $301,095 |
| Single Unknown Access DDBM | | 56 | $2,993,572 |
| Additional Costs | | | |
| 1 KU band VSAT Hub | | | $125,000 |
| Bandwidth (yr) | | | |
| Short DBM equipment (2) | | | $6,800 |
| **Total Year 1-5 PBO MRE Cost** | | | **$9,149,737** |
| | | **Prorated Add'l Costs** | **Total** |
| Strainmeter MRE Costs | $1,928,875 | $10,448 | $1,939,323 |
| GPS MRE Costs | $7,089,062 | $121,352 | $7,210,415 |
| **Total** | **$9,017,937** | **$131,800** | **$9,149,737** |

## Personnel

The Plate Boundary Observatory MREFC budget covers costs associated with station deployment, data flow, archiving, and product generation. These efforts, to be managed by UNAVCO, Inc., will require approximately 55 staff positions distributed across several organizations to meet the needs of the proposed PBO management plan (Figure II-2.24). Approximately 22 of these positions are operational personnel assigned to regional offices to handle local station reconnaissance, permitting, installation, and maintenance tasks (Figure II-2.25). Five UNAVCO Facility operations positions include a Senior Engineer, a technician managing deployment of the campaign instruments, and three technicians handling the equipment depot that supports receiving, testing, inventory and shipping functions for all equipment components and fabricated systems. Fourteen positions are allocated for data archiving and products generation. Administrative personnel include eight positions for contracts, purchasing, finance, accounting, property management, configuration management, safety, Web support and general administration. UNAVCO, Inc. Headquarters personnel include the PBO Director, Operations Manager, Data Integrator/Manager, Geo-PBO Coordinator, Reconnaissance and Permitting Coordinator, and Safety Officer.

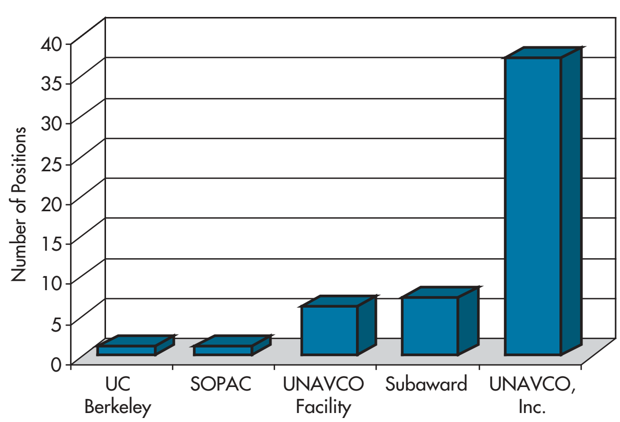



Figure II-2.24. Proposed staffing levels by organization.

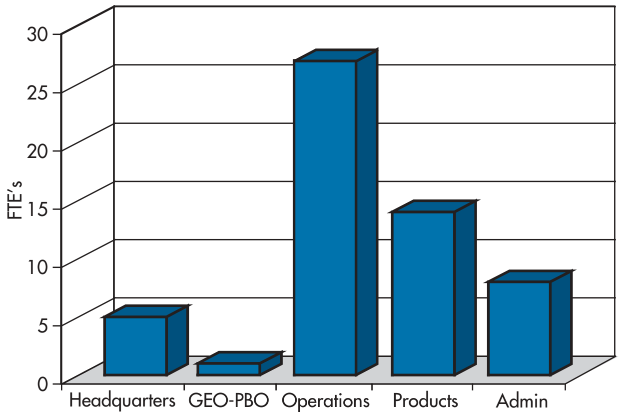



Figure II-2.25. PBO positions by task.

Early hiring of operational staff is critical so that reconnaissance and permitting activities can commence immediately after project approval. To conserve the budget, hiring of data management, archive and data products staff is deferred to Year 2. As the build out of the network nears completion in Year 5, appropriate operations staff will transition into a maintenance role. A list of PBO job titles and Years 1-5 salaries can be found at the UNAVCO, Inc. web site on the URL referenced previously. Salaries are increased by 3% per year for inflation and the benefits rate is 30.55% on 100% of salary.

To facilitate management of PBO installations, the PBO network is divided into six geographic regions (Table II-2.9). A UNAVCO, Inc. Engineer will manage each region and be responsible for all installations and data flow within the region. The regional Engineers will be trained in both GPS and strainmeter installations, however given the complexity of strainmeter installations, two dedicated Strainmeter Engineers will be responsible for installation and training operations in southern and northern California. As previously discussed, the cost and complexity of installing and maintaining the PBO Facility will be different in each region, e.g., Alaska stations are estimated to be ~10-30% more expensive with more difficult long-term maintenance and logistic concerns than similar installations in California. The Senior Engineer at the Facility will work as a roving resource to assist the regional Engineers with training, troubleshooting problem stations, and general support within their region.

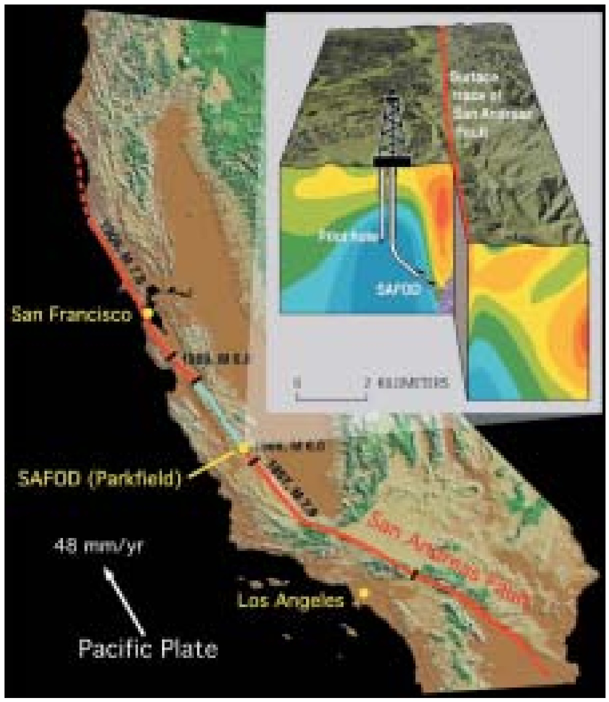
Table II-2.9. Engineering Resources Allocated for Each PBO Region.

| Region | Strainmeters | GPS | Engineers |
|---|---|---|---|
| Alaska | 13 | 151 | 3 |
| Pacifici Northwest | 8 | 149 | 3 |
| Northern California | 86 | 261 | 5 |
| Southern California | 64 | 170 | 5 |
| Rocky Mountain | 4 | 54 | 3 |
| Basin and Range | 0 | 90 | 3 |

## Administrative Costs

Administrative costs include non-project related travel support (meetings and training), office and warehouse space, computers, communications charges, furniture, vehicles and trailers, and relocation expenses. Each regional office will have ~2,000 $ft^2$ of warehouse/storage space with the Boulder Facility allocated ~10,000 $ft^2$ for equipment assembly, testing, shipping and storage. Each region is allocated one 4X4 field vehicle and one trailer for tools and installation equipment. Each PBO staff member will have an office space allocation of 120 $ft^2$ at $15/ $ft^2$ (~$1,800). Each employee is provided a phone, systems administration, and Internet budget of $7,500/year, a $1,000 furniture budget and is allocated a $2000 computer. Ten percent of staff to be hired are allocated a relocation budget. A detailed listing of administrative costs can be found on the UNAVCO, Inc. web site.

# 3. SAFOD: The San Andreas Fault Observatory at Depth


San Francisco
SAFOD (Parkfield)
48 mm/yr
Pacific Plate
Los Angeles
San Andreas Fault
SAFOD

# 3.1. Field Systems: Technical Description

## Scientific Motivation for SAFOD

While the last several decades have seen a greatly improved understanding of the kinematics of the San Andreas and other plate-bounding fault systems around the world, the physical and chemical processes that control earthquake nucleation and rupture propagation remain a mystery. Not surprisingly then, myriad untested and unconstrained hypotheses fill the geophysical literature based on inferences from laboratory and theoretical studies. Today, we know virtually nothing about the composition of the fault at depth, its constitutive properties, the state of *in-situ* stress or pore pressure within the fault zone, the origin of fault zone pore fluids, or the nature and significance of time-dependent fault zone processes.

The central scientific objective of the San Andreas Fault Observatory at Depth (SAFOD) is to study directly the physical and chemical processes that control deformation and earthquake generation within an active plate-bounding fault zone. A detailed scientific rationale and experimental plan for SAFOD can be found in a proposal that was submitted to NSF in August 1998 (available at the SAFOD web site: http://www.icdp-online.de/html/sites/sanandreas/news/). The 1998 proposal also includes synopses of an integrated suite of allied scientific investigations proposed by 33 researchers from 19 U.S. universities, about 15 scientists from the U.S. Geological Survey (USGS) and other national labs, and scientists from 12 institutions in 4 foreign countries. These proposals —and doubtless many more—will be resubmitted to NSF and other U.S. and international funding agencies under EarthScope.

SAFOD will enable a broad spectrum of the Earth science community to address multiple scientific objectives:

- Through long-term fault zone monitoring and *in-situ* observations of the earthquake source, we will be able to test and improve models for earthquake rupture dynamics, including such effects as transient changes in fluid pressure, fault-normal opening modes and variations in slip pulse duration. These observations can be used directly in attempts to generate improved predictions of near-field strong ground motion (amplitude, frequency content and temporal characteristics) and more reliable models for dynamic stress transfer and rupture propagation. These latter processes are believed to control earthquake size (i.e., whether or not a small earthquake will grow into a large one) and, hence, are crucial to long-term probabilistic assessments of earthquake hazard.

- By directly evaluating the roles of fluid pressure, intrinsic rock friction, chemical reactions and the physical state of active fault zones in controlling fault strength we will provide earthquake researchers the opportunity to simulate earthquakes in the laboratory and on the computer using representative fault zone properties and physical conditions. These studies will also allow for improved models of static stress transfer and earthquake triggering at a regional scale and between specific faults, as needed for intermediate-term seismic hazard forecasting following large earthquakes.

- The results of the proposed experiment are critical to development of more realistic models for the seismic cycle and assessment of the practicality of short-term earthquake prediction in two ways. First, in the fault zone monitoring phase of the proposed experiments, we will be able to determine if earthquakes are preceded by accelerating fault slip (e.g., a nucleation phase) and/or transient changes in fluid pressure. Second, we will be able to determine whether or not factors that might dramatically lower fault strength (high pore pressure and/or chemical fluid-rock interactions, for example) are closely related to the processes controlling earthquake nucleation. Our current knowledge of fault zone processes is so poor that not only are we unable to make reliable short-term earthquake predictions, but we cannot scientifically assess whether or not such predictions are even possible.

- As the weakness of plate boundaries (relative to plate interiors) is a fundamental aspect of plate tectonics, how and why plate boundary faults lose their strength is of first-order importance for understanding where plate boundaries form, how they evolve with time and how deformation is partitioned along them.

While the idea of drilling into the San Andreas Fault has arisen many times over the past several decades, this project had its origin in December of 1992 when a workshop was convened on scientific drilling into the San Andreas Fault zone at the Asilomar Conference Center in Pacific Grove, California. The purpose of this workshop, which was attended by 113 scientists and engineers from seven countries, was to initiate a broad-based scientific discussion of the issues that could be addressed by drilling and direct experimentation in the San Andreas fault, to identify potential drilling sites and to identify technological developments required to make this drilling possible. As discussed at Asilomar and numerous workshops since then, there are a number of critical scientific questions about the mechanics of faulting and earthquake generation that can only be addressed by drilling (see SAFOD web site). In the context of the present proposal—to conduct drilling, sampling, *in-situ* measurements, and long-term monitoring to depths of 4 km with SAFOD—these questions include:

- What are the mineralogy, deformation mechanisms, and constitutive properties of the fault gouge? Why does the fault creep? What are the strength and frictional properties of recovered fault rocks at realistic *in-situ* conditions of stress, fluid pressure, temperature, strain rate, and pore fluid chemistry? What determines the depth of the shallow seismic-to-aseismic transition? What is the nature and extent of chemical water-rock interaction and how does this effect fault zone rheology?

- What is the fluid pressure and permeability within and adjacent to the fault zone? Are there superhydrostatic fluid pressures within the fault zone and through what mechanisms are these pressures generated and/or maintained? How does fluid pressure vary during deformation and episodic fault slip (creep and earthquakes)? Do fluid pressure seals exist within or adjacent to the fault zone and at what scales?

- What are the composition and origin of fault-zone fluids and gasses? Are these fluids of meteoric, metamorphic or mantle origin (or combinations of the three)? Is fluid chemistry relatively homogeneous, indicating pervasive fluid flow and mixing, or heterogeneous, indicating channelized flow and/or fluid compartmentalization?

- How do stress orientations and magnitudes vary across the fault zone? Are the principal stress magnitudes higher within the fault zone than in the country rock, as predicted by some theoretical models? What is the strength of the shallow (creeping) fault and how does this compare with depth-averaged strengths inferred from heat flow and far-field stress directions?

- How do earthquakes nucleate? Does seismic slip begin suddenly or do earthquakes begin slowly with accelerating fault slip? Do the size and duration of this precursory slip episode, if it occurs, scale with the magnitude of the eventual earthquake? Are there other precursors to an impending earthquake, such as changes in pore pressure, fluid flow, crustal strain, or electromagnetic field?

- How do earthquake ruptures propagate? Do earthquake ruptures propagate as a uniformly expanding crack or as a "slip pulse"? What is the effective (dynamic) stress during seismic faulting? How important are processes such as shear heating, transient increases in fluid pressure, and fault-normal opening modes in lowering the dynamic frictional resistance to rupture propagation?

- How do earthquake source parameters scale with magnitude and depth? What is the minimum size earthquake that occurs on the fault? How is the long-term energy release rate at shallow depths partitioned between creep dissipation, seismic radiation, dynamic frictional resistance, and grain size reduction (i.e., by integrating fault zone monitoring with laboratory observations on core)?

- What are the physical properties of fault-zone materials and country rock (seismic velocities, electrical resistivity, density, porosity)? How do physical properties from core samples and downhole measurements compare with properties inferred from surface geophysical observations? What are the dilational, thermoelastic, and fluid-transport properties of fault and country rocks and how might they interact to promote either slip stabilization or transient over-pressurization during faulting?

- What processes control the localization of slip and strain? Are the fault surfaces defined by background microearthquakes and creep the same? Would the active slip surface(s) be recognizable (through core analysis and downhole measurements) in the absence of seismicity and/or creep?

An important scientific benefit of conducting this project at Parkfield comes from the fact that by working at Parkfield we will be drilling in an area of active creep and microseismicity. By drilling in an actively slipping portion of the fault, we will be able to study the nucleation and rupture processes of microearthquakes with near-field seismic recordings, investigate whether temporal variations in pore pressure occur during fault slip (creep and earthquakes) and study the processes responsible for shear localization.

## The Need for SAFOD

In spite of the enormous amount of field, laboratory, and theoretical work that has been directed toward the mechanical and hydrological behavior of faults over the past several decades, it is currently impossible to differentiate between—or even adequately constrain—the broad range of conceptual models currently extant in the geological and geophysical literature. For this reason, the Earth science community is left in the untenable position of having no generally accepted paradigm for the mechanical behavior of faults at depth. One of the primary causes for this dilemma is the difficulty of either directly observing or inferring (with some degree of confidence) physical properties and deformation mechanisms along faults at depth.

Most of what we now know about the structure, composition and deformation mechanisms of crustal faults has been learned from geological investigations of exhumed faults, particularly in normal and reverse faulting environments were erosion has exposed previously deeply buried foot- and hanging-wall rocks. These field observations have proven particularly useful for several reasons. First, field observations of exhumed faults allow broad coverage with respect to variations in faulting style (e.g., comparing strike slip, normal and reverse faults), fault movement history and local geology. Secondly, where sufficient surface outcrops exist, field observations can readily address issues related to geometrical complexity and spatial heterogeneity in physical properties and fluid composition.

However, as valuable as these investigations have been, they suffer from several severe limitations when one attempts to draw inferences about active processes operating during faulting at depth. Foremost among these limitations is the fact that constraints on the mechanical state and physical properties of active fault zones (e.g., fluid pressure, stress and permeability) from surface observations are, of necessity, indirect and subject to alternate interpretations. For example, as noted by numerous participants in the USGS Conference on the Mechanical Involvement of Fluids in Faulting (see *J. Geophys. Res.*, **100**, 12,831-12,840), stress heterogeneities induced by fault slip can lead to considerable uncertainties in inferring past fluid pressures from observations of vein geometry in outcrop. In all of these investigations, a complex history of uplift and denudation may have severely altered, or even destroyed, evidence for deformation mechanisms, fault zone mineralogy and fluid composition operative during fault slip. This problem is especially acute for solution-transport-deformation mechanisms (e.g., pressure solution and crack healing/sealing) and other low-activation-energy processes, as the deformation microstructures formed at great depth are easily overprinted by ongoing deformation as the fault rocks are brought to the surface. Finally, with the rare exception of localized melts generated by rapid seismic slip (i.e., the pseudotachylytes occasionally found in exhumed fault zones), there are currently no reliable microstructural indicators that can be used to differentiate between seismic slip and creep. Thus, the importance of fluids in earthquake generation and rupture is impossible to assess with any degree of certainty based solely on studies of exhumed fault rocks.

Drilling and downhole measurements in active fault zones would provide critical tests of interpretations and hypotheses arising from laboratory rock mechanics experiments and geological observations on exhumed faults. Drilling provides the only direct means of measuring pore pressure, stress, permeability, and other important parameters within and near an active fault zone at depth. It is also the only way to collect fluid and rock samples from the fault zone and wall rocks at seismogenic depths and to monitor time-dependent changes in fluid pressure, fluid chemistry, deformation, temperature, and electromagnetic properties at depth during the earthquake cycle. In the context of the key scientific questions presented above, *in situ* observations and sampling through drilling would perform two critical, and unique, functions. First, sampling of fault rocks and fluids and downhole measurements would provide essential constraints on mineralogy, grain size, fluid chemistry, temperature, stress, pore geometry, and other parameters that would allow laboratory investigations of fault zone rheology and frictional behavior to be conducted under realistic *in-situ* conditions. Second, by *in situ* sampling, downhole measurement and long-term monitoring in active fault zones we would be able to test and refine the broad range of current theoretical models for faulting and seismogenesis by providing realistic constraints on fault zone physical properties, loading conditions and mechanical behavior at depth. In particular, by comparing results of microstructural observations and rheological investigations on core with measurements of microseismicity, fluid pressure, and deformation during the fault zone monitoring phase of this experiment, we would be able to differentiate among fault zone processes (e.g., fluid pressure fluctuations) associated with fault creep versus earthquakes.

## Overview of SAFOD

The SAFOD drill site is located on a segment of the San Andreas Fault that moves through a combination of aseismic creep and repeating microearthquakes (Figure II-3.1). It lies at the northern end of the rupture zone of the 1966, Magnitude 6 Parkfield earthquake, the most recent in a series of events that have ruptured the fault five times since 1857. The Parkfield region is the most comprehensively instrumented section of a fault anywhere in the world, and has been the focus of intensive study for the past two decades as part of the USGS Parkfield Earthquake Experiment (see http://quake.usgs.gov/research/parkfield/index.html).

A key aspect of the implementation plan for SAFOD is to rely on conventional rotary drilling to penetrate through the entire fault zone (Figure II-3.2). The trajectory shown was designed to satisfy the following geological and geophysical constraints: (1) to move the surface position of the hole far enough to the west so that it will avoid a fault trending subparallel to—and southwest of—the San Andreas fault zone and be well outside of the low-resistivity anomaly coincident with the fault zone, (2) to get as close as possible to the microearthquake hypocenters, (3) to pass all the way through the "geophysically anomalous" fault zone as well as through the vertical projection of the surface trace, terminating drilling in Franciscan rocks on the northeast side of the fault, and (4) to make it possible to measure the relevant geophysical parameters (stress, fluid pressure, permeability, etc.) and obtain rock and fluid samples in a continuous profile across the entire San Andreas Fault Zone.

A

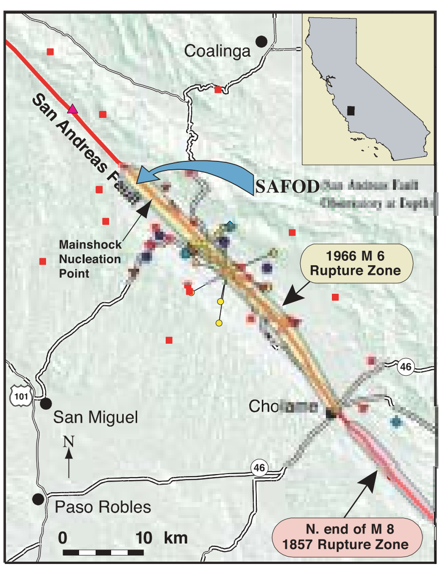
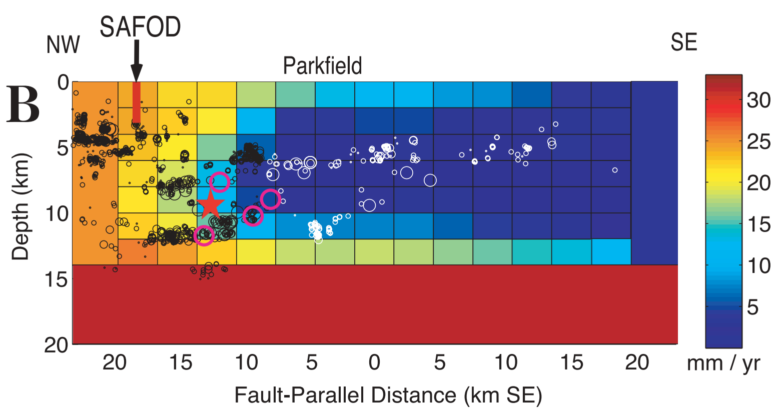



Figure II-3.1. A) Map showing the location of SAFOD together with seismometers, creepmeters, strainmeters, laser rangefinders, GPS receivers and other monitoring instruments associated with the USGS Parkfield Earthquake Experiment (colored symbols; only some of these instruments are shown). B): Cross section along the San Andreas Fault at Parkfield showing time-averaged slip rates inferred from surface geodetic measurements during the time period 1966-1991. Circles denote locations and magnitudes (up to M 5) of microearthquakes located using the double-difference technique for the time period 1984-1999. The hypocenter for the 1966 M 6 Parkfield earthquake is shown as a red star. Note that the SAFOD borehole (red line) is designed to penetrate into or very close to a repeating cluster of M 2 earthquakes at about 3.5 km depth.

B



Rotary drilling, geophysical logging, casing, and cementing of such deviated holes are routine in the petroleum industry, even in poorly consolidated and overpressured formations. Thus, by using a rotary drilling strategy to penetrate the entire fault zone, it should be possible to drill through the fault zone even if the rock is seriously disaggregated and pore pressures are quite high. After casing the rotary-drilled hole and monitoring this fault crossing for two years, four continuously cored "multi-laterals" will be drilled off of the main hole at carefully selected locations. Once this is complete the borehole will be used to deploy an array of seismometers, strainmeters, and other geophysical instruments to make direct, continuous near-field observations of faulting processes and earthquake generation at depth.

The overall experiment is explained in more detail in Section 3.3; the key operational elements of the project we propose are as follows (Figure II-3.2):

1. Rotary drilling a hole to 4 km depth through the entire San Andreas Fault zone in an area characterized by creep and microearthquakes. A site near Parkfield, CA was chosen for drilling because of the occurrence of shallow seismicity and particularly good knowledge of fault structure at depth (e.g., Figures II-3.1B and II-3.2). During drilling we will use advanced logging-while-drilling (LWD) techniques, collect spot cores and cuttings, and continuously sample fluids and gases in the drilling mud.

2. After conducting side-wall coring and open-hole geophysical logs (as permitted by hole conditions), the hole will then be completely cased and cemented. A suite of fluid sampling, permeability, and hydraulic fracturing stress measurements will be made through perforations in the casing. The perforations will be sealed after each test, except for a single interval that will be left open for fluid pressure monitoring

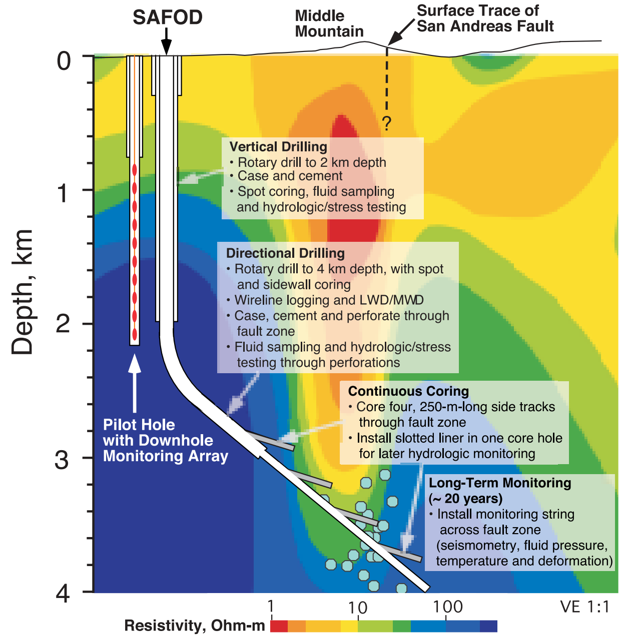



Figure II-3.2. Schematic representation of the SAFOD borehole and pilot hole. The background colors show the resistivity structure of the upper crust determined from surface magnetotelluric profiling, with blue dots representing and the approximate locations of microearthquakes located by the USGS and UC Berkeley seismology laboratories. The drill site will be located sufficiently far from the San Andreas Fault (as determined by surface fault creep, magnetotelluric imaging and microearthquake locations) to allow for rotary drilling and coring through the entire fault zone starting at a depth of about 3 km and continuing until relatively undisturbed country rock is reached on the far side of the fault. The main SAFOD hole will be drilled at the same surface location as the pilot hole, but offset from the pilot hole by about 20 m.

3. An array of seismometers will be deployed in the hole to make near-field observations of earthquakes and to help determine the exact position(s) of the active trace(s) of the fault. Fluid pressure will be continuously monitored at a carefully chosen depth and the hole will be logged repeatedly to identify zones undergoing casing deformation and, hence, the location of active shear zones.

4. While the monitoring "string" of seismometers is in place, a number of surface-based and surface-to-borehole geophysical measurements will be made to characterize the physical properties of the fault zone and the surrounding crust.

5. After identifying the active fault trace(s), using results from drilling and downhole measurements and fault-zone monitoring, 250-m-long continuous core holes will be drilled off of the main hole at four different locations where windows will be cut through the casing. In this manner, we plan to obtain a total of ~1000 m of core material from multiple sites directly within and adjacent to the active fault zone

6. Following coring, we will re-deploy an instrumentation array to permanently monitor earthquakes, deformation, fluid pressure, and ephemeral properties of the fault zone at depth.

Rock and fluid samples recovered from the fault zone and country rock will be extensively tested in the laboratory to determine their composition, origins, deformation mechanisms, frictional behavior, and physical properties (permeability, seismic properties, etc.).

The project we propose will provide the kinds of data needed to constrain the many theories currently being debated about fault zone processes. By obtaining direct information on the composition and mechanical properties of fault zone rocks, the nature of the stresses responsible for earthquakes, the role of fluids in controlling faulting and earthquake recurrence, and the physics of rupture propagation, this project could revolutionize our understanding of earthquake physics. Moreover, although it has been hypothesized that a wide range of deformation processes may precede seismic rupture, they have not been unequivocally detected by surface measurements. By making continuous observations directly within the San Andreas fault zone at seismogenic depths, we will be able to directly test and extend current theories about phenomena that might precede an impending earthquake.

## Scientific Components of SAFOD

The three main scientific components of the SAFOD project are: i) continuous monitoring of fault zone processes and microseismicity, ii) sampling of fault zone materials and fluids, iii) direct measurements of the physical properties and mechanical state of the fault zone at depth.

### Fault Zone Monitoring

Once constructed, the SAFOD facility will provide the opportunity to continuously monitor an active fault at seismogenic depths and will answer many questions about transient, and possibly precursory, fault zone processes related to earthquake rupture nucleation and propagation, and fault creep. These measurements are intended to continue for a period of at least 20 years after the observatory has been constructed. Prior to this, there will be two preliminary stages of fault zone monitoring (see Section 3.3 for details). The first of these stages already occurred in the summer of 2002, with instrumentation of the SAFOD pilot hole to a depth of 2.2 km using a continuous string of seismometers (see Figure II-3.2). The purpose of the pilot hole array is to accurately locate microearthquakes to be targeted by the main SAFOD borehole and to facilitate imaging of the crust adjacent to the San Andreas Fault during active-source seismic experiments conducted in October 2002 and planned for 2003. The second stage of monitoring will consist of emplacing a strainmeter and seismometer in the main SAFOD hole after reaching a vertical depth of 3 km, to record near-field strain and seismic activity during the approximately 8-month hiatus in rotary drilling prior to crossing through the active fault zone. The third, and final, stage of SAFOD monitoring will begin during the two-year period between the rotary drilling and continuous coring phases of the project. During this stage, a removable seismic monitoring string will be installed across the fault zone and removed periodically to log the hole for casing deformation. The purpose of this two-year monitoring effort is to locate, with extreme precision, the position of the fault patches generating repeating microearthquakes as well as location of actively creeping strands within the overall San Andreas fault zone. This information will be critical in deciding where to conduct the continuous coring operations off of the main SAFOD hole. This monitoring string, augmented by additional strainmeters and other instruments, will then be redeployed in the borehole at the conclusion of coring to commence the 20 years of continuous fault-zone monitoring.

## Rock and Fluid Sampling

Rock and fluid samples recovered from the fault zone and country rock will be extensively tested in the laboratory to determine their composition, origins, deformation mechanisms, frictional behavior, and physical properties (permeability, seismic properties, etc.). The sampling strategy has been designed to maximize the scientific return from this experiment, regardless of any operational difficulties that may be encountered, and to allow for continual improvement in our knowledge of the composition and structure of the fault zone during the experiment so that subsequent sampling operations can be carried out with a maximum of efficiency.

Rock samples will be obtained from the fault zone and adjacent crust in four ways:

1. During the initial rotary drilling phase, cuttings will be continuously collected, described, and logged. The drilling budget includes additional geologists to work in the mud logging unit 24 hours a day to assure that appreciable cuttings are collected, accurately described, and properly archived. These geologists will be trained and supervised by the principal investigators responsible for core analysis. The procedure for conducting this cuttings logging, preparation and archiving was already developed and tested during drilling of the SAFOD pilot hole and worked extremely well (see SAFOD web site).

2. Three 20-m-long spot cores will be collected during rotary drilling of the SAFOD hole after setting casing at vertical depths of 2, 3, and 4 km (see Figure II-3.2); these spot core holes will also be used for fluid sampling and measurements of permeability and stress, as described below. The first core will be obtained in the Salinian granite basement at a depth of 2 km, the second just outside the fault zone at a depth of 3 km, and the last core at the bottom of the hole after crossing through the entire fault zone (presumably in rocks from the Franciscan Complex).

3. Assuming that hole conditions permit, side-wall cores will be collected prior to casing the hole, principally from within the fault zone. We have budgeted for a side-wall coring technology—using a wireline tool to core multiple diamond core holes out the side of the hole—that will work in "hard" rocks. The use of more conventional (percussive) side-wall coring is contingent on "soft" formation conditions, as the side-wall sampling tool explosively shoots the core barrel into the formation. We have both technologies available and hole conditions will determine which technology, if either, can be used for side-wall core recovery.

4. As mentioned above (and described in more detail in Section 3.3), a separate continuous coring phase will be conducted two years after the end of the rotary drilling phase. We propose to drill four continuous core holes, each ~250 m in length, as "laterals" from the main borehole (Figure II-3.2). The locations of these coreholes will be carefully selected on the basis of the results obtained in the initial rotary drilling phase and the subsequent two-year period of fault zone monitoring.

Sampling of fluids for geochemical measurements will be obtained in four ways:

1. During both the initial drilling phase and the final continuous coring phase of operations, gases dissolved in the drilling mud will be analyzed on a continuous basis utilizing extraction and analysis techniques developed during drilling of the German KTB borehole by Joerg Erzinger (Univ. of Potsdam) and used in numerous scientific drilling projects since then. Importantly, this system was used successfully during drilling of the SAFOD pilot hole, where it identified several transient gas anomalies (mostly methane and radon) associated with secondary fractures and faults.

2. Large-volume fluid samples will be extracted from each of the three 20-m-long spot core holes discussed above, in association with industry-standard Drill Stem Tests (DSTs). These DSTs, which will be conducted immediately prior to hydraulic fracturing stress measurements planned for each core hole, will provide relatively large volumes of formation fluid for subsequent geochemical and isotopic analyses along with measurements of the in-situ formation permeability and fluid pressure. Several different tracers (such as fluorescene) are being considered for use in the drilling mud during SAFOD drilling to make it easier to differentiate between drilling and formation fluids.

3. After drilling and casing of the rotary-drilled hole to total depth (TD) of 4 km, a profile of 10 DSTs will be conducted across the San Andreas fault zone through perforations in the cemented casing (i.e., at vertical depths of 2.5 to 4 km). As with testing planned for the spot core holes, these tests will provide large-volume fluid samples together with measurements of formation permeability and fluid pressure, to be immediately followed by hydraulic fracturing stress tests. The procedure for conducting these tests is described in more detail below.

4. Finally, small-volume fluid samples will be extracted from core samples in the laboratory, in particular those obtained from the 250-m-long continuous core holes within and immediately adjacent to the fault zone. Again, "tagging" of the drilling mud used during coring will be used to differentiate between drilling and formation fluids.

Taken together, these multiple sampling strategies should provide ample rock and fluid samples for the principal investigators to use in their studies.

### Downhole Measurements

Downhole measurements of physical properties and mechanical state are critical to understanding overall fault-zone properties and behavior. Accordingly, a multiple measurement strategy is planned to assure their success (Figure II-3.3).

1. First, hole conditions permitting, a comprehensive suite of wireline geophysical logs will be run prior to casing each section of the borehole. The only exception to this being the upper 2-km section of SAFOD, as this depth range was already extensively logged during drilling of the pilot hole, which is located at the same surface location as SAFOD. These logs will be acquired commercially using state-of-the-art technology currently used in the petroleum industry. *In situ* temperature measurements will be made by USGS personnel at various times after the hole is cased, to determine variations in heat flow with depth and proximity to the San Andreas Fault.

2. Since it is possible that unstable hole conditions within the fault zone might seriously curtail the geophysical logging program, a state-of-the-art

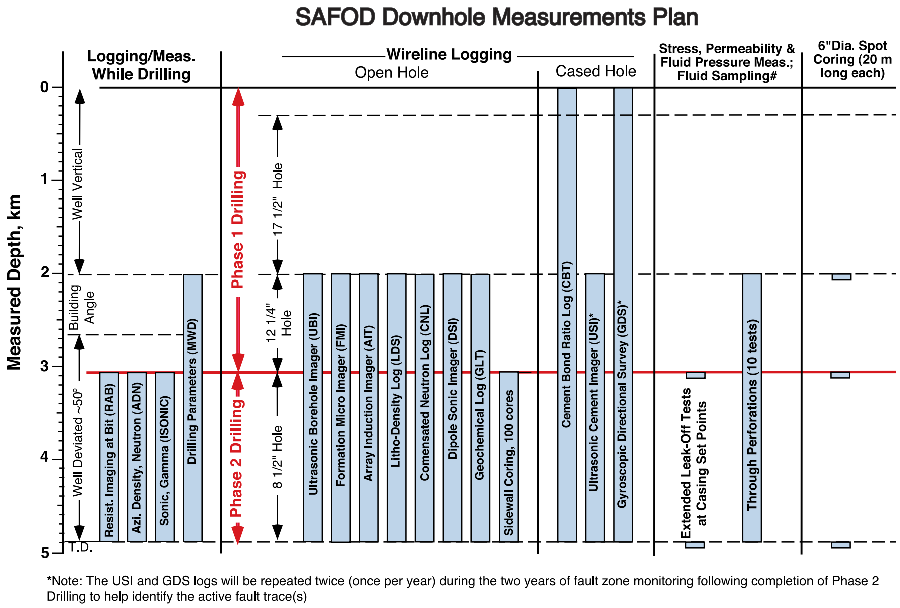



Figure II-3.3. Overview of the downhole measurement program proposed for the SAFOD hole as a function of measured depth. Note that while the total vertical depth to be reached with the hole is 4 km, the total measured depth of the hole will be almost 5 km. The vertical, angle building and deviated sections of the hole as shown in Figure II-3.2 are also indicated.

commercial Logging While Drilling (LWD) and Measurements While Drilling (MWD) system will be used during rotary drilling of the inclined portion of the SAFOD hole. This system, which is described in more detail in Section 3.3, will ensure that the most important in-situ physical property measurements are made in real time as we drill across the fault zone. Results from the LWD suite and the wireline geophysical logs will be compared to a detailed Vertical Seismic Profile (VSP) and other surface-to-borehole seismic imaging experiments already planned for the pilot hole and main SAFOD hole. This will allow the physical property measurements made in the borehole (and on the core) to be "scaled up" and extrapolated away from the borehole.

3. To assess pore pressure, permeability and stress, a comprehensive suite of packer tests will be made after the casing is cemented and perforated. The packer tests will be made by Zoback and Hickman, who have extensive experience with such tests. The techniques that we will use employ relatively standard well-test and hydraulic fracturing stress measurement methodologies that are well-established for determination of the least principal stress. These measurements of least principal stress will be integrated with quantitative analyses of borehole wall failure from wireline and LWD image logs to fully constrain the 3-D state of stress within and adjacent to the fault zone.

The series of pore pressure and least principal stress measurements that we propose to make at various positions with respect to the active trace of the San Andreas Fault will test directly several of the hypotheses proposed to explain the weakness of the fault (see SAFOD web site for a discussion of the "stress/heat flow paradox" and the broad range of deformation mechanisms proposed to control fault strength at depth). While performing these measurements at 3-4 km might not show whether such weakening processes are operating at much greater depth, these measurements will represent an important first step towards testing these and other hypotheses pertaining to the mechanical behavior of the San Andreas Fault.

## SAFOD Pilot Hole

To lay the scientific and technical groundwork for SAFOD, a 2.2-km-deep pilot hole was drilled in the summer of 2002 at the SAFOD site (see Figure II-

3.2). Drilling of the pilot hole was funded by the International Continental Drilling Program (ICDP), with considerable scientific and logistical support provided by NSF and USGS. The scientific rationale for the pilot hole as well as daily reports on the drilling and field operation can be found on the SAFOD web site. (This web site, which was created and maintained in close collaboration with the ICDP using their Drilling Information System, is a prototype for the real-time drilling and data tracking system to be employed during SAFOD drilling.)

As presented in several talks and posters from the 2002 annual meeting of the American Geophysical Union, significant progress has already been made in achieving the scientific and technical goals for the SAFOD pilot hole. These goals include:

1. Seismic monitoring instrumentation deployed in the pilot hole are facilitating precise earthquake hypocenter determinations that will guide subsequent SAFOD scientific investigations as well as drilling and coring activities in the fault zone. While precise relative hypocentral locations have been obtained from the permanent surface seismic stations, there remained several hundred meters of uncertainty in the absolute locations of these events. Funded by NSF, Peter Malin (Duke University) successfully installed a 38-level seismic string in the pilot hole in the summer of 2002. An example of recordings from this downhole array for a local, small-magnitude earthquake is presented in Figure II-3.4. Note the clear arrival of P, S, and other phases in these recordings as well as the high signal-to-noise ratio.

2. As discussed below, subsurface instrumentation deployed in the pilot hole recorded surface seismic sources (and provided near-surface velocity control) for seismic imaging experiments already conducted in October 2002 and planned during 2003.

3. Downhole measurements of physical properties, stress, fluid pressure, and heat flow in the pilot hole are characterizing the shallow crust adjacent to the fault zone. These measurements are

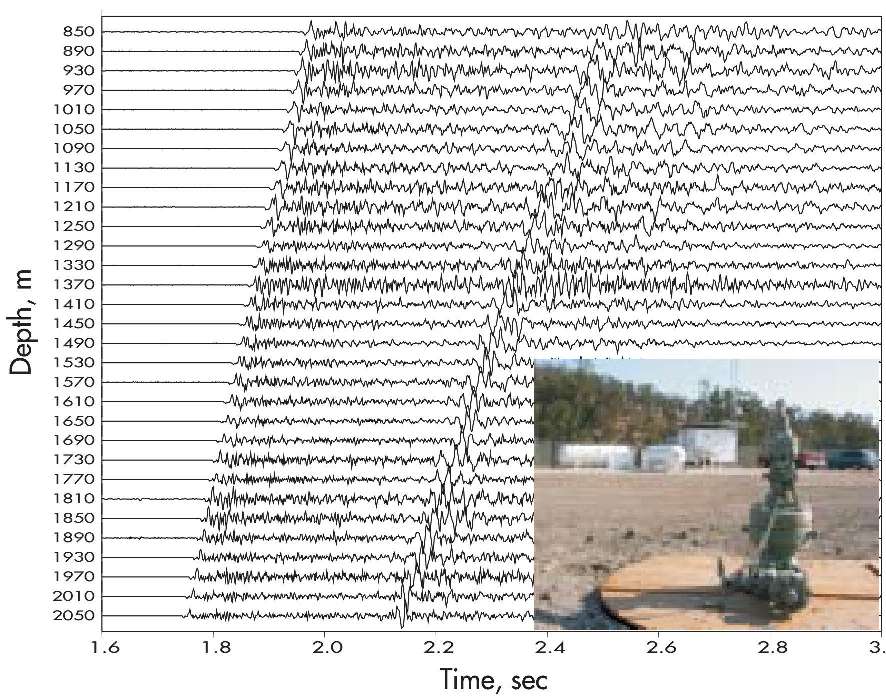



Figure II-3.4. Sample seismograms recorded on the pilot hole seismic array from a M 0 earthquake on October 2, 2002, located about 1 km southwest of the pilot hole and at a depth of 4 km. Only the output from the vertical component of these 3-component, high-frequency (15 Hz) geophones is shown. INSET: photograph of the multichannel pilot hole seismic recording and radio/satellite telemetry building, with pilot hole wellhead in the foreground.

being used to help calibrate physical properties inferred from surface-based geophysical surveys (e.g., seismic velocities, anisotropy, resistivity and density) and better constrain the strength of the San Andreas Fault Zone and adjacent crust prior to SAFOD drilling.

4. Long-term seismic, pore fluid pressure, strain, and temperature monitoring in the pilot hole will make it possible to assess time-dependant changes in the physical properties and mechanical state of the crust adjacent to the fault zone for comparison with similar measurements to be recorded in SAFOD. Also, as discussed in Section 3.3, the pilot hole will provide a critical facility for developing and testing long-term monitoring instrumentation to be used in the main SAFOD hole.

5. Although our plan to collect a 60-m-long spot core at the bottom of the pilot hole was not successful due to a logging tool that became stuck in the hole, drill cuttings were continuously collected and described during drilling of the pilot hole. Laboratory studies of these rock samples will determine the nature and extent of fluid-rock interaction along the San Andreas Fault and the sources and transport paths for fault-zone fluids.

6. Multi-level seismic monitoring in the pilot hole (and at the surface) during SAFOD drilling using the drill bit as a seismic source will allow us to attempt high-resolution, real-time imaging of the San Andreas fault zone using the drill bit as a seismic source.

7. From a strictly technological point of view, the pilot hole provided detailed information about subsurface geologic conditions and optimal drilling techniques/parameters that have proven invaluable in designing the drilling plan (presented below) for the main SAFOD hole.

## Recent Geophysical Studies at the SAFOD Site

Over the past several years, a wide variety of geophysical investigations have been carried out at and around the SAFOD pilot hole site. These studies include deep electromagnetic soundings, gravity and magnetic profiles, geologic mapping, and high-resolution seismic reflection and refraction profiles. In addition, as part of continuing education and outreach efforts, a number of shallow exploration techniques were employed at the drill site during Duke University's NSF-sponsored Parkfield field camp. Information about the Parkfield field camp is available at http://www.eos.duke.edu/Research/seismo/parkfield.htm.

Of course, monitoring of the Parkfield region by the USGS and U.C. Berkeley continues as part of the Parkfield Earthquake Experiment, with networks of borehole strainmeters, global positioning system (GPS) receivers, water wells, creepmeters, magnetometers, high-gain seismometers, and strong motion accelerometers. Work is presently underway to expand the continuous GPS network. Information about deformation monitoring at Parkfield is available at http://quake.usgs.gov/research/deformation/parkfield/index.html.

As mentioned above, a major, NSF-funded microearthquake experiment—the Parkfield Area Seismic Observatory (PASO)—was just completed around the SAFOD site using portable seismic instruments. These stations are augmented by permanent stations of the USGS Northern California Seismic Network and the Parkfield High Resolution Seismic Network, run by U.C. Berkeley (see http://quake.geo.berkeley.edu/hrsn.overview.html). In October 2002, PASO scientists set off a series of calibration shots at the sites of their stations that were recorded by the seismic receivers within the pilot hole in order to test and calibrate their 3-D seismic velocity model. Joint seismic imaging and earthquake relocations conducted using the pilot hole downhole array, together with analysis of data from PASO and the other local networks, are currently underway and are already providing more accurate earthquake locations and a more refined image of the sub-surface velocity structure at the SAFOD site. A description of the PASO instrumentation network and preliminary scientific results can be found at http://gretchen.geo.rpi.edu/roecker/paso_home.html. The instrumentation used in the PASO deployment is identical to that proposed to be made available through EarthScope's USArray component.

Through these investigations, a fairly good picture of subsurface conditions is emerging in the area chosen for drilling. Figure II-3.5 is a cross-section through the proposed SAFOD and pilot hole site along a high-resolution seismic refraction/reflection line conducted in 1998. This figure is a composite of two independent studies. The colored geologic "base" results from an interpretation of aeromagnetic profiling, ground magnetic and ground gravity data. West of the San Andreas, Tertiary and Quaternary sedimentary rocks (TQs) overlie fractured Salinian granite (Kgr). East of the San Andreas, Franciscan rocks (KJf; including serpentinite at ~2 km depth) underlie Tertiary sediments (Te). Note that the location of the drill site was chosen to be on the west side of the fault to avoid serpentinite at depth and to be "outboard" of the abrupt step in the depth of basement about 1.4 km west of the fault. As this abrupt step in the top of basement is likely fault controlled, it is desirable to start drilling "outside" this structure. The contour lines indicate P-wave velocities that were determined through tomographic inversion of first arrivals from this high-resolution seismic line. The velocity contours end at the depth where seismic ray coverage no longer constrains velocity. Note that the potential field model and the velocity model are in very good agreement, in that the low velocity zone centered about 500 m SW of the surface trace of the San

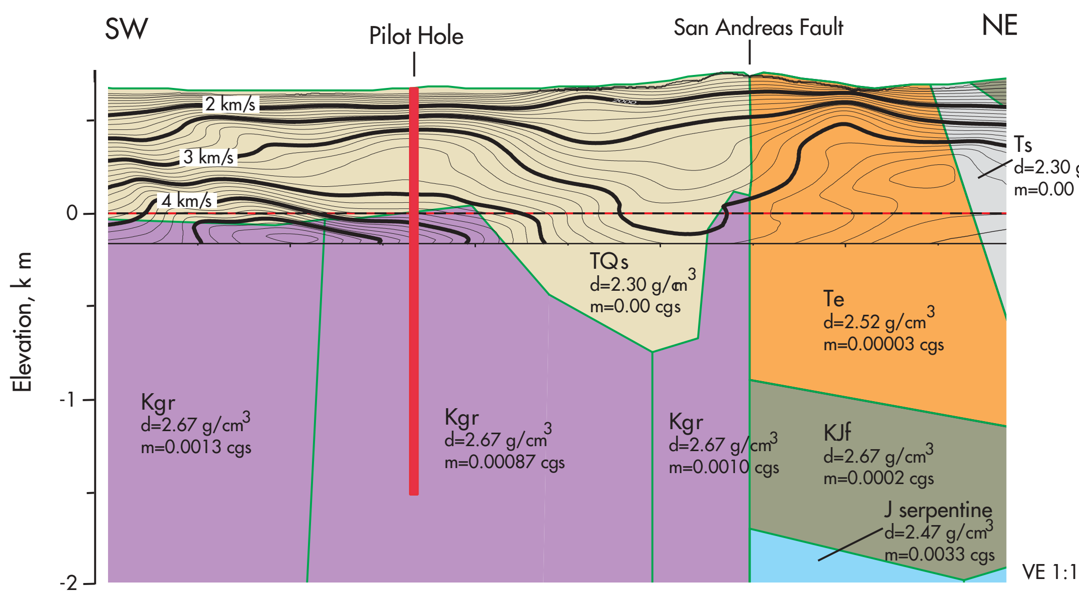



Figure II-3.5. Cross-section through the SAFOD site along the high-resolution seismic profile conducted in 1998, with the pilot hole shown as a red line. West of the San Andreas Fault, Tertiary and Quaternary sedimentary rocks (TQs) overlie fractured Salinian granite (Kgr). East of the San Andreas, Franciscan rocks (KJf, including serpentinite at ~2 km depth) underlie Tertiary sediments (Te). Note that the location of the drillsite is "outboard" of the abrupt step in the depth of basement located about 1.4 km SW of the surface trace of the San Andreas fault. The contour lines indicate P-wave velocities determined through tomographic inversion of first arrivals from this seismic profile.

Andreas fault occurs at the same location where the potential field data indicates locally greater depth to basement.

Analysis of the steep gradients in P-wave velocities (Figure II-3.5) and the loss of coherent reflections in the high-resolution seismic reflection image, presumably at the base of the sedimentary section, were used to predict a depth to granite basement of about 700-750 m at this site. This basement depth was used to design the drilling and casing program for the SAFOD pilot hole.

One of the most gratifying aspects of the SAFOD pilot hole project was confirmation of our preliminary geologic model for the SAFOD site by drilling. In particular, the predicted depth to basement (700-750 m) was very close to the basement depth of 768 m actually encountered during drilling. From this point until reaching total depth, the pilot hole remained in fractured granite, as predicted by members of our science team based upon the velocity and potential field models presented in Figure II-3.5. Finally, the electrical resistivity measured in the pilot hole by wireline logs increased with depth from about 50 Ohm-m at 0.8 km to about 800 Ohm-m at 2.2 km, which agrees quite well with the resistivities inferred using surface-based magnetotelluric measurements (Figure II-3.2).

The next phase of the geophysical exploration of the fault zone and surrounding crust is planned for the spring and summer of 2003, through projects already funded by NSF and international sources. This phase will be conducted by a joint U.S./German scientific team and will include a 50-km-long seismic reflection/wide-angle refraction profile across the San Andreas Fault Zone through the SAFOD site. This long-baseline survey will be supplemented by a high-resolution profile between the SAFOD site and the San Andreas, as well as along two shorter high-resolution lines perpendicular to this main line and crossing through the SAFOD site and along the San Andreas Fault. The long-baseline seismic line will constrain the deep structure of the San Andreas Fault system at Parkfield and help place SAFOD in a regional geophysical context, whereas the high-resolution add-on studies will be used to determine the velocity structure in the immediate vicinity of the pilot hole (by recording at the surface and on the pilot hole array) and the distribution and geometry of secondary faults between the drill site and the San Andreas. Additionally, observations of fault-zone guided waves using the high-resolution arrays deployed along and perpendicular to the San Andreas Fault will help determine the magnitude and width of velocity anomalies associated with the San Andreas Fault where it will be crossed by the SAFOD drill hole.

In many ways, the coalescence of these studies at Parkfield, together with the seismic and deformation monitoring carried out at Parkfield by the USGS, U.C. Berkeley, and other institutions over the past 15-20 years, represents an excellent example of the type of synergy that will result from utilization of the various EarthScope components over the coming years. This comprehensive suite of geophysical investigations in and around the drill site are achieving a number of critical milestones. These include better defining the absolute locations of repeating microearthquakes to be targeted with the main SAFOD hole, the structure and geophysical setting of the San Andreas fault zone at Parkfield, and the deformation field associated with aseismic and seismic slip on the San Andreas and other nearby faults.

# 3.2. Site Selection and Permitting

## Why Parkfield?

When considering potential sites along the San Andreas fault system for the SAFOD observatory and related experiments, we focused on sites with shallow seismicity, a clear geologic contrast across the fault, and good knowledge of the structure of the fault zone and surrounding crust. The requirement for shallow seismicity was key for two reasons. First, we would like to be able to conduct experiments within (and adjacent to) seismically active parts of the fault. Second, we intend to use ongoing seismicity to tell us the precise location of the active trace of the fault. In a sense we will use the background seismic activity as "guide stars" to direct the fault zone crossing.

To identify potential sites a systematic search was conducted of the strike-slip faults in California, identifying all faults that met the shallow seismicity criteria. To our surprise, these criteria eliminated all candidate faults in southern California. In central and northern California only three fault segments met the criteria for reasonably complete geological and geophysical control. These were the Hayward Fault near San Leandro, the San Andreas Fault in the Cienega Road to Melendy Ranch region and the Middle Mountain region along the Parkfield segment. We convened a workshop on the scientific goals, experimental design, and site selection for SAFOD at the USGS in Menlo Park that was attended by about 45 people. Although all three potential sites had unique advantages, it became clear that the Middle Mountain site at Parkfield was the best place to conduct the proposed experiment because:

- Surface creep and abundant shallow seismicity allow us to accurately target the subsurface position of the fault (Figure II-3.1B).
- There is a clear geologic contrast across the fault, with shallow granitic rocks on the west side of the fault and Franciscan melange on the east (Figure II-3.5). The granitic rocks provide for good drilling conditions.
- This segment of the fault has been the subject of an extensive suite of investigations establishing its geological and geophysical framework and is centered within the most intensively instrumented part of a major plate-bounding fault anywhere in the world.

An important new discovery about Parkfield that strongly supports its selection as the drilling target and adds a new scientific dimension to the experiment is the observation that the majority of the earthquakes there repeat in a characteristic manner. The upshot is that we will be targeting specific earthquake source zones with the drill hole, and have a very high expectation that the target earthquakes will repeat numerous times over the lifetime of the experiment.

At the surface near the SAFOD site, the San Andreas is creeping at a rate of about 2 cm/year (Figure II-3.1B), with most of the fault displacement localized to a zone no more than 10 m wide. Numerous earthquakes occur directly on the San Andreas Fault in the depth interval from about 3 to 12 km. The shallow seismicity at Parkfield occurs in tight clusters of activity that have remained spatially stationary for at least the past 20 years.

Although uncertainties exist in the exact location of the earthquakes, the integration of improved velocity models resulting from the PASO array and recordings from the pilot hole array are yielding greatly improved hypocentral locations. Figure II-3.6 shows the locations of some of the microearthquakes recorded on pilot hole array (as viewed from depth looking up at the surface and drillsite). While efforts to improve the locations of these events are still underway, the cluster of events shown by the green dot are the shallowest earthquakes in the area to be intersected by the SAFOD hole.

An important feature of the microearthquakes beneath Middle Mountain is that they occur in families of repeating events. Individual earthquakes have been observed to recur numerous times using the U.C. Berkeley High Resolution Seismic Network (HRSN), at precisely the same location and with the same magnitude. Repeating sources of up to M=2 are located at drillable depths beneath the proposed drill site. Thus, a major goal of this experiment will be to drill as close as possible to one or more of these sources and to follow the build-up of strain and its release through multiple earthquake cycles during the monitoring phase of the experiment.

Almost all events along this fault segment have right-lateral strike-slip focal mechanisms, corresponding to the geologic sense of movement on the fault. Non-San Andreas type earthquakes close to the San Andreas include strike-slip, normal, and reverse faulting mechanisms, the vast majority of which have P- or T-axis orientations in agreement with a north-south shortening and east-west extension within the fault zone. The few events that locate more than about 5 km from the San Andreas Fault, however, commonly have P axes oriented at a high angle to the fault, which is consistent with the regional framework of fault normal compression and a weak fault. Also, recent heat-flow determinations in 17 wells located within 10 km of the San Andreas Fault near Parkfield—including a 1.6-km-deep well located 12 km from the proposed drill site—confirm previous conclusions that there is no heat flow anomaly associated with the San Andreas fault in central California, indicating that the fault is sliding under low levels of resolved shear stress.

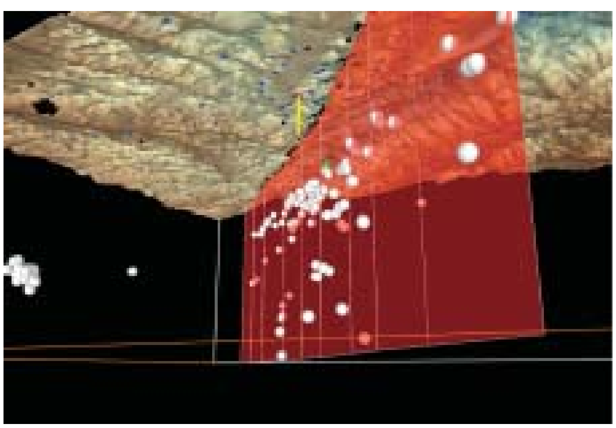


Figure II-3.6. View from depth of the SAFOD pilot hole, San Andreas Fault and microearthquakes recorded on the pilot hole array in the Fall of 2002 (between 2 and 4 events per day on the San Andreas are recorded on the vertical array). The green dot represents the shallowest events on the fault in the area where the SAFOD hole will penetrate it.

## The Expected M ~ 6 Earthquake

The site we have selected also lies in close proximity to the 1966 Parkfield earthquake hypocenter (Figure II-3.1). Thus, one final question about the seismicity at Parkfield deserves some discussion: What would happen should the anticipated Parkfield mainshock occur either before or after the drilling experiment is completed? Should the earthquake occur before the hole is either drilled or completed, we can anticipate an enhanced production rate of shallow earthquakes as part of the aftershock sequence, which would add to the return of the fault zone monitoring stage of the experiment.

Should the Parkfield mainshock occur after the hole is completed, it is likely that the coseismic displacement of the earthquake would extend to within a few km of the SAFOD fault crossing. This presents the possibility that we might observe the nucleation and initial rupture propagation of a M=6 earthquake at close range. While this is not an earthquake prediction experiment, the opportunity to make observations of seismicity, pore pressure, deformation, and temperature directly within a fault zone preceding and during a moderate earthquake is a truly unique opportunity. If the

M=6 Parkfield earthquake should occur during the lifetime of the experiment, we would make unique observations not only of preparatory fault zone processes but also of the dynamics of rupture propagation and the energetics of large-scale faulting.

As noted above, the dominant pattern is spatial stationarity of the seismicity (clusters), even through two Parkfield earthquake cycles. The spatial stationarity of seismicity through other mainshock events elsewhere in the San Andreas fault system is the norm, and has been well-documented in many cases. Furthermore, it is now known that repeating earthquake sources can be triggered into rapid repetition as aftershocks, when located near or within a mainshock rupture zone. Thus, should the M~6 Parkfield earthquake occur during the lifetime of the experiment, we might also have an unparalleled opportunity to observe time-dependent loading and frictional behavior in the near field.

## Permits and Permissions

One point that should not be overlooked is the difficulty of obtaining permission to drill holes of any kind in California. At Middle Mountain, however, the once off-limits southwestern approach to the fault has become accessible due to the inheritance of the land by a cooperative new landowner. Thus, logistical as well as scientific considerations also favored the Parkfield site. We have a signed agreement with the landowner at Parkfield that will allow us to carry out the proposed drilling and downhole measurements and then access the site for 20 years during the fault zone monitoring phase of the experiment. In addition, all of the necessary environmental approvals and permits have already been obtained for the SAFOD site.

# 3.3. Site Installation and Detailed Experimental Plan

In this section, we provide an overview of the operational details that must be addressed to make sure that the scientific objectives of SAFOD are met. These operational issues are grouped into the following categories:

- rotary drilling and continuous coring
- testing through perforations
- fault zone monitoring
- downhole measurements
- measurements on core, cuttings and fluids
- on-site technical personnel.

To insure the success of this project, we are requesting all of the funds necessary to carry out these operational aspects of the SAFOD experiment in the present proposal. Detailed work plans and budgets for the scientists seeking funding from NSF to participate in SAFOD will be submitted as separate "stand alone" proposals to NSF. The USGS and DOE scientists (as well as those from other countries) will provide detailed work plans and budgets to their respective funding agencies.

## Rotary Drilling and Continuous Coring

As a result of our experience in drilling the pilot hole, the drilling plan for the main hole has been slightly modified (with respect to the plan in the 1998 SAFOD proposal) and will be carried out in three distinct phases. These phases have been designed to: (i) optimize acquisition of key scientific data (*in situ* measurements, core and fluid recovery, etc.), (ii) facilitate deployment of different types of fault zone monitoring instrumentation at various levels (seismic, deformation, pore pressure, etc.), (iii) minimize drilling costs, and (iv) use drilling technologies that are most likely to work effectively in the highly fractured, altered and possibly overpressured rocks comprising the San Andreas fault zone. The drilling plan described below has been developed in consultation with Mr. Louis Capuano, President of ThermaSource, Inc. ThermaSource was the prime contractor of the SAFOD pilot hole and both Mark Zoback and Steve Hickman have worked successfully with Mr. Capuano on other scientific drilling projects. This information is excerpted from a highly detailed report entitled, "San Andreas Fault Zone Drilling Project: Drilling Program and Cost Estimates," that was prepared by Mr. Capuano in 1998 and has been modified taking into account our experiences in drilling the SAFOD pilot hole. Copies of this drilling plan are available on request.

### Phase 1: Drilling to 3 km

As shown in Figure II-3.7A, except for its much larger diameter, the upper part of the SAFOD main hole will be quite similar to that already drilled in the pilot hole. After setting 13 3/8" casing in a 17" vertical hole at 2.0 km, two 10-m-long cores will be cut from the bottom of the hole (using a 6", or larger, core bit). After the spot cores are obtained, an extended leak off test (a small hydrofrac) will be conducted in the core hole at the bottom of the 13 5/8" casing.

The primary objective of Phase 1 will be to directionally drill a 12 1/4" hole to a total vertical depth (TVD) of 3.0 km (corresponding to a measured depth, MD, along the hole of 3.3 km) and install 9 5/8" cemented casing. Fluid pressures are expected to be normal, but a 10,000 psi blow out preventer (BOP) will be used as a precaution.

As illustrated in Figure II-3.7A, the hole will be drilled vertically to 2.0 km, at which point the well will be kicked-off to the northeast, toward the San Andreas fault. The build angle will be 2.5° per 100'. The end of the build angle will be at a deviation of 50.5° at a MD of 2.6 km. This deviation will be held to the total depth of Phase 1, resulting in a horizontal offset of 750 m from the surface location of the hole. As was done for the pilot hole, extensive cuttings will be collected and drilling fluids and gases will be analyzed in real time during drilling. All of the methodologies to be used were successfully employed in the pilot hole. In addition, the ICDP Drilling Information System (DIS) was successfully used during pilot hole drilling to create a real-time database and synthesis of all of the scientific and operational information collected.

After completing the 12 1/4" hole, a wireline logging program will be conducted in the open hole section (from 3.3 to 2.0 km MD). The logs to be run are shown in Figure II-3.3. The 9 5/8" casing is then to be run to the surface and completely cemented. Two, 10-m-long spot cores will be obtained (again using a 6", or larger, core bit) after setting the 9 5/8" casing. After the spot cores are obtained, an extended leak off test (a small hydrofrac) will be conducted in the core hole at the bottom of the 9 5/8" casing.

The weather window for drilling at the SAFOD site is from May through October. Phase I is expected to take 131 days. We anticipate drilling to begin in May 2004.

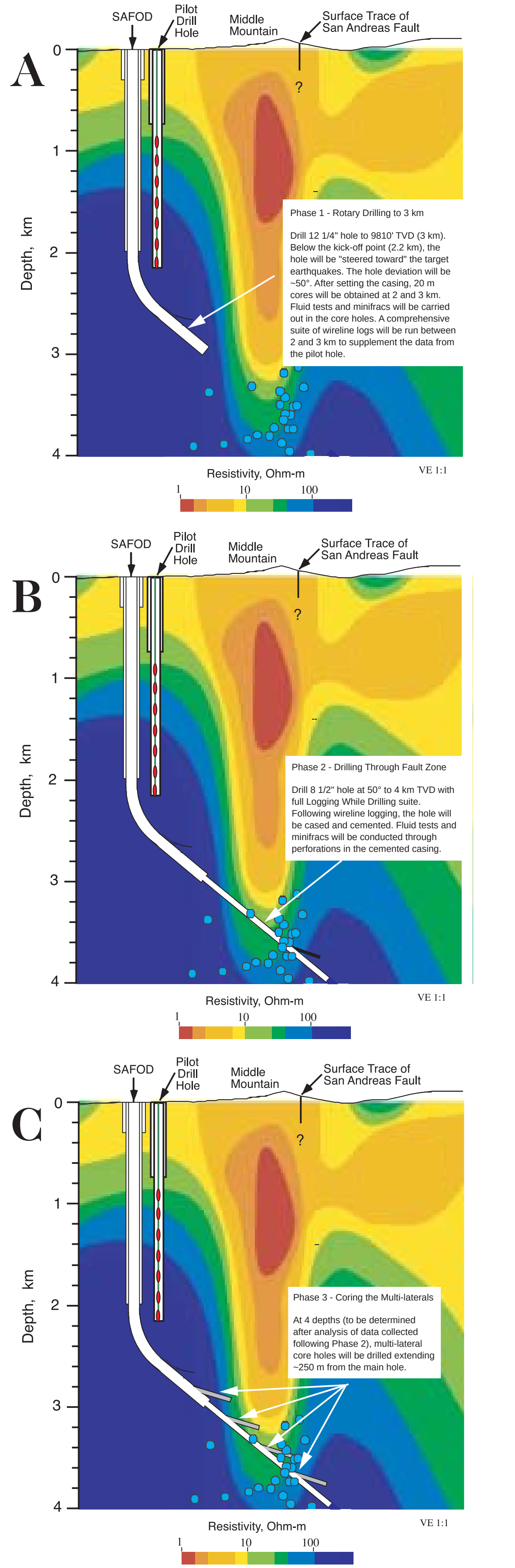



Figure II-3.7. Schematic drilling plan for SAFOD. A) During Phase 1, the SAFOD hole will be drilled as close to the pilot hole as possible, (not taking the risk of intersecting it). The hole will be terminated in the high resistivity, fractured granitic rock, outside the intensely deformed fault-zone rocks. B) Phase 2 of the drilling plan is to directionally drill a deviated well through the fault zone, eventually passing to the northeast side of the active trace of the fault, terminating in the Franciscan formation. C) Phase 3 of drilling involves using multi-lateral drilling technology to create four, directionally-drilled core holes with carefully selected depths and trajectories. The core holes (shown schematically in the figure) will each be approximately 250 m in length.

### Phase 2: Drilling Through the San Andreas Fault Zone to 4 km Depth

After a ~9 month hiatus, the objective of Phase 2 is to directionally drill a 8 1/2" hole to a TVD of 4.0 km (MD = 4.9 km) and install 7" cemented casing (Figure II-3.7B). The expected lithology is highly fractured granite and crushed rock (probably largely altered to clay gouge). Fluid pressures are unknown and could range from normal (hydrostatic) to severely overpressured. A 15,000 psi BOP stack will be used during Phase 2 as a precaution. A comprehensive suite of LWD measurements will be acquired (see Figure II-3.3) to assure that as much geophysical data as possible is collected as the well is drilled, in case hole stability problems preclude conventional logging data from being acquired. As in Phase 1, extensive cuttings will be collected and drilling fluids and gases will be analyzed in real time. A contingency drilling plan has been developed in case of severe drilling difficulties crossing the San Andreas fault zone. Using this plan, an extra "string" of 5" casing will be cemented into the hole.

The 50.5° deviation will be held approximately constant to the total depth, resulting in a total horizontal borehole offset of 2.0 km. However, the hole will, in fact, be "steered" so as to intersect the fault zone in the vicinity of seismogenic patches where repeating microearthquakes occur.

After drilling the 8 1/2" hole through the fault zone, a wireline logging program will be carried out in the open hole section. The logs to be run are shown in Figure II-3.3. After logging, the 7" liner is to be run into the 9 5/8" casing, "tied-back," and cemented. After the hole is cased and cemented, 10 intervals will be perforated between 2.0 and 4.9 km MD for hydraulic tests (fluid sampling, pore pressure, and permeability measurements) and minifrac tests to determine the magnitude of the least principal stress. The procedure used to conduct these tests through perforations are described below.

After the perforations are sealed-off, the cement will be drilled out and two 10-m-long spot cores will be obtained at the bottom of the hole. A prototype instrumentation system will be deployed in the hole during the ~ 2 year interval between Phases 2 and 3 (see below).

Phase 2 is expected to take a total of 108 days for drilling and testing. Drilling is expected to begin in May 2005.

### Phase 3 – Coring in the San Andreas Fault Zone

Approximately two years after the completion of Phase 2, a hybrid rig (a conventional rotary rig with top drive) will be used to carry out wireline coring operations through four multi-laterals at depths to be determined after analysis of data obtained during Phases 1 and 2 and the precise locations of microearthquakes (Figure II-3.7C). The prospects of sampling both seismogenic patches and stably sliding sections of the San Andreas Fault, as well as sub-parallel faults that are no longer active are especially exciting. The multi-lateral technology to be used (i.e., drilling holes from a main hole that is cased and cemented) has been developed and used routinely by the petroleum industry over the past 10 years.

Each core hole will be approximately 250 m in length. The current plan is for DOSECC (Drilling, Observation and Sampling of the Earth's Continental Crust, a nonprofit corporation providing technical assistance on scientific drilling projects in the United States) to carry out this phase of the project. To do so, DOSECC will use the drill rig they recently acquired and the top drive coring system they successfully used in scientific drilling projects in Long Valley, Hawaii, and elsewhere. This type of coring assures the best possible core retrieval, especially in broken-up rock.

After coring, each hole will be used for hydraulic testing and a minifrac. It is likely that three of the four coreholes will then be squeezed with cement to seal off the holes in order to prevent fluid flow between the core holes.

With a slotted steel liner in one corehole to allow for long-term fluid pressure monitoring, a retrievable geophysical instrument package will be lowered into the borehole via small diameter pipe or coil tubing for long-term monitoring.

Phase 3 is expected to take 96 days to complete, starting in May 2007.

## Testing Through Perforations

The procedures for fluid sampling and pore pressure, permeability, and least principal stress (i.e., hydrofrac) measurements through perforations were developed to take advantage of equipment and procedures used routinely in the petroleum industry. These measurements require the cemented casing to be perforated at 10 different depths, packers to be used to isolate the test zone from the rest of the hole, and all of the test intervals to be re-cemented prior to the fault zone monitoring phase of the experiment. To minimize the rig time and costs associated with this part of the project, a number of experimental procedures were investigated. The procedure decided upon is termed a "Squeeze Retainer Procedure" and permits the tests to be conducted in sequence (see Drilling Report). This procedure involves the following steps, working from the deepest test interval upward:

1. Perforate the test zone with a wireline casing gun.
2. Run in with a composite packer on the drill string and set it above the perforations.
3. Conduct a drill stem test (DST) to estimate formation permeability and pore pressure from pressure build-up; use a wireline sampler inside the drill pipe to obtain fluid samples (26 hours).
4. Conduct hydraulic fracturing test with multiple pumping cycles to determine the least principal stress (6 hours).
5. Pull drill pipe out of the packer; displace almost all of the fluid out of the pipe with cement.
6. Stab pipe back into packer and squeeze cement below packer into perforations.
7. Pull drill pipe out of packer and wait for cement to cure.
8. Perforate next test zone with wireline casing gun.

There is a prescribed sequence of operational steps to make this possible. It is estimated to take approximately 61 hours to conduct each measurement; the next test interval will then be perforated and the entire procedure repeated.

When all of these tests are complete, the composite packers and residual cement inside casing will be drilled out to leave the borehole with all the perforations plugged. Pressure testing will be done to assure that this is the case. Any leakage from perforations will be re-cemented ("squeezed"). This entire downhole measurement program will take about 3 weeks of rig time to complete and should yield a comprehensive suite of fluid samples and pore pressure, permeability and least principal stress measurements at varied depths and positions within and adjacent to the fault zone. At the end of this sequence of measurements, the spot core will be obtained from the bottom of the hole and a single interval will be perforated in order to monitor fluid pressure during the initial fault zone monitoring phase of the experiment. The drill rig will then be demobilized.

## Fault Zone Monitoring

The goal of fault zone monitoring is twofold: (1) to make *in situ* measurements of deformation, pore pressure, seismic wave radiation, and other relevant parameters in the nearfield of earthquakes, and (2) to select the optimal intervals for continuous coring through the fault zone during Phase 3 of drilling, as described above. We expect to observe multiple earthquake cycles for repeating earthquakes (M ~ 2) in the target zone at distances of less than a few hundred meters to about 1.5 km over SAFOD's 20-year lifetime. We may also observe the rupture of the fault in a large-magnitude (M~6) event over this same time period.

A team of scientists and engineers with extensive experience in the design, manufacture, and installation of borehole instruments has been assembled to assist in the construction and deployment of the borehole monitoring systems. The functional design of the removable monitoring array has been set by a combination of scientific and technical considerations, the latter as a consequence of extensive discussions with industry and the substantial experience of members of the design team with similar instrumentation. This monitoring array will consist of multiple, three-component seismic sensors of proven design for long-term deployment in deep boreholes. A number of the sensor packages will contain gimbaled three-component seismometers with natural frequencies around 4.5 Hz. Our recent experience recording earthquakes at 2 km depth in Long Valley at hypocentral distances as short as 1.4 km demonstrates that moving-coil geophones can detect kilohertz energy at close range. Other sensor packages will contain internal fluid-damped, three-component accelerometers with (undamped) frequencies around 30 Hz. Overdamped accelerometers of this design have been in operation in the 1-km-deep Varian well at Parkfield for over a decade, where they provide wideband acceleration response for recording in the nearfield. All data will be digitized at the surface using a dedicated data collection platform with high-sample-rate, high-resolution digitizers. Such a system is currently being employed at the SAFOD site to record data from the downhole pilot hole array, such as that shown in Figure II-3.4.

As illustrated in Figure II-3.8, a multi-stage strategy has been devised to establish a comprehensive borehole observatory at the SAFOD site. There is essentially no instrumentation "off-the-shelf" that is suitable for SAFOD because of the depths (pressures) and temperatures at which it will have to perform. Through this multi-stage strategy, our goal is to have both redundancy and the flexibility to deploy new instrumentation as it is developed.

### Stage 1: Monitoring in the Pilot Hole

When pilot hole drilling was completed in July 2002 a 38-level, three-component seismic recording system was deployed in the pilot hole that was manufactured by GERI (GeoSpace Engineering Resources International), a subsidiary of OYO corporation. The data being recorded by this array (shown schematically in Figure II-3.8a) is helping refine the location of earthquake hypocenters to be targeted during drilling and coring in Phases 2 and 3 of SAFOD as well as the seismic velocity structure of the upper crust. On average, between two and four microearthquakes per day are being recorded by the pilot hole array in the vicinity of SAFOD (Figure II-3.6).

Prior to the start of Phase 1 drilling of the SAFOD main hole, the existing GERI/OYO seismic array in the pilot hole will be removed and checked for corrosion and wear. Once the array is out of the hole, several hydraulic fracturing tests will be conducted to help constrain stress magnitudes outside the fault zone. Also, other test instruments will be deployed in the hole, such as a vertical, clamping seismic array that is being made available at no cost to this project by Paulsson Geophysical, Inc. Following this, a new, retrievable GERI/OYO string will be deployed with hydraulically clamped strain and tilt meters as well as a high dynamic range seismometer at bottom. As the hydraulically clamped tilt and strain sensors are experimental, it may be

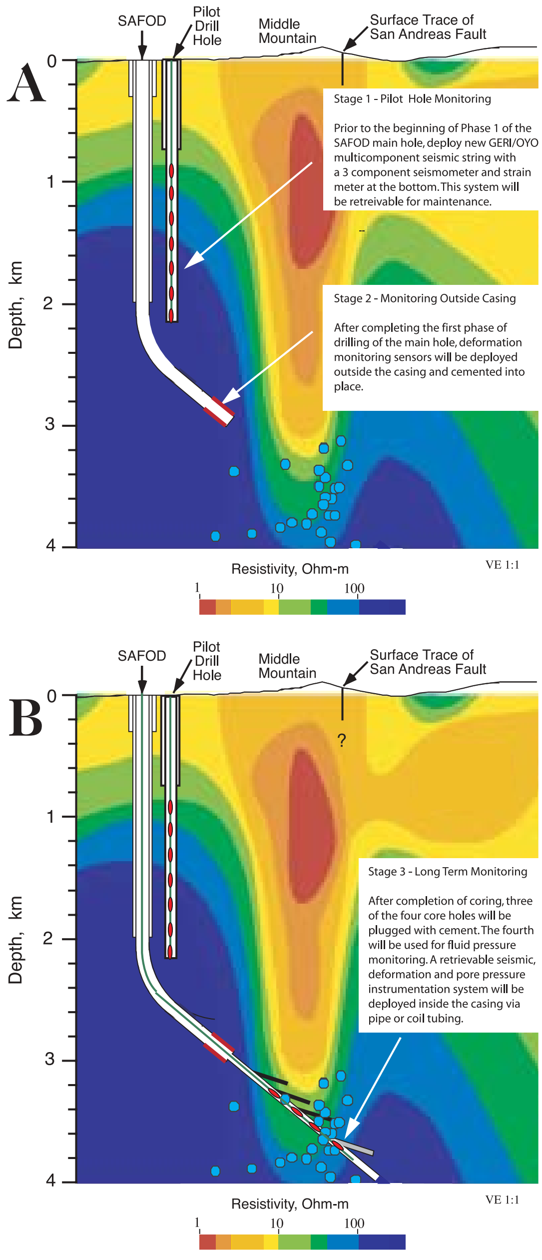



Figure II-3.8. Schematic monitoring plan for SAFOD. a) Stage 1 of SAFOD monitoring involves utilizing the pilot hole for a retrievable vertical array of seismometers with hydraulically clamped strain and tilt sensors and a high-dynamic-range seismometer at the bottom of the hole. Stage 2 will involve the permanent installation of strain monitoring instrumentation outside the casing at 3 km depth. b) During Stage 3 of SAFOD monitoring, a retrievable seismometer, hydraulically clamped strainmeter and tiltmeter, and pore pressure system will be used for long-term fault zone monitoring. A prototype array will be deployed inside the casing during the 2-year period between drilling Phases 2 and 3.

necessary to retrieve this string at a later date so as repair or change these sensors. The pressure and temperature at the bottom of the pilot hole are 20 MPa and 93°C.

The strain and tilt measurements at 2 km depth in the pilot hole will represent the deepest-ever deployment of instrumentation of this type. While the relatively hostile environmental conditions represent a formidable technical challenge, the low noise environment (and proximity to the fault) will reveal new insights into fault behavior. For example, it might be possible to detect episodes of aseismic slip at depth that have never been observable before. The high dynamic range seismometer (possibly MEMS) at the bottom is needed to record strong ground motions that would not be recordable with the vertical array. The Stage 1 monitoring instrumentation in the pilot hole will have other uses as well. For example, while the vertical array will continue to be invaluable for studying small earthquakes, it will also be in place to record surface seismic sources during seismic profiling experiments now planned to cross the fault near the drill site in 2003. This array will also allow "noise" from the drill bit during SAFOD drilling to be used as a seismic source to help better image the near-fault environment.

## Stage 2: Long Term Monitoring at 3 km Depth

At the conclusion of Phase 1 SAFOD drilling, a 9 5/8" casing will be cemented into place in the 12 1/4" hole at a vertical depth of 3 km and bottom hole temperature close to 120° C (Figure II-3.8a). This will afford us the opportunity to permanently deploy instrumentation outside casing and cement it into place in such a manner as to not interfere with subsequent drilling operations.

Possible instruments for this behind-casing installation include a modified (i.e., annular) Sacks/Evertson volumetric strain meter with the electronics at the surface (hydraulic lines will be strapped to the outside of the casing), fiber optic strain meters and temperature sensors deployed outside the casing and cemented in place, as well as solid-state seismometers and MEMS seismometers that are currently under development. Needless to say, it will be necessary to mechanically protect these lines so that they are not damaged as the casing is deployed. A prototype annular strain meter is being deployed in the Long Valley Exploration Well in the summer of 2003. This instrumentation was developed jointly by NSF and ICDP, in part because of its potential use in the SAFOD borehole.

Because there will be a hiatus of ~9 months between Phase 1 and Phase 2 drilling, it will also be possible to temporarily deploy a seismometer and other instruments via wireline inside the casing for testing and evaluation.

### Stage 3: Long Term Monitoring

We will deploy retrievable instrumentation inside the casing in the deviated section of the borehole that will be used for long-term monitoring of the fault zone (Figure II-3.8b). The instrumentation is to be deployed on a small pipe (or coil tubing) to assure retrievability and to provide a source of hydraulic pressure for coupling strain and tilt monitoring instrumentation to the borehole wall and/or casing. This type of locking mechanism has been used for some time in the petroleum industry, although the complexity of this system is admittedly at the edge of available technology. Our discussions with industry do not indicate that there are any insurmountable technical problems with this design. This array will be deployed initially for a two-year period following Phase 2 drilling: from late summer 2005 until the beginning of the Phase 3 coring program in late summer 2007. Following the completion of coring, we will re-instrument the borehole with this removable array for long-term (c.a. 20 years) monitoring of the San Andreas fault zone at depth.

The instrumentation to be deployed will include seismometers, pore pressure transducers, deformation sensors (strainmeters and/or tiltmeters), and temperature sensors. For the long-term installation following Phase 3 drilling, a downhole packer will be used to isolate one core hole for pore pressure monitoring (the remaining three core holes will be sealed with cement after coring). We may also cement instrumentation at the bottom of the hole, but the connection would be lost when the other instruments were pulled out of the hole for maintenance or repair. There are several deep-sea technologies (so-called wet-connects) that might be useful to carry this out. The estimated bottom hole temperature is 150ºC.

During the temporary installation after Phase 2 drilling, the removable monitoring array will be pulled out of the borehole after about one year to conduct a high-precision borehole directional survey and ultrasonic cement imaging (USI) log. These measurements will be used to identify any changes in casing shape or cement bond integrity behind the casing to determine if any of the faults crossed by the hole are actively creeping or if broad-scale deformation is occurring. Along with earthquakes located by the removable downhole array, the locations of these actively deforming zones will be used to select locations for the continuous core holes to be drilled in Phase 3. The USI tool uses a rotating acoustic transducer and receiver to measure the internal radius of the casing, the resonance properties of the casing itself and the acoustic impedance of the casing/cement interface. This log yields casing radius to an accuracy of ± 0.2 mm. The gyroscopic directional tool to be used has an absolute accuracy of about 0.1° in azimuth, with repeatability considerably better than this. Repeat measurements of casing ovality and trajectory over time using casing shape logs and gyroscopic directional surveys similar to those we are proposing have identified casing offsets as small as 1 cm over a 5-m-wide shear zone.

Inclusion of tiltmeters and strainmeters in the removable monitoring array will permit us to critically examine the nucleation process of earthquakes in the target cluster, to document the interplay between interseismic deformation in the fault zone and the rupture of discrete patches in earthquakes, and to unravel the spatial connection between repeating earthquakes at a common centroid. Our experience with borehole strainmeters and seismometers at Parkfield has been uniformly excellent, where instruments of the designs being considered for SAFOD are now well into their second decade of operation. Because a traditional strainmeter must be installed in an open (uncased) hole, we may elect to install it in the bottom open-hole section of the SAFOD hole. We may also elect to install one or more clamping tiltmeters or borehole extensometers in the cased hole, depending on how these devices perform during prototype testing in the pilot hole. Ultra-low noise borehole tiltmeters (1 nanoradian resolution) have been developed by a member of the design team at Lawrence Livermore National Laboratory, who was awarded a Department of Energy (DOE) R&D 100 Award in 1997 for this instrument. Additional sensors that are being considered include thermistor arrays for measuring transient heating from earthquakes, fiber optic Fabre-Perot strain interferometers, and electrodes for measuring differential resistance within the fault zone.

### Monitoring Implementation Plan

As discussed in more detail in the Budget Summary, to carry out the plan described above we intend to issue two separate subcontracts for monitoring system integration and deployment. These subcontracts could be issued to universities, research institutes and laboratories, or private companies. The system integration contractor must be able to take full advantage of developments in other countries (Japan and Germany, for example) as well as in other programs (such as the Ocean Drilling Program and the DOE Geothermal Program).

Duke University has been extensively involved in deployment of the existing pilot hole array and is a possible candidate as the system integration contractor for Stage 1. Similarly, Sandia Labs has been working extensively with high temperature sensors and monitoring systems and is a possible candidate as the system integration contractor for Stages 2 and 3. However, no decision has been made in either of these cases and the subcontracts will be awarded on the basis of engineering competence, prior experience and cost.

## Downhole Measurements

As shown in Figure II-3.3, the four principal types of downhole measurements to be conducted in the SAFOD hole are LWD, open-hole geophysical logging, cased-hole logging, and stress/permeability measurements.

### Logging While Drilling

Using instrumentation located just above the bit, we will conduct MWD and LWD during Phase II of drilling (Figure II-3.7B). MWD data will be acquired starting at the beginning of directional drilling to help the drillers "build angle" properly, whereas LWD data will acquired starting when the final deviation angle is attained and continuing to Total Depth (TD). The three types of LWD measurements we are proposing will provide real-time measurements of geophysical properties across the entire fault zone and will be contracted through Anadrill/Schlumberger or similar companies. The ISONIC tool will provide sonic velocity and natural gamma information, the ADN tool will provide density and neutron porosity information and the RAB tool will provide a 360° resistivity image of the borehole wall.

The logic for running LWD tools is twofold. First, if hole conditions are so bad that open-hole geophysical logging (described immediately below) is impossible or severely restricted, then the LWD program will insure that a continuous profile of critical geophysical measurements are made through the fault zone prior to running casing. The other reason for conducting logging while drilling is to identify zones with anomalous physical properties as they are being encountered. For example, if an overpressured zone is suddenly penetrated by the drill bit it should be indicated by anomalously high porosity, low sonic velocity and low resistivity. This is important to know while drilling is taking place, both for scientific and safety reasons (e.g., as an indication that the mud weight needs to be increased). Several members of our science team have appreciable experience with LWD measurements in the Ocean Drilling Program.

### Open-Hole Geophysical Logging

The *in situ* physical properties of the fault zone and country rock will be assessed by conducting a comprehensive geophysical logging program prior to casing each section of the borehole. This open-hole logging program will be conducted in 2 stages, starting at a depth of 2 km (see Figure II-3.3). An initial suite of logs will be run from 2 km to a measured depth of ~3 km, just as the broad fault zone is being entered. A second suite of logs will be run when the well has been drilled to completion at a measured depth of 5 km. These logs will be acquired commercially using state-of-the-art technology currently used in the petroleum industry.

As shown in Figure II-3.3, the measurements to be made include resistivity (AIT), density (LDS), porosity (CNL), P- and S-wave sonic velocity (DSI) and elemental composition (GLT). In addition, ultrasonic televiewer (UBI) and electrical image (FMI) logging will be used to obtain oriented, 360° images of the borehole wall for characterizing fractures, lithostratigraphic variations, stress-induced breakouts, and other features encountered in the borehole. Interpretation and analysis of these logs will be conducted by the SAFOD science team, funded through their respective agencies.

### Cased-Hole Logging

Three logs will be run after each section of the hole is cased and cemented. First will be an extremely precise well trajectory using a gyroscopic directional survey (GDS) log. Then, a cement bond log (CBT) and ultrasonic cement imager (USI) log will be run to assure that the cement has filled the annulus between the casing and borehole and that the cement and casing are well bonded. Effective cementing is required both for maintaining hole integrity over time and to facilitate measurements of stress, pore pressure and permeability, and fluid sampling through perforations.

These measurements will be repeated mid-way through the initial two-year deployment of the fault-crossing array (i.e., about one year after Phase 2 drilling is complete) and then again just before the coring program commences during Phase 3 drilling. As discussed above, in conjunction with analyses of seismic data collected by the downhole seismic array, these repeat logs will be used to help identify portions of the fault zone that are actively deforming and, hence, suitable for continuous coring.

Finally, detailed *in situ* temperature measurements will be made repeatedly by USGS personnel after drilling is completed and the entire hole is cased. These measurements, when coupled with thermal conductivity and radiogenic heat production measurements on core and cuttings, will provide important constraints on the thermal regime, hydrologic circulation and sliding resistance within and adjacent to the San Andreas Fault Zone.

### Stress, Pore Pressure and Permeability Measurements, and Fluid Sampling

A comprehensive suite of packer tests will be conducted to measure variations in pore pressure, permeability, and *in situ* stress magnitudes adjacent to and across the fault zone. We are planning to conduct three of these tests in the short holes produced during spot coring. However, because of likely hole stability problems, most of the fluid pressure, permeability and hydraulic fracturing stress measurements within the fault zone itself will have to be made after the casing is cemented and perforated, as discussed above. These tests will be conducted using commercially available, drill-pipe deployed casing packer systems by the PI's Mark Zoback and Stephen Hickman, who have extensive experience with such tests.

The experimental procedure will start with a series of tests in "pilot" holes drilled below each casing set point. After the borehole is cased and cemented to measured depths of 2, 3, and 5 km, a 20-m section of hole will be drilled below the casing that will be used first for conducting a drill stem test (DST). During this DST, a packer will be set in the casing and a valve opened to allow flow into the partially evacuated drill pipe. The subsequent pressure buildup will enable us to determine pore pressure and permeability using standard well test procedures and to obtain uncontaminated, large-volume fluid samples. After the DST, each of these pilot holes will be hydraulically fractured to determine the magnitude of the least principal stress. Finally, to make least principal stress and hydrologic measurements at 10 different positions within and adjacent to the fault zone, drill stem tests and hydraulic fracturing measurements will be made through perforations in the cemented casing using the procedures outlined above. Taken together, these tests will result in a complete profile of least principal stress, pore pressure, and permeability measurements across the fault zone. This procedure will also result in a profile of relatively uncontaminated fluid samples across the fault zone; the degree of pore fluid contamination by drilling mud—if any—will be determined by "spiking" the drilling mud with a stable tracer such as fluorescene.

In addition to measuring the least principal stress, we will also determine the full stress tensor along the entire well path using an integrated analysis of hydraulic fracturing tests and borehole image logs. To accomplish this, we will use a series of techniques that Zoback and his colleagues have developed which combine knowledge of the least principal stress, pore pressure, and vertical stress, with observations of compressive and tensile wellbore failure (e.g., borehole breakouts) in borehole image logs. Such observations often make it possible to constrain both the orientations and the magnitudes of the three principal stresses and are especially effective in deviated wells. A detailed methodology and comprehensive suite of software routines known as SFIB (Stress and Failure of Inclined Boreholes) was developed to accomplish this. SFIB is currently being widely used in the petroleum industry for this purpose. One technical note is that it is not necessary to assume that the principal stresses are in a horizontal and vertical plane. Still another method that will be used to assess the complete stress tensor is the measurement of small-scale rotations in breakout azimuth (imaged with the UBI) and resulting from localized stress anomalies caused by slip on small faults penetrated by the hole.

A final set of permeability measurements will be attempted after the four continuous core holes are drilled, using a packer in the main borehole that facilitates the coring process. This packer will seal off the main borehole, making it possible to do a bulk permeability test of each of the cored intervals.

## Measurements on Core, Cuttings, and Fluids

Comprehensive sampling of fault zone rocks and fluids will be conducted as part of the SAFOD experiment by scientists at various U.S. universities, the USGS, foreign institutions and possibly DOE labs. Key features of the sampling and analysis protocol we have established for the SAFOD project are presented in this section.

### Real-Time Gas Analysis

To compliment laboratory analyses of large-volume fluid samples recovered during the packer tests (described above), real-time analysis of gases dissolved in the drilling mud will be carried out. The system that will be used has the capability to do both automated measurements and automated sampling for subsequent analysis. The gases from a mud degasser will be run into an automatic gas mass spectrometer and gas chromatograph and quantitatively analyzed for $N_2$, $O_2$, Ar, He, $CO_2$, $H_2S$, $SO_2$ $CH_4$, $C_2H_6$, $C_3H_8$ and $C_4H_{10}$. A radon spectrometer will also be used to detect $^{222}Rn$ and $^{220}Rn$. Known quantities of pure and mixed gases are added to the mud system before being circulated into the hole for calibration purposes. This real-time study will provide critical samples and analyses of ephemeral gas/fluid pockets penetrated during drilling that might otherwise escape unnoticed, and will provide essential guidance for decisions related to later fluid sampling and *in situ* hydrologic testing.

## Core and Cuttings Handling, On-Site Analysis and Sampling Protocol

As outlined previously, both drill cuttings and core will be acquired from SAFOD. Geologists working for a commercial mud logging company will continuously monitor and record changes in cuttings mineralogy, mud chemistry, and drilling parameters (penetration rate, torque, pump pressure, etc.) during both rotary and core drilling and will bag and label cuttings for later analyses by interested investigators.

Three different types of core samples will be acquired during drilling. Three spot cores will be collected during the main (rotary) drilling phase of the experiment: one in the granite country rock, one just outside the fault zone and one at the bottom of the hole. These cores will be approximately 20-m-long and range in diameter from 12 to 17 cm. These spot cores will be supplemented by approximately 100 sidewall cores acquired below a depth of 2 km using a wireline-deployed coring tool (see Figure II-3.3). These sidewall cores will be 1.9 cm in diameter and 5.1 cm long. Finally, during Phase 3 of drilling, four 250-m-long continuous core holes will be drilled off of the main hole (see Figure II-3.7C), providing the bulk of the core to be used in laboratory analyses and mechanical testing. The diameter of these cores depends on the diameter of the casing off of which these sidetracks are drilled, and will be 6.4, 6.7 or 10.2 cm (the smallest core size would be necessitated by use of the 5” contingency casing string during completion of the main rotary hole through the fault zone).

Core handling and processing will utilize a newly refurbished mobile core lab and associated equipment to be supplied by the USGS Core Research Center in Denver. Routine processing of spot, sidewall and continuous core will be performed by graduate students and principal investigators associated with the SAFOD Core and Cuttings Team. As outlined in Figure II-3.9, this processing will include cleaning, reorienting and labeling the core; generating preliminary petrographic descriptions; photographing and scanning the core; and boxing the core for long-term storage at the USGS Core Research Center in Denver. Core will be scanned using a digital color core scanner developed for the German KTB project and available through the ICDP. These scanned images, along with drilling information and other data acquired during core processing, will be entered into a computer data base developed especially for this purpose by the ICDP. In addition to this routine core processing, we anticipate that several members of the science team will be on site during drilling to prepare detailed petrographic and mineralogical descriptions of the core; prepare core and cuttings samples for later laboratory analyses; and conduct XRD studies on selected drill cuttings and rock flour. As was the case during drilling of the SAFOD pilot hole, lodging (i.e., trailers) will be provided at the drill site free-of-charge for visiting scientists.

To meet the sample needs of the current science team, yet retain a sufficient quantity of core for later analyses by these and other investigators, it is clearly essential that we develop a careful yet responsive sampling protocol. Once the SAFOD project is underway, we will establish a sampling committee to review and evaluate requests for

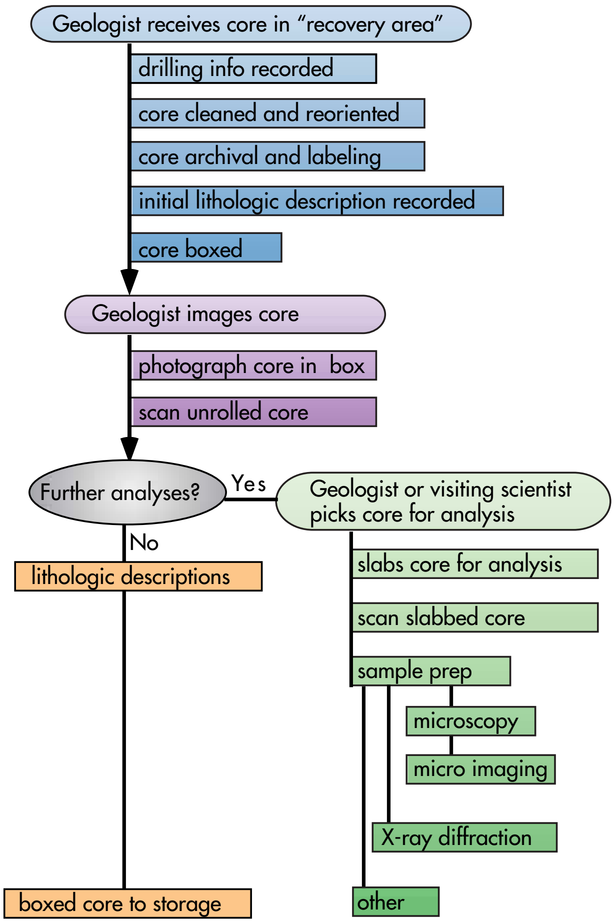



Figure II-3.9. Flow chart illustrating the handling, processing and archiving protocol to be used on core and cuttings samples from SAFOD.

core, cuttings and fluid samples. The sampling procedures and protocol we employ will be based upon our experience with other large, international drilling projects (e.g., the KTB and Long Valley projects) and will be developed in close consultation with the ICDP.

## On-Site Technical Personnel

The detailed drilling plan and budget includes a number of cost items associated with personnel. While budgets are presented and discussed below, there are several points to note here because of their overall affect on operations. First, the budgets include all supervisory personnel associated with drilling. Thus, in addition to the personnel provided by the drilling contractor(s), there will be personnel on site 24 hours/day representing the project science team who will be providing supervision of drilling operations, keeping track of progress and expenditures, and working with the scientific project management team to assure that the goals of the project are met on time and on budget. Special equipment, such as the gas collection/gas chromatograph/mass spectrometer system, requires dedicated on-site personnel that will be provided by the responsible PI.

Finally, we have budgeted for two graduate students to function as data managers, who will be on site during the entire rotary drilling and continuous coring phases of the project. These individuals will be able to assist the science team with the innumerable on-site technical activities, including:

- Keeping track (for the science team) of the cuttings, fluids and gases being sampled continuously.
- Preparation of samples and conducting x-ray diffractometry on selected cuttings and core samples.
- Helping with handling of the three spot cores and approximately 100 sidewall cores to be obtained during rotary drilling.
- Maintaining the DIS (Drilling Information System)—a complete digital database of all downhole data, sample descriptions, and drilling parameters from this hole. The DIS database system is to be provided by ICDP.
- Assisting with the appreciable continuous core handling activities during Phase 3 of drilling and entering of this data into the ICDP database. This includes scanning core, describing core, and preparation of digital input for DIS.

Operations at Long Valley and the Hawaii deep drilling project indicate that a three-person staff is needed on a 24-hour basis to keep up with continuing coring operations. As a member from the PI team will be on site continuously, the two positions budgeted here will assure that adequate personnel will be on site to handle incoming core. The budget includes costs for trailers to provide on-site office space and housing for both supervisory and scientific personnel.

## Activities in Conjunction with ICDP

A proposal will be submitted to the International Continental Drilling Program to provide assistance in the following areas:

- Maintaining a Comprehensive, Real-Time Database and Archive: A great deal of engineering and scientific data will be obtained from a wide variety of sources over the life of SAFOD. The Drilling Information System (DIS) developed by the ICDP for organizing real-time drilling and scientific data, and making these data available over the Internet, will be of great help to this project. We plan to use the DIS software system for maintaining a comprehensive data base, providing tools for manipulating and plotting data and for disseminating SAFOD data and results to interested scientists and the public.

- Core Handling: The experience obtained with core handling during the KTB project and ICDP projects preceding this one (Hawaii, Long Valley, etc.) will be very beneficial to SAFOD. We hope to take advantage of available ICDP equipment and personnel in SAFOD core handling operations. This includes having the ICDP provide and train us in the use of their 360° digital core scanner.

- National and International Scientific Participation: If the proposed project becomes a reality, it will be a source of scientific opportunity for scientists from around the world. Our hope is that the ICDP will provide a key link to the global scientific community in two regards: (1) to let them know about the scientific opportunities presented by this project through the ICDP web site and ICDP-sponsored workshops, and (2) to help provide funding for SAFOD-related science through proposals submitted to the ICDP by scientists in ICDP-member countries.

# 3.4. Management

## Project Management

The principal management team for SAFOD consists of the project PIs: Mark Zoback, Steve Hickman, and Bill Ellsworth. Working together, these PIs have hosted numerous planning meetings and workshops, represented this project at many national and international scientific meetings, and worked closely together over the past 10 years to develop this project. As shown in Figure II-3.10, the PI team will share responsibility for management of the various facets of SAFOD. In addition to facility management, Zoback, Hickman, and Ellsworth, as representatives of the different science teams, will continue to coordinate the various groups of scientists as follows:

- Operational supervision of on-site activities: Mark Zoback and Steve Hickman
- Downhole measurements: Mark Zoback
- Measurements on core, cuttings, and fluids: Steve Hickman
- Geological and geophysical site characterization: Steve Hickman
- Fault zone monitoring: Bill Ellsworth and Mark Zoback

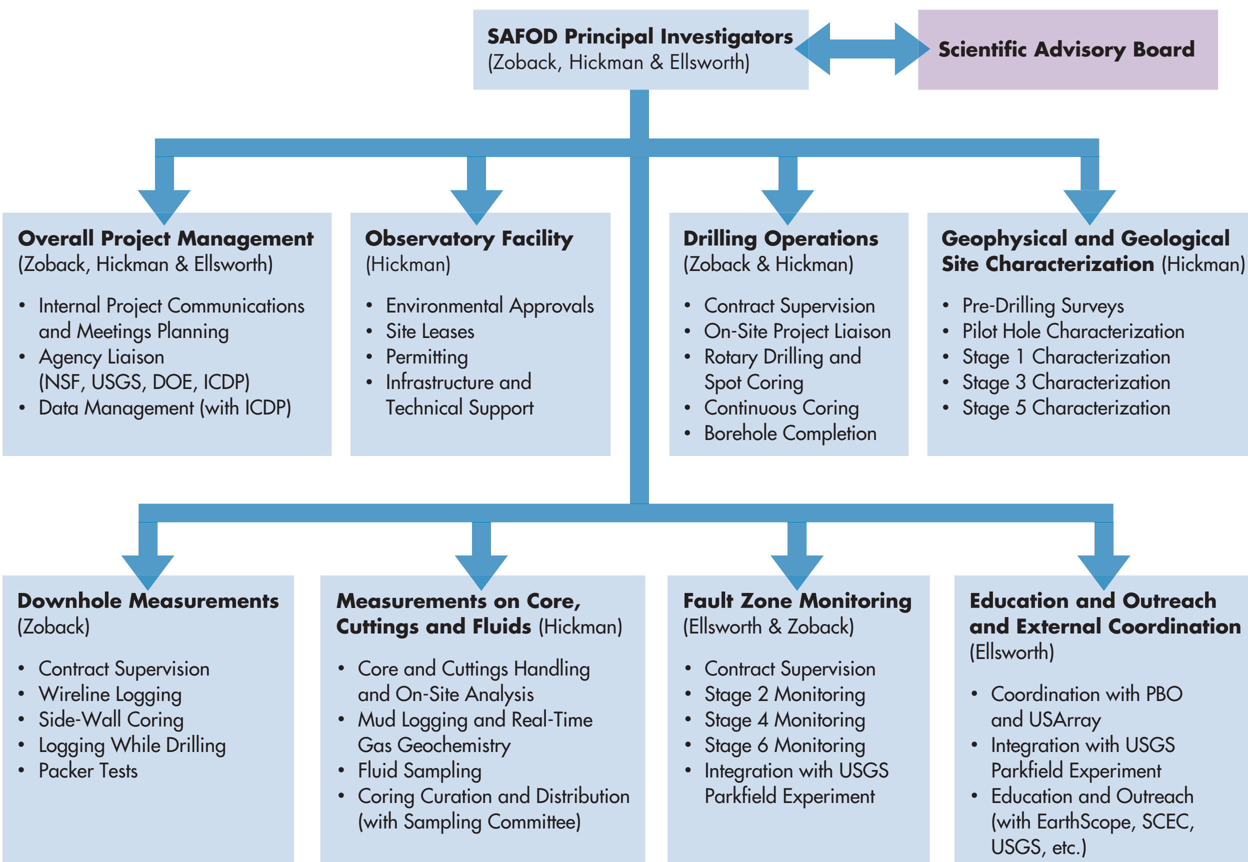



Figure II-3.10. Management structure proposed for the SAFOD project.

Additional steps that will be taken to assure optimal project management are as follows:

- Establish a Scientific Advisory Board: The purpose of this board is to provide independent advice to SAFOD on an as-needed basis. Participants will come from both within and outside the project science team.

- Planning Workshops: We will be convening project-wide, three-day-long planning workshops in the San Francisco Bay area during the first, third, and fifth years of this project. Members of our science team will be asked to budget travel and per diem to attend these workshops.

- Special Sessions: Special sessions will be held at regularly scheduled national and international scientific meetings (AGU, GSA, SSA, IUGG, etc.) as appropriate.

- Annual Sub-Group Meetings: We will also be holding annual meetings of smaller groups of principal investigators to discuss operational and scientific details associated with downhole measurements, core and fluids studies, site characterization, and fault zone monitoring. These meetings will be timed to coincide with the Fall AGU meeting in San Francisco.

- Sampling Committee: As discussed above, this committee will be established to develop protocols for handling and distribution of core, cuttings, and fluid samples.

## Data Management

Responsibility for long-term maintenance of SAFOD monitoring instrumentation, data telemetry, and data archiving and distribution will be shared by NSF-funded institutions and the USGS. NSF will be primarily responsible for funding the initial development, testing, installation, and (when needed) recovery and redeployment of the downhole monitoring instrumentation, through this proposal and related proposals from university investigators. The USGS will be responsible for maintaining the surface installation facility and telemetry links back to the centralized data repository; this includes routine maintenance and repair visits to the SAFOD site by field personnel associated with the USGS offices in Menlo Park and Parkfield (see attached letter of support from the USGS).

All data from downhole monitoring instruments operating in SAFOD will be made available in real-time to the international scientific community via the Internet. Data acquired from individual PI-driven studies, such as geophysical studies in and around SAFOD and laboratory studies on rock and fluid samples, will be released to the public and scientific community in accord with NSF policy.

# 3.5. Budget Summary

Table II-3.1 provides an overview of the principal expenditures associated with the SAFOD project over the duration of EarthScope. A brief explanation of each budget category is provided below. It should be noted that no separate proposal for expenses associated with Operations and Maintenance of the SAFOD facility is being submitted for Years 1-5. As described above, the facility is being developed in distinct drilling stages which are closely integrated with phases of instrument deployment over the five-year period of this request; thus, O&M costs for years 1-5 are built into this single proposal.

## Drilling Subcontract

Under supervision of the PIs, a subcontract will be granted to ThermaSource, Inc. to serve as prime contractor for all drilling and drilling-related activities. As mentioned above, ThermaSource is the drilling engineering company that designed the SAFOD borehole as part of a previous proposal submitted to NSF in 1998. Their engineering design and budget were reviewed by a special panel convened by NSF in 1998, during which the Thermasource drilling plan and budget (along with the rest of our proposal) received excellent reviews. Over the past five years, Thermasource has participated in numerous meetings with the PIs and scientists involved in this project and has provided key technical advice and recommendations on essentially all aspects of drilling and construction of this observatory.

As prime contractor for the construction of SAFOD, ThermaSource will be responsible for carrying out all aspects of well construction and drilling-related activities. These include engineering design, project management, and supervision of service providers. During construction of SAFOD, ThermaSource will provide the PIs a comprehensive summary and assessment of all expenses encountered to date (including copies of all invoices) and provide a comprehensive projection of forthcoming activities and associated costs.

The budget for drilling and drilling-related activities was prepared in two steps. First, the budgets for Phases 1 and 2 (Years 1 and 2) were prepared by ThermaSource, Inc. by updating the detailed drilling and operations plan (and budgets) originally developed for SAFOD in 1998. As mentioned above, this plan and budget were previously reviewed (and endorsed) by the special technical review panel convened by NSF. The updated drilling plan was then slightly modified based on the experience gained from the SAFOD pilot hole. Table II-3.2 is a breakdown of costs associated with Phases 1 and 2 as prepared in this manner by ThermaSource.

Table II-3.1. Budget Summary ($M)

| | Year 1 | Year 2 | Year 3 | Year 4 | Year 5 | 5 Year Total |
|---|---|---|---|---|---|---|
| Stanford Personnel and Mgmt Costs | 0.14 | 0.20 | 0.20 | 0.21 | 0.16 | 0.91 |
| Subcontract for Drilling and Coring* | 6.84 | 6.79 | 0 | 2.74 | 0.15 | 16.52 |
| Subcontracts for Monitoring Instr* | 0.25 | 0.73 | 0.61 | 0.79 | 0.18 | 2.56 |
| Indirect Costs | 0.10 | 0.10 | 0.11 | 0.10 | 0.08 | 0.49 |
| **Total** | **7.33** | **7.82** | **0.92** | **3.84** | **0.57** | **20.48** |

*Including contingency costs

Table II-3.2. Budget Breakdown for Phases 1 and 2 prepared by ThermaSource, Inc.

| Acct Codes | Descriptions of Costs | Phase 1 131 Days | Phase 2 108 Days |
|---|---|---|---|
| **Tangible Drilling Costs** | | | |
| 21 | Casing | $750,000.00 | $150,000.00 |
| 22 | Tubing and Drill Pipe | $30,000.00 | $60,000.00 |
| 23 | Wellhead Assembly | $270,000.00 | - |
| 25 | Other Well Equipment, Liner hanger, etc. | $90,000.00 | $45,000.00 |
| **Total of Tangible Drilling Costs** | | **$1,140,000.00** | **$255,000.00** |
| **Intangible Drilling Costs** | | | |
| 45 | Permits & Site | $80,000.00 | $60,000.00 |
| 46 | Mobilization and Demobilization | $170,000.00 | $170,000.00 |
| 49 | Contract Drilling Rig at $12,500 per day | $1,650,000.00 | $1,400,000.00 |
| 50 | Site Abandonment and Restoration | - | $36,100.00 |
| 51 | Direct Supervision | $200,000.00 | $200,000.00 |
| 52 | Bits, Stabilizers, Reamers, & Hole Openers | $400,000.00 | $250,000.00 |
| 53 | Rotary Drilling Muds, Additives, & Service | $150,000.00 | $260,000.00 |
| 54 | Casing tools and Services | $60,000.00 | $40,000.00 |
| 55 | Cement and Cementing Services | $360,000.00 | $200,000.00 |
| 56 | Other Drilling Tools, Jars, Shock subs, etc | $80,000.00 | $80,000.00 |
| 57 | Mud Logging and H2S Monitoring & Equip. | $195,000.00 | $160,000.00 |
| 58 | Blow out Preventer Rentals & Top Drive | $85,000.00 | $120,000.00 |
| 59 | Hydraulic Testing, Fluid Sampling, & Coring | $150,000.00 | $650,000.00 |
| 61 | Electrical Logging (cased and open hole) | $200,000.00 | $200,000.00 |
| 62 | Welding and Inspection | $20,000.00 | $20,000.00 |
| 63 | Directional Tools and Engineering & LWD | $450,000.00 | $1,090,000.00 |
| 64 | Fishing Tools and Services | $61,800.00 | $60,000.00 |
| 66 | Drilling Tools and Services + Drill Pipe | $85,000.00 | $100,000.00 |
| 67 | Rental Mud treatment equipment | $95,000.00 | $90,000.00 |
| 68 | Small Tools and Supplies | $30,000.00 | $30,000.00 |
| 69 | Transportation | $40,000.00 | $40,000.00 |
| 72 | Fuel, Water and Power | $225,000.00 | $225,000.00 |
| 73 | Communications | $20,000.00 | $20,000.00 |
| 74 | Well Insurance | $15,000.00 | $15,000.00 |
| 77 | Perforating | - | $40,000.00 |
| 78 | Completion Costs | $50,000.00 | $50,000.00 |
| 79 | Camp Costs and Living Expenses | $140,000.00 | $135,000.00 |
| 84 | Miscellaneous Expenses | $80,000.00 | $80,000.00 |
| 85 | Abandonment Costs | - | - |
| 91 | District Expenses | $50,000.00 | $50,000.00 |
| 92 | Administrative Overhead | $50,000.00 | $50,000.00 |
| **Total Intangible Drilling Costs** | | **$5,191,800.00** | **$5,921,100.00** |
| **Total Tangible & Intangible Costs** | | **$6,331,800.00** | **$6,176,100.00** |
| **Contingency (8% Phase 1, 10% Phase 2)** | | **$506,544.00** | **$617,610.00** |
| **Total Drilling Costs** | | **$6,838,344.00** | **$6,793,710.00** |

The budgets include contingency funds, as experience demonstrates the need to allow for unexpected events in any drilling project. The pilot hole, for example, was drilled in almost exactly the number of days originally predicted, but because of unusually high rates of wear of bits and stabilizers and the necessity to fish a lost temperature probe out of the bottom of the hole, the project was approximately 10% over budget. We have budgeted an 8% contingency for Phase 1 (having already incorporated additional costs for bit and stabilizer wear into the budget) and a 10% contingency into Phase 2.

The drilling budget for Phase 3—coring of the four multi-lateral core holes—was prepared by DOSECC, Inc., based on use of their newly acquired drill rig, outfitted with a top drive for coring. This budget is presented in Table II-3.3, and includes a 20% indirect fee. Because coring of this type (and at these depths and in these types of materials) has not previously been attempted, and because of the importance of core retrieval in the fault zone to meet the scientific goals of the project, a 20% contingency is included for this phase of the project.

## Monitoring Instrumentation Subcontracts

The types of sensors to be used in the SAFOD observatory typically originate from individual university researchers, government labs, or small commercial firms, and then must be integrated into a single borehole array to ensure their successful deployment and retrieval. Our strategy for this phase of the experiment is to contract with institutions that will serve as prime contractors, with the responsibility for integration and deployment of the various sensors associated with each phase of monitoring instrumentation.

Duke University has been actively involved in the deployment of fault zone monitoring equipment in the SAFOD pilot hole. As the Stage 1 plan for SAFOD monitoring is to deploy a new suite of instrumentation for the pilot hole, Duke University will be the prime contractor charged with integration of monitoring devices and their deployment in Stage 1 of SAFOD monitoring. As such, Duke University will be responsible for carrying-out all aspects of instrumentation design, construction and deployment in the pilot hole. On a monthly basis, Duke will provide the SAFOD PIs a comprehensive summary and assessment of all expenses encountered to date (including copies of all invoices) and provide a comprehensive forecast of forthcoming activities and associated costs. All field activities associated with Stage 1 monitoring in the pilot hole, as well as activities associated with monitoring installation in the main SAFOD hole during subsequent phases, are subject to advance review and approval by the SAFOD PIs.

Discussions are still underway for selection of the system integration and deployment contractor for Stages 2 and 3. The Geothermal Research Department at Sandia National Lab has been actively involved in the development of geophysical monitoring equipment capable of operating at high temperature and pressure for extended periods of time. As the Stage 3 plan for SAFOD monitoring is to deploy a suite of instrumentation in the main hole at high pressure (40 MPa) and temperature (150°C), the successful deployment and operation of such equipment will be a formidable challenge. It is likely (but not yet certain) that Sandia Lab will be the prime contractor charged with development and integration of monitoring devices and their deployment during Stages 2 and 3 of SAFOD monitoring. The responsibilities and reporting/oversight requirements for the prime contractor for Stages 2 and 3 of monitoring will be the same as outlined above for Stage 1.

Table II-3.3. Phase 3 Budget Prepared by DOSECC, Inc.

| Mobilization & Miscellaneous | Units | $/unit | Amount |
|---|---|---|---|
| Pre-spud meeting | 1 | $1,750.00 | $1,750.00 |
| Preparation in yard | 1 | $30,000.00 | $30,000.00 |
| Mobilize rotary rig | 1 | $50,000.00 | $50,000.00 |
| Crane in Rexberg yard | 1 | $3,000.00 | $3,000.00 |
| Trucking Rexberg to site (DHCS) | 8 | $1,500.00 | $12,000.00 |
| Crane in Rexberg | 1 | $7,940.00 | $7,940.00 |
| Mob directional equipment | 1 | $11,850.00 | $11,850.00 |
| Mob directional crew | 4 | $6,450.00 | $25,800.00 |
| Whipstocks etc. | 4 | $20,000.00 | $80,000.00 |
| Motor maintenance | 4 | $650.00 | $2,600.00 |
| Mills | 4 | $3,000.00 | $12,000.00 |
| Mud/Polymer | 3200 | $15.00 | $48,000.00 |
| 5” liner | 4000 | $12.00 | $48,000.00 |
| Inspections | 1 | $50,000.00 | $50,000.00 |
| Water | 94 | $450.00 | $42,300.00 |
| Fishing Tools | 94 | $200.00 | $18,800.00 |
| Slotted liner | 1000 | $10.00 | $10,000.00 |
| Guide shoes/tools | 4 | $2,200.00 | $8,800.00 |
| Cement & Cement Services | 1 | $35,000.00 | $35,000.00 |
| Boxes for substructure | 4 | $25,000.00 | $100,000.00 |
| BOP rental | 94 | $600.00 | $56,400.00 |
| Core bits | 4 | $750.00 | $3,000.00 |
| Core Boxes | 400 | $8.00 | $3,200.00 |
| **Total Mob** | | | **$660,440.00** |
| **Operations** | **Days** | **Rate** | **Amount** |
| Rig Up | 5 | $7,940 | $39,700.00 |
| Drill Rig | 58 | $10,640 | $617,120.00 |
| Directional Coring | 28 | $16,180 | $453,040.00 |
| Rig Down | 5 | $7,940 | $39,700.00 |
| **Subtotal** | | | **$1,149,560.00** |
| **Demobilization** | **Days** | **Rate** | **Amount** |
| Crane at site | 1 | $3,000.00 | $3,000.00 |
| Truck rotary rig | 1 | $35,000.00 | $35,000.00 |
| Truck DHCS | 7 | $1,500.00 | $10,500.00 |
| Return pipe to SLC | 1 | $1,500.00 | $1,500.00 |
| Crew Transportation | 1 | $7,940.00 | $7,940.00 |
| Unload and clean up | 1 | $20,000.00 | $20,000.00 |
| Crane at yard | 1 | $3,000.00 | $3,000.00 |
| **Total Demob** | | | **$80,940.00** |
| **Project Subtotal** | | | **$1,890,940.00** |
| **Indirect @ 20%** | | | **$378,188.00** |
| **Contingency @ 20%** | | | **$456,662** |
| **Total** | | | **$2,739,972.00** |

Table II-3.4. SAFOD Monitoring Instrumentation ($M)

| | Year 1 | Year 2 | Year 3 | Year 4 | Year 5 | 5 Year Total |
|---|---|---|---|---|---|---|
| Stage 1 - Seismic array with moving coil and MEMS seismometers, MT coil, strain and tiltmeter | 0.25 | 0.13 | 0.05 | 0.1 | 0 | 0.53 |
| Stage 2 - Dilatometer behind casing, fiber optic temperature sensor | 0 | 0.34 | 0 | 0 | 0 | 0.34 |
| Stage 3 - High T pressure transducer, seismometers, thermistors, clamped tilt and strain meters | 0 | 0.2 | 0.56 | 0.51 | 0.08 | 1.35 |
| 5 km tubing | 0 | 0 | 0 | 0.12 | 0 | 0.12 |
| Workover rig for installation | 0 | 0.06 | 0 | 0.06 | 0.1 | 0.22 |
| **Total** | **0.25** | **0.73** | **0.61** | **0.79** | **0.18** | **2.56** |

Table II-3.4 is a breakdown of the instrumentation costs for the three Stages of instrumentation deployment described above. The breakdown shown in this table represents known costs for the:

- Stage 1 integrated system
- Stage 2 fiber optic temperature sensors
- Stage 3 high-temperature pressure transducer and thermistors
- Tubing and work-over rig for Stage 1 and Stage 3 deployments

In addition, estimated costs are indicated for the:

- Stage 2 volumetric strainmeter
- Stage 3 high temperature seismometers and clamped tilt/strain meters

These estimated costs are based on related equipment deployed in ODP boreholes and estimated costs for high temperature sensor development.

## Stanford Personnel

Table II-3.5 is a breakdown of the Stanford budget over the duration of this project. Salary is requested for one of the PIs (Mark Zoback) for one month during the summer and one month during the academic year. Zoback was at the drill site half the time for drilling of the pilot hole (sharing supervisory duties with Steve Hickman) and will do the same during the SAFOD main drilling phases. Moreover, there are appreciable responsibilities associated with managing SAFOD throughout the year. In addition, funding is requested for a half-time administrative assistant (Susan Moskowitz), who will coordinate logistics, travel and payment of the invoices and other expenses associated with this project as well as serving as a liaison to press and those involved with EarthScope E&O activities.

Funding is requested for two graduate students, who will serve as Data Managers for the duration of the project. Initially, one of these students will be Naomi Boness, who served as Data Manager on the pilot hole project. She had principal responsibility for synthesizing all of the scientific and operational data being gathered during drilling (description and photography of cuttings, real-time fluid and gas chemistry, penetration rates, mud properties, etc.) and entering all of this information into the ICDP Drilling Information System. As the pilot hole was a ~45 day, 24 hour/day operation, it was necessary for Naomi to assemble a collection of volunteer Stanford students for several days to one week at a time to assist her in carrying out these functions. Drilling in Phases 1 and 2 will be more demanding, as each drilling phase will be approximately three times the duration of the pilot hole. Thus, it is necessary to have two students assigned to this task. During Phase 3, the two students will be available to assist with core handling operations.

Funds budgeted for Meetings and Project Coordination in Table II-3.5 refer principally to travel and related expenses for groups of scientists and engineers to meet to discuss different aspects of the project (rock and fluid sampling, downhole measurements, monitoring instrumentation, etc.) as well as regular meetings of the SAFOD Scientific Advisory Board (see Figure II-3.10). Travel and Field Work expenses are associated with domestic travel related to project management and accommodation costs during drilling. Finally, while full indirect costs (60% of Direct Costs, or MTDC) is charged for expenses directly associated with Stanford personnel, indirect costs are charged to only the first $25,000 of each of the three subcontracts referred to above (ThermaSource, Duke, and Sandia). Thus, in aggregate, the indirect costs associated with this proposal ($0.49M) comprise only 4% of the total request.

Table II-3.5. Summary of Stanford Staff and Related Expenses

| | Year 1 | Year 2 | Year 3 | Year 4 | Year 5 | Total 5 yrs. |
|---|---|---|---|---|---|---|
| Salary and Fringe | | | | | | |
| Mark Zoback (1 mo. Sum. 1 mo aca.) | $30,000 | $31,500 | $33,075 | $34,729 | $36,465 | $165,769 |
| Admin Assistant @ 50% | $25,000 | $26,250 | $27,563 | $28,941 | $30,388 | $138,141 |
| Subtotal Salary | $55,000 | $57,750 | $60,638 | $63,669 | $66,853 | $303,910 |
| Fringe @24.8% | $13,640 | $14,322 | $15,038 | $15,790 | $16,580 | $75,370 |
| 1st grad student | $24,000 | $25,200 | $26,460 | $27,783 | - | $103,443 |
| 2nd grad student | | $25,200 | $26,460 | $27,783 | $29,172 | $108,615 |
| Total Student | $24,000 | $50,400 | $52,920 | $55,566 | $29,172 | $212,058 |
| Student Fringe @3.3% | $792 | $1,663 | $1,746 | $1,834 | $963 | $6,998 |
| Total Salary and Fringe | $93,432 | $124,135 | $130,342 | $136,859 | $113,567 | $598,335 |
| Travel | $10,000 | $16,000 | $16,000 | $10,000 | $12,000 | $64,000 |
| Equipment | - | $5,000 | $5,000 | $5,500 | - | $15,500 |
| Supplies | $5,000 | $8,000 | $8,000 | $8,000 | $5,000 | $34,000 |
| Publications | - | $1,000 | $3,000 | $3,000 | $5,000 | $12,000 |
| Tuition (4 quarters/year) | $15,710 | $32,992 | $34,640 | $36,372 | $19,096 | $138,810 |
| Meetings and Project Coord. | $12,000 | $10,000 | $8,000 | $8,000 | $6,000 | $44,000 |
| **Total Direct** | **$136,142** | **$197,127** | **$204,982** | **$207,731** | **$159,663** | **$905,645** |
| **MTDC** | **$120,432** | **$159,135** | **$165,342** | **$165,859** | **$140,567** | **$751,335** |
| **Indirect 60%** | **$72,259** | **$95,481** | **$99,205** | **$99,515** | **$84,340** | **$450,801** |
| **Stanford** | **$208,401** | **$292,608** | **$304,187** | **$307,246** | **$244,003** | **$1,356,446** |
| **Subaward (3)** | **$7,090,000** | **$7,530,000** | **$600,000** | **$3,530,000** | **$325,000** | **$19,075,000** |
| **Indirect for subawards 60%** | **$30,000** | | **$15,000** | | | |
| **Total Cost** | **$7,328,401** | **$7,822,608** | **$919,187** | **$3,837,246** | **$569,003** | **$20,476,446** |

# Part III. Management and Budget

# 1. Management of Project Execution

## 1.1. Management Goals

The management structure for the EarthScope MREFC is designed to:

1. ensure the project is in compliance with NSF policies and procedures and Federal regulations,
2. manage the project "to the baseline" – meet approved cost, schedule, and performance requirements for the project, and
3. be both representative of, and accountable to, the Earth science community at large.

The management structure is based on the principles of broad and equal community representation for the major components of EarthScope, while providing NSF with a single point of contact. Specifically, we view EarthScope's project management as an "enabling technology" to help NSF dollars go further.

The management structure described in this section has been approved by the IRIS and UNAVCO Boards of Directors. A formal Memorandum of Understanding, with associated by-laws to govern operations, will be developed between IRIS, UNAVCO, and the SAFOD project.

The EarthScope facility management will oversee the installation and operation of the EarthScope facility as funded by NSF through the Major Research Equipment and Facilities Construction (MREFC) program under cooperative agreements with IRIS, UNAVCO, and Stanford University. The separate task of coordinating EarthScope science and education activities will occur through the recently appointed EarthScope Science and Education Committee.

## 1.2. EarthScope Facility Executive Committee

Full power in the management of the EarthScope Facility will be vested in the EarthScope Facility Executive Committee (EFEC). The Executive Committee will be chaired by the EarthScope Facility Director. The EarthScope Facility Director will serve as the single point of contact for NSF on overall management of the EarthScope facility.

The EarthScope Facility Executive Committee will consist of seven members: one elected by two-thirds majority of the IRIS Executive Committee, one elected by two-thirds majority of the UNAVCO Board, one elected by the SAFOD project, the three PIs of the EarthScope Cooperative Agreements, and the EarthScope Facility Director. All positions will also require approval by a simple majority of a combined council consisting of the seven-member IRIS Executive Committee, the seven member UNAVCO Board, and the three-member SAFOD management team.

All members of the EarthScope Facility Executive Committee will serve at the pleasure of their respective Boards with two-year renewable appointments and without specific term limits. Because the IRIS and UNAVCO Boards represent their membership, EarthScope management is "accountable" to the broad community, and no single EarthScope component can operate unilaterally, or exert disproportionate influence.

Specific responsibilities of the Executive Committee include:

- perform on-going evaluations to determine progress against the Baseline Project Definitions.

- review the on-going management procedures, work breakdown schedules, milestones, and risk mitigation strategies.
- review any significant deviations from the original design plans and critical risk mitigation decisions, and make recommendations to NSF through the Facility Director to ensure that the project remains on schedule and within cost and that it meets intended design goals and infrastructure needs of the scientific community.
- interact with the EarthScope Science and Education Committee to ensure that the facility remains responsive to the science needs of EarthScope and that there is coordination between the EarthScope facility and the EarthScope science and education programs.

The Executive Committee will meet at least four times a year. Each year, one meeting will be at UNAVCO, one meeting will be at SAFOD, and one meeting will be at IRIS, during which an on-site review of the program will be performed. As a result, USArray, SAFOD, and PBO will each undergo an on-site review each year by the Executive Committee. A fourth meeting will be held jointly with the EarthScope Science and Education Committee.

Action requires a vote at an EFEC meeting that has a quorum. The EFEC will require a quorum consisting of the EarthScope Facility Director and at least one representative from each of the three EarthScope components. Provided a quorum exists, a second representative may provide his or her proxy to the other representative from the same EarthScope component. A motion carries if at least two-thirds of the members present at a meeting vote in favor of the motion. In the difficult case where only one of the EarthScope components is in disagreement with a motion, the Facilities Director effectively decides based on the best interests of EarthScope as a whole. All three EarthScope components can over-rule the Facility Director (including the power to remove the Facility Director).

## 1.3. EarthScope Facility Director

The Facility Director will chair the EarthScope Facility Executive Committee and have overall responsibility to NSF for implementation of the EarthScope Project under the MREFC account. The Project Facility Director will serve as the single point of contact for the EarthScope MREFC to NSF, oversight organizations, media, and the community. Specific responsibilities include:

- overall management of the EarthScope Facility Office located in Washington, DC
- chair the EarthScope Facility Executive Committee
- review and evaluate project progress against milestones
- provide NSF with quarterly reports and briefings, and participate in the development and review of the cooperative agreements for the different components of EarthScope.

## 1.4. Reporting

The Facility Director will submit quarterly reports and provide quarterly briefings to NSF identifying progress made relative to the timelines and milestones identified in the EarthScope project plan. If the project does not meet any of the major milestones, the Facility Director, in consultation with the Executive Committee, will propose to NSF a remedial action in the quarterly report.

For the first two years, we propose that NSF establish an EarthScope "Tiger Team" to review program progress, with broad representation including the Geoscience Directorate, the Directorate for Education and Human Resources, the Office of Finance and Award Management, the Office of Legislative and Public Affairs, and the Office of the Inspector General.

USArray, SAFOD, and PBO will each appoint a single "Point of Contact" to the EarthScope Facility Office. The Point of Contact will be responsible for providing to the EarthScope Facility Director quarterly summaries of the program status, financial accounting, problems and changes, etc. The information will be provided to the Facility Director in a common format determined by the Executive Committee and NSF, and will be independently verified by the Executive Committee each year during site reviews.

## 1.5. Advisory Committees

The Facility Director and the EFEC may assemble *ad hoc* advisory panels and task forces to address specific issues and provide recommendations to the EFEC. The scope of such committees will be specified by the EFEC. No committees shall have powers which are not authorized by the EFEC.

Each of the EarthScope project components (USArray, SAFOD, and PBO) will appoint an advisory committee. The members will serve two-year terms, but with no term limits. The recommendations of these committees will be transmitted both to the Principal Investigator of the respective EarthScope component and to the Facility Director. The purpose of the advisory committees will be both to franchise the broader community and to bring ideas, suggestions, concerns, and criticisms from the broad EarthScope community to the attention of the Facility Director and the EFEC.

In addition, the Facility Director will organize "listening sessions," briefings, and forums, at meetings such as those of the American Geophysical Union, the Seismological Society of America, the Geological Society of America, the American Association of Petroleum Geologists, the National Science Teachers Association, the American Association of State Geologists, the National Science Funding Coalition, the IRIS Workshop, the SCEC Workshop, and the UNAVCO workshop, to describe publicly the status of the project and to receive input from the more general scientific and educational communities.

## 1.6. EarthScope Facility Office Budget

The budget shows all costs, not readily attributable to the costs of administering USArray, SAFOD, and PBO, of operating a corporate office for the EarthScope Facility in Washington, DC. The EarthScope Facility corporate office is less than 3% of the overall budget for the facility.

The EarthScope Facility Office, located in Washington, DC, will serve as the single point of contact for the EarthScope facility to NSF, oversight organizations, media, and the community. It will be responsible for record keeping, and demonstrating compliance with NSF policies and procedures and Federal regulations. The office will manage the EFEC and oversee workshops, conferences, meetings, web site, display booths, electronic newsletters, etc. related to the EarthScope facilities. The office will have an analytical capability to produce independent assessments of program performance, and produce customized analysis for oversight agencies and committees, and outreach.

The EarthScope Facility Office will work in partnership with the support structure developed for the EarthScope Science and Education Committee (ESEC). To the maximum extent possible, the EarthScope Facility Office will also support the activities of the ESEC to ensure that the facility remains responsive to the evolving needs of the research and education communities.

EarthScope Facility Office will be initially collocated with the IRIS Consortium, so that it can share resources and/or personnel and begin operations quickly. Funding for the staffing and operations of the EarthScope Facility Office will be administered as a separate Cooperative Agreement to IRIS from NSF. The costs and accounting associated with the EarthScope Facility Office will be separately administered and identified.

### Table III-1. EarthScope Facility Office Budget (Management)

| | Year 1 | Year 2 | Year 3 | Year 4 | Year 5 | 5-Year Total |
|---|---|---|---|---|---|---|
| **Direct Costs** | | | | | | |
| Salaries | | | | | | |
| Earthscope Facility Director | | | | | | |
| Business Officer | | | | | | |
| EFEC Coordinator | | | | | | |
| Program Analyst | | | | | | |
| Publications Manager | | | | | | |
| Subtotal: Salaries | $389,000 | $400,670 | $412,690 | $425,071 | $437,823 | $2,065,254 |
| Fringe Benefits @ 35% | $136,150 | $140,235 | $144,442 | $148,775 | $153,238 | $722,840 |
| Subtotal: Salaries & Fringe Benefits | $525,150 | $540,905 | $557,132 | $573,846 | $591,061 | $2,788,094 |
| Travel | | | | | | |
| Staff | $35,000 | $35,000 | $35,000 | $35,000 | $35,000 | $175,000 |
| Committee | $24,000 | $24,000 | $24,000 | $24,000 | $24,000 | $120,000 |
| Subtotal: Travel | $59,000 | $59,000 | $59,000 | $59,000 | $59,000 | $295,000 |
| Participant Support Costs | | $35,000 | $35,000 | $35,000 | $35,000 | $140,000 |
| Materials and Supplies | $35,000 | $35,000 | $35,000 | $35,000 | $35,000 | $175,000 |
| Publications and Printing | $25,000 | $25,000 | $25,000 | $25,000 | $25,000 | $125,000 |
| Consulting Services | $8,000 | $8,000 | $8,000 | $8,000 | $8,000 | $40,000 |
| Software | $12,000 | $12,000 | $12,000 | $12,000 | $12,000 | $60,000 |
| Other | $20,000 | $20,000 | $20,000 | $20,000 | $20,000 | $100,000 |
| **Subtotal: Direct Costs** | **$684,150** | **$734,905** | **$751,132** | **$767,846** | **$785,061** | **$3,723,094** |
| **Indirect Costs** | | | | | | |
| DC Office Overhead @ 38% | $147,820 | $152,255 | $156,822 | $161,527 | $166,373 | $784,797 |
| G&A @ 16% | $133,115 | $136,346 | $139,673 | $143,100 | $146,629 | $698,863 |
| Management Fees | $75,000 | $75,000 | $75,000 | $75,000 | $75,000 | $375,000 |
| **Subtotal: Indirect Costs** | **$355,935** | **$363,601** | **$371,495** | **$379,627** | **$388,002** | **$1,858,660** |
| **Total Costs** | **$1,040,085** | **$1,098,506** | **$1,122,627** | **$1,147,473** | **$1,173,063** | **$5,581,754** |

## Salary

We anticipate a consistent level of staffing throughout the duration of the project (5 FTEs). Major responsibilities of the personnel are described below.

*EarthScope Facility Project Director (1 FTE)*
The EarthScope Facility Project Director will chair the EarthScope Facility Executive Committee and have overall responsibility to NSF for implementation of the EarthScope Project under the MREFC account. The Facility Director will serve as the single point of contact for the EarthScope facilities to NSF, oversight organizations, media, and the community. Specific responsibilities include:

- overall management of the EarthScope office located in Washington, DC
- chairmanship of the EarthScope Executive Committee
- review and evaluation of project progress against milestones
- providing NSF and federal funding and oversight agencies with quarterly reports and briefings, and participating in the development and review of the cooperative agreements for the different EarthScope components.

*EarthScope Facility Business Officer (1 FTE)*
The EarthScope Facility Business Officer will be responsible for demonstrating compliance with NSF policies and procedures, and federal regulations. Specific responsibilities include:

- financial record-keeping and accounting
- integrated financial reports for NSF and oversight board
- business and legal affairs for the organization

*EarthScope Facility Executive Committee Coordinator (1 FTE)*
The Coordinator will manage the EFEC and administer workshops, conferences, meetings, web site, booth, electronic newsletters, etc. related to the EarthScope Facility. The Coordinator will:

- administer and staff the EFEC
- schedule EFEC and EFEC Project Director activities and meetings
- maintain administrative data bases

*EarthScope Facility Program Analyst (1 FTE)*
The EarthScope Facility Office will have an analytical capability to produce independent assessments of program performance, and produce customized analysis for oversight agencies and committees, and outreach. The EarthScope Facility Project Analyst will:

- evaluate data collection and recovery rates against program milestones
- analyze performance and data quality against baseline goals
- maintain GIS capability for data displays and presentations

*EarthScope Facility Publications Manager (1 FTE)*
The EarthScope Facility Office will include a publications capability to produce outreach and customized project materials related to the EarthScope Facility. The publications manager will:

- produce EarthScope Facility publications and graphics
- produce customized project materials
- maintain an EarthScope Facility web site and electronic newsletter

## Travel

Funds are budgeted for domestic and foreign travel (Canada, Mexico) of the staff, and domestic travel of the EarthScope Facility Executive Committee members.

### Participant Support Costs

Participant support costs are to fund technical workshops for facility personnel to assist in the coordination among the various EarthScope components.

### Materials and Supplies

Materials and supplies include office equipment, computing hardware, and software.

### Publications and Printing

Publications and printing charges cover printing costs for EarthScope facility publications including posters and annual reports/yearbooks, which will be distributed free of charge to individuals and institutions.

### Consulting Services

To keep permanent staffing at lean levels, the EarthScope Facility Office will use temporary personnel and consultant services for outsourcing as necessary.

### Software

Software costs include analytical software such as GIS that will be used for programmatic evaluation and the production of specialized publications for the EarthScope facility.

### Management Fee

Management fees are requested annually to develop a pool of unrestricted funds to offset exposures inherent in managing a multi-million dollar program. A fund balance is required to pay for unanticipated or common unallowable expenses incident to operating a corporate entity under a federal award.

# 2. Educational Impact of EarthScope

Although the primary motivation for EarthScope is the fundamental advance of scientific discovery, the initiative is also a unique opportunity for Earth science education and for reaching out to the general public. EarthScope will be a tool for communicating both the results that emerge from a national scientific effort, and perhaps as importantly, the nature of the scientific method.

As EarthScope observatories are installed across the nation, students and the public will be introduced to scientific questions and the role that their region plays in understanding the formation of the North American continent. EarthScope will enable a broad range of students and the public to participate in a national experiment and for the first time to observe and measure geological processes within the time frame of an academic school year. EarthScope will provide a compelling example of how our scientific understanding advances as new data become available and new hypothesis are tested, and will attract outstanding young people to careers in Earth sciences.

We recognize that for EarthScope data to be useful to the educational community, it must be provided in formats and as products that are accessible to educators and students. In addition, appropriate teaching modules must be developed that will allow the EarthScope resources to be incorporated into an inquiry-based learning experience consistent with the national educational standards.

Coincident with the development of the EarthScope facilities have been a series of workshops and discussions on the educational and outreach opportunities. The workshops have resulted in a set of education and outreach goals. While the achievement of these goals is beyond the scope of this facility proposal, the goals do define the data streams, complementary geological data sets, and the scientific results that will be accessible to a wide audience via close collaboration with the EarthScope facilities. They include:

- Create a high-profile public identity for EarthScope that emphasizes the integrated nature of the scientific discoveries and the importance of EarthScope's various research initiatives.
- Establish a sense of project ownership among scientific, professional, and educational communities and the public so that a diverse group of individuals and organizations can and will make contributions to EarthScope.
- Promote science literacy and understanding of the EarthScope experiment among all audiences through informal education venues.
- Advance formal Earth science education by promoting inquiry-based classroom investigations that focus on understanding Earth and the interdisciplinary nature of the EarthScope experiment.
- Foster use of EarthScope data, discoveries, and new technology in resolving challenging problems and improving our quality of life.

The wealth of education and outreach opportunities that can be closely linked to EarthScope can be found in the report titled, *EarthScope: An Unprecedented Opportunity for Education and Outreach in the Earth Sciences*, which is available on the EarthScope.org web site. The plan calls for an EarthScope Education and Outreach Network (EON) to support these goals through: (1) resource development and dissemination, and (2) program development and implementation. Resource development includes creating public relations information, posters, fact sheets, and news releases; producing educational videos; developing supplemental curriculum resources and visualization and analysis tools; and sponsoring museum exhibits. The effort is at the core of creating a unified EarthScope identity. Program development and implementation activities include public relations support for deployment, solicitation of partnerships and opportunities for knowledge transfer to other technical professionals, formal education programs such as K-16 faculty professional development, and informal education activities at parks and community centers.

Within this proposal, each of the EarthScope components describe how they will make data available and how they plan specifically to leverage the infrastructure of the EarthScope facilities for educational and outreach purposes. It will be through close collaboration with the EarthScope Education and Outreach Program that the potential for these resources are fully realized. The newly formed EarthScope Science and Education Committee will provide the formal structure for such coordination and interaction.

# 3. Data and Instrument Policies

## 3.1. Data Distribution Policy

It will be the policy of EarthScope that all data will be openly available without restriction or cost and with minimal delay. The Earth Science Division at NSF has recently (April 2002) issued a Data Sharing Policy that will be adhered to as the overarching policy for EarthScope (www.geo.nsf.gov/ear/EAR_data_policy_204.doc).

EarthScope's open data policy is intended to maximize participation from the scientific community and to provide on-going educational opportunities for students at all levels. In addition to issues related to the access to data and data sharing, it is essential that all EarthScope data be preserved for future generations of Earth scientists. As discussed in Part II of this proposal, the EarthScope facilities have well-established procedures and archives in place to ensure the long-term survivability of raw and derived data as well as related metadata.

## 3.2. Instrument Use Policy

The core instruments of the EarthScope Observatory are permanent installations or transportable arrays, installed and operated by EarthScope-funded staff as a community resource. For instruments that are available for use in separately funded PI-driven experiments, special instrument use and data release policies will be established. Detailed arrangements governing the use of these instruments will be implemented by the EarthScope Facility Executive Committee based on EarthScope-wide policies established in consultation with NSF and the EarthScope Science and Education Committee. In general, any research or educational institution may request use of USArray Flexible Array instruments and PBO portable GPS receivers in EarthScope science projects as identified by NSF.

# 4. EarthScope Facility Budget Overview

While the details and justification for the project budgets are provided with the individual project descriptions in Section II, a summary is presented in this section to provide an overview of the complete project.

The full budget request for support of "EarthScope: Acquisition, Construction and Facility Management" consists of the following parts:

## 4.1. Equipment Acquisition and Construction

A collaborative 5-year proposal (July 1, 2003 to June 30, 2008) to the NSF Major Research Equipment and Facility Construction Account to create and manage the EarthScope Observatory. This proposal requests support for capital equipment, installation, infrastructure support and initial deployment of USArray, PBO and SAFOD. A separate budget is presented for coordination and management through an EarthScope Facility Office.

The parts of the collaborative EarthScope Facility MREFC facility proposal are:

a) USArray: A proposal from the IRIS Consortium for acquisition and installation of USArray. Support is requested to acquire all of the hardware for USArray and associated data management activities, install the Backbone Network, complete the first deployment of the Transportable Array and prepare the Flexible Array equipment for use in separately funded EarthScope experiments.

b) PBO: A proposal from UNAVCO Inc for acquisition, installation and operation of the Plate Boundary Observatory. Support is requested to acquire the hardware for all PBO instruments, install the GPS, strainmeter and associated instruments and complete deployment of the permanent backbone stations and clusters.

c) SAFOD: A proposal from Stanford University to drill, sample and instrument the SAFOD observatory at Parkfield.

d) EarthScope Facility Office: The EarthScope Facility Office will initially be collocated with the IRIS Consortium offices in Washington, DC. Funding is requested through IRIS to establish and host the office. The primary responsibilities of the office will be to support the activities of the EarthScope Facility Executive Committee, coordinate interactions between the facility operators, and serve as the point of contact with NSF and the EarthScope Science and Education Committee. As EarthScope develops and evolves, the office structure and operation will be reviewed in consultation with NSF and the EarthScope Science and Education Committee

## 4.2. Operation and Maintenance

A collaborative 5-year proposal (July 1, 2003 to June 30, 2008) as a separate submission to the NSF Division of Earth Sciences, Research and Related Activities Account for operation and maintenance of the EarthScope Observatory. This proposal presents a plan for how, as the components of the EarthScope facility become operational, support transitions from a construction and installation phase to an operational phase. This transition is designed to be consistent with NSF policy regarding the development and operation of large facilities under which the MREFC account is used to support facility construction and the R&RA account is used to support operations. In addition to annual costs for the transition phase during Years 1 to 5, while the MREFC funding is in effect, the O&M proposal includes an estimate for the annual costs for full facility operation in Years 6 to 10 (2008 – 2013) following completion of the MREFC funding.

The parts of the collaborative proposal for EarthScope Facility operations and maintenance (O&M) parallel the structure of the MREFC proposal, with collaborative submissions from IRIS and UNAVCO.

The following tables summarize the budget components for the two proposals and provide an estimate of operational costs for Years 6-10. A more detailed budget structure for each of the EarthScope components (USArray, PBO, and SAFOD) is provided in the project descriptions in Section II of this proposal. The budget structure for the EarthScope Facility Office is found earlier in this section. More detail on the MREFC budgets is to be found in the following section of this proposal, which presents the institutional budget submissions from IRIS, UNAVCO, and Stanford. The details of the O&M budgets for Years 1-5 and the estimate for Years 6-10 are presented in the accompanying R&RA proposal.

### Table III-2. MREFC Budget

(July 1, 2003 to June 30, 2008; $M)

| | Year 1 2003 | Year 2 2004 | Year 3 2005 | Year 4 2006 | Year 5 2007 | 5-Year Total |
|---|---|---|---|---|---|---|
| USArray | 15.18 | 14.01 | 15.93 | 16.14 | 8.59 | **69.85** |
| PBO | 10.30 | 19.21 | 27.99 | 27.09 | 15.42 | **100.00** |
| SAFOD | 7.33 | 7.82 | 0.92 | 3.84 | 0.57 | **20.48** |
| Management | 1.04 | 1.10 | 1.12 | 1.15 | 1.17 | **5.58** |
| **Total** | **33.85** | **42.14** | **45.96** | **48.21** | **25.75** | **195.91** |

### Table III-3. Operations and Maintenance Budget Years 1-5

(July 1, 2003 to June 30, 2008; $M)

| | Year 1 2003 | Year 2 2004 | Year 3 2005 | Year 4 2006 | Year 5 2007 | 5-Year Total |
|---|---|---|---|---|---|---|
| USArray | 0.37 | 1.44 | 2.40 | 3.14 | 7.29 | **14.65** |
| PBO | 0.00 | 0.26 | 1.05 | 2.13 | 3.12 | **6.57** |
| **Total** | **0.37** | **1.70** | **3.45** | **5.27** | **10.41** | **21.21** |

### Table III-4. Annual O&M Estimate Years 6-10

(July 1, 2008 to June 30, 2012; $M)

| | Year 6 estimate | 5 year total, with inflation |
|---|---|---|
| USArray | 12.39 | 65.77 |
| PBO | 9.07 | 47.66 |
| SAFOD | 0.45 | 2.38 |
| **Total** | **21.91** | **115.81** |

# 5. Supporting Letters

United States Department of the Interior

U.S. GEOLOGICAL SURVEY
Reston, Virginia 20192

In Reply Refer To:
Mail Stop 905

January 22, 2003

Dr. Margaret Leinen
Assistant Director for Geosciences
National Science Foundation,
4201 Wilson Boulevard.
Arlington, Virginia 22230

Dear Dr. Leinen:

We are writing to express the strong support of the U.S. Geological Survey's (USGS) Earthquake Hazards and Volcano Hazards Programs for the EarthScope initiative. Progress in understanding earthquakes, volcanic eruptions, and their effects requires a substantial increase in instrumental observations of earthquakes, tectonic and magmatic processes, as well as direct observation and sampling of the earthquake source. The USGS is taking an active partnership role in planning and implementing the key components of EarthScope—USArray, Plate Boundary Observatory (PBO), San Andreas Fault Observatory at Depth (SAFOD), and InSAR—to ensure that these new observational systems are well integrated with existing seismic and geodetic networks, and efficiently utilized to better understand and mitigate the risks posed by earthquakes and other natural hazards.

*USArray*. The Advanced National Seismic System (ANSS) is a USGS initiative to modernize, expand, and integrate earthquake monitoring nationwide, with particular emphasis on completing the permanent "backbone" of the U.S. National Seismic Network (USNSN) and creating dense monitoring networks in high-risk urban areas. The USGS is working with the USArray element of EarthScope to achieve the goal of expanding the USNSN. The "backbone" stations included in the EarthScope facilities proposal are viewed by the USGS as an integral part of the ANSS plan, and were developed in close collaboration with the ANSS effort. The USGS, through its Albuquerque Seismological Laboratory (ASL), will be responsible for coordination and installation of these permanent stations through a subaward from the Incorporated Research Institutions for Seismology (IRIS). As part of ANSS, the USGS is seeking support for the long-term operation and maintenance of these permanent stations.

***Plate Boundary Observatory (PBO)***. The USGS looks forward to full cooperation and collaboration with the planning and implementation of the PBO effort, as evidenced by our intimate involvement in the National Science Foundation (NSF)-funded mini-PBO effort in the San Francisco Bay Area. USGS support for the PBO will include advice and consultation by USGS experts on the installation and maintenance of global positioning system (GPS) receivers and borehole strainmeters, magnetometers and tiltmeters, as well as consulting advice on data processing for borehole strainmeters. We will also provide, through our ASL and other Earthquake Program offices, cooperation in the installation of GPS stations at USNSN stations and stations associated with other currently supported or permitted USGS regional seismic network stations. Through our Volcano Hazards Program, the USGS is developing network strategies that include PBO instruments in our volcano monitoring systems for Alaska, the Cascades, and Yellowstone Caldera. Volcano Hazards Program scientists have been active participants in the PBO Magmatic Systems workshops, and coordinated EarthScope-USGS strategies are being incorporated in the Volcano Program's new 5-year (FY 2004-FY 2009) science plan.

***San Andreas Fault Observatory at Depth (SAFOD).*** Building on more than 15 years of detailed scientific investigations conducted as part of the USGS Parkfield Earthquake Experiment, the USGS is committed to playing key leadership, scientific, and technical roles in the SAFOD. In particular, our interaction will be achieved through the continued support of USGS scientists, Dr. Steve Hickman and Dr. William Ellsworth, as SAFOD co-PIs and through the direct involvement of USGS specialists in laboratory rock mechanics, borehole geophysics, geochemistry, seismic and potential field imaging, earthquake seismology and geologic mapping in all aspects of the SAFOD experiment. We will also collaborate with NSF-funded institutions in the long-term operation and maintenance of SAFOD, through installation and routine maintenance of the SAFOD surface facility (building, power, security, etc.) and data telemetry systems by USGS field personnel. This will ensure that the infrastructure necessary to support SAFOD monitoring systems is well maintained and that the resulting data streams are fully integrated into existing long-term USGS monitoring efforts at Parkfield.

EarthScope, including all four components (USArray, PBO, SAFOD, as well as InSAR) will be an important facility for hazard assessment, with the potential to do hazard-focused experiments on scales never before possible. As discussed previously with NSF managers, we hope to formalize the commitments in this letter as annexes to the existing Memorandum of Agreement for Cooperation in the Earth Sciences between NSF and the USGS. We look forward to working closely with NSF and the university community to ensure the success of this exciting new initiative.

Sincerely yours,

John R Filson

John R Filson, Coordinator
USGS Earthquake Hazards Program

J S Pallister

John S. Pallister, Coordinator
USGS Volcano Hazards Program

INTERNATIONAL CONTINENTAL SCIENTIFIC
DRILLING PROGRAM

icdp

Dr. H. Zimmerman
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Potsdam, January 15, 2003

Dear Herman,

On behalf of International Continental Drilling Program, it is a pleasure to write this letter of support for the San Andreas Fault Observatory at Depth ( SAFOD) initiative. ICDP has long been supportive of the scientific objectives of this project and it is gratifying to see it come to fruition as part of the EarthScope initiative of the U.S. National Science Foundation. As you know, the highly successful SAFOD pilot project was carried out as a collaboration between NSF, USGS and ICDP and we look forward to continued involvement in the SAFOD project itself.

There are a number of areas where ICDP will provide support for the SAFOD project. Firstly, we are pleased to provide our comprehensive real-time data base, the Drilling Information System and to assist the PI's in all technical aspects of its installation and operation. This system is accessible via the internet to both active investigators and the public-at-large and has proven to be of great value in scientific drilling projects around the world. The SAFOD PI's made extensive use of this system in the pilot hole project. Secondly, the ICDP is prepared to provide equipment, personnel and training associated with the core handling facility to be established at the site. This includes several key pieces of analytical equipment as well as core scanning instrumentation, etc. Finally, ICDP will be pleased to serve as a liaison to the international scientific community engaged in research who will undoubtedly be interested in the results obtained by the SAFOD project.

Yours sincerely,

Rolf Emmermann

Prof. Dr. Dr. h.c. R. Emmermann
Chairman, Executive Committee
International Continental Scientific Drilling Program, ICDP

cc. Prof. Dr. M. Zoback

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Jan. 21, 2003.

Margaret Leinen, Assistant Director,
Directorate for Geosciences
The National Science Foundation
4201 Wilson Boulevard
Arlington, Virginia 22230, USA

Dear Dr. Leinen:

As director of the Geological Survey of Canada (GSC) - Pacific Division, I wish to express my strong support for the EarthScope initiative. Under our National Earthquake Hazards Program, we have carried out integrated studies of the structure and dynamics of the crustal margin in southwestern British Columbia using strategies and techniques that mirror those outlined in the EarthScope proposal. The success of our studies, although confined to a more limited geographical scale, convince me that the EarthScope program will lead to significant advances in the understanding of our continental structure and the nature of the dynamic processes that characterize the tectonic activity of the western margin of the North American Plate.

Although the focus of EarthScope is on the United States side of our common border, clearly geologic structures and the processes that lead to earthquakes and volcanoes are not constrained by political boundaries. EarthScope's unprecedented capabilities to study the Earth beneath our feet will also impact the Canadian geoscience community. The attendance of one of our scientists, Dr. H. Dragert, at three Plate Boundary Observatory workshops and his striking a Canadian Working Group to promote the scientific program of EarthScope within Canada, attests to our interest in this experiment. As EarthScope gets under way, we hope to cooperate where possible: either by facilitating US efforts in Canada or initiating complementary efforts on our side of the border. In particular, GPS data from existing GSC sites in Canada will be shared freely and continue to supplement studies of the Pacific-North America plate boundary as well as investigations into the true stability of "stable" North America.

In summary, I believe that EarthScope will provide a facility for the next generation of geoscientists that will have a profound impact on our knowledge of the structure and dynamics of the Earth, analogous to the impact of the Hubble Telescope on astronomical science. I strongly support this initiative and look forward to its inception with great anticipation.

Sincerely yours,

Dr. Sandy Colvine
Division Director
Geological Survey of Canada-Pacific

cc: William Prescott, President, Unavco Inc.
David Simpson, President, IRIS

Canada

Western
Science

January 23, 2003

Dr. Margaret Leinen
Assistant Director
Directorate for Geosciences
National Science Foundation
4201 Wilson Boulevard
Arlington, Virginia
U.S.A. 22230

Dear Dr Leinen,

I am sending this letter on behalf POLARIS, a consortium of Canadian Earth scientists whose interests focus on understanding the structure of the Earth's interior, the nature of earthquakes and the hazards that they pose. We have followed with interest the evolution of EARTHSCOPE over the past few years and are very pleased to hear that a proposal is now in preparation and that the project is moving closer to implementation. Four years ago, we undertook the POLARIS initiative with the aim of improving Canadian geophysical infrastructure. We are presently engaged in several ambitious projects to enhance our knowledge of Canadian seismicity and lithospheric structure. Our enthusiasm for EARTHSCOPE stems from the prospect of fruitful collaboration and/or data exchange with the USArray component of EARTHSCOPE. Our current suite of experiments will finish in 2005, in the same time frame that USArray stations are likely to be deployed along the northern United States. The realization of common scientific goals would clearly benefit from a coordinated international campaign which exploits our combined resources. We note, moreover, that POLARIS has already adopted a free-data policy, and that our data are available in near-real time on the Internet.

We would like to express our strong endorsement for the EARTHSCOPE initiative, and, in particular, USArray. Its objectives are bold and its approach is innovative. In scope, EARTHSCOPE is unprecedented in international Earth-scientific endeavours. We congratulate you and the Directorate for Geosciences at the National Science Foundation on the success of EARTHSCOPE to date and look forward to the opportunity for expanded collaboration in the near future.

Sincerely yours,

David W. Eaton

*Dr. David W. Eaton, Assoc. Professor, Dept. of Earth Sci., University of Western Ontario, London, ON, N6A 5B7*
*Rm 167 Biological and Geological Sciences Building, deaton@uwo.ca, Tel: 519-661-3190, FAX: 519-661-3198*

CICESE

Centro de Investigación Científica y de Educación Superior de Ensenada, B. C.

DIRECCION GENERAL

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January 16, 2003

Ref. No. DG/2003-019
1/2

**Margaret Leinen**
**Assistant Director**
**Directorate for Geosciences**
**National Science Foundation**
**4201 Wilson Blv.**
**Arlington Virgina 22230**

El Centro de Investigación Científica y de Educación Superior de Ensenada, Baja California, (CICESE) is a Mexican research institution which through 30 years of existence has been collaborating with many USA research institutions such as Scripps Institutions of Oceanography, Oregon State University, NASA, JPL, MIT, University Miami and many more. Together with these institutions, CICESE has many research projects in Baja California and adjacent areas. The main objectives of the projects are to understand the geological evolution tectonic processes that operate in this region and evaluate the seismic risk and geological hazard associated with abundant active faults that cross the peninsula connecting the Gulf of California with the Pacific Continental Border Line. Since the early 1970's we started a collaboration with seismologist from Scripps-IGPP installing and operate a seismic network around the Gulf of California. In the 1980's together with investigators from Oregon State University, NASA and JPL we deployed a geodesic network to study the evolution of the Pacific-North America plate, along the Gulf of California. Additionally, working with colleges from JPL and University of Miami and as well with researchers from Imperial College and MIT, we extended the geodesic network in northern Baja California, using GPS.

Baja California and California are located within the same tectonic province and are subjected to the same geological process where there is no distinction between geographic and political boundaries. Therefore, it is necessary to study the area as a whole, and we fully support projects such as the **PLATE BOUNDARY OBSERVATORY (PBO)**, which is a part of the Earthscope Proposal, to extend operations into Mexico. We would like to see more collaborations like those that have expanded the GPS network of permanent stations of California into Baja California. Currently, four permanent stations

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Ref. No. DG/2003-019
2/2

have been installed in Baja California as part of the Global Network and are being operated by investigators from the CICESE's Earth Science Division. Future collaborations such as this are critical to generate a regional network covering the entire Pacific-North America Plate Boundary.

As CICESE general Director I support both the proposal through which the PBO will extend into Baja California and the investigators who will participate is this project.

Sincerely,

Dr. Francisco J. Mendieta
General Director

cc. Dr. William H. Prescott UNAVCO inc
cc Dr. Yehuda Bock SOPAC-IGPP-UCSD
cc Dr. Enrique Gomez T., Director of the Earth Science Division, CICESE.

FJMJ/FSV/chf

New Mexico Tech

801 Leroy Place
Socorro, NM 87801-4796

Office of the President

505/835-5600 Telephone
505/835-5655 Facsimile
lchavez@admin.nmt.edu

November 5, 2002

Dr. David W. Simpson, President
Incorporated Research Institutions for Seismology
1200 New York Avenue, NW, Suite 800
Washington, DC 20005

Dear Dr. Simpson:

This is a letter of support from the New Mexico Institute of Mining and Technology (NMT) to provide facilities for EarthScope USArray, and to operate these facilities under subcontract from IRIS.

Building on a longstanding and productive relationship between NMT and IRIS, we propose, using NMT resources, to enlarge our existing IRIS/PASSCAL Instrument Center on the NMT campus to accommodate USArray Operations and Maintenance Facility. We envision that the national scientific community would be well served by ensuing stimulating, productive, and cost-effective interactions between USArray operations, other components of EarthScope, and continuing NSF and other activities at the PASSCAL Instrument Center.

We propose that NMT would provide: 1) Approximately 7,000 square feet of assembly area for USArray stations and components in the warehouse space adjacent to the existing PASSCAL facility, and 2) Approximately 5,000 square feet of new custom-designed dedicated office and laboratory space to accommodate 12 full-time professional USArray employees.

The accompanying figure shows our current draft plan for how this would be accomplished by allocating existing warehouse space and by constructing a new wing to the north of the IRIS/PASSCAL facility. The current IRIS/PASSCAL building progressed from architect's plans to occupancy in less than 10 months (between January and October 1998). We would strive for a comparable construction time frame as soon as USArray funding could be confirmed.

I understand that you are working with Drs. Rick Aster and Harold Tobin of our Department of Earth and Environmental Sciences to define the level of personnel support that will be required to operate the USArray Operations and Maintenance Facility as part of EarthScope under subaward to IRIS. As in our PASSCAL interactions, you have my commitment that NMT will continue to provide the highest quality of personnel and resources to support these new USArray operations.

New Mexico Tech is delighted to have the opportunity of partnering with the IRIS consortium in this historic effort.

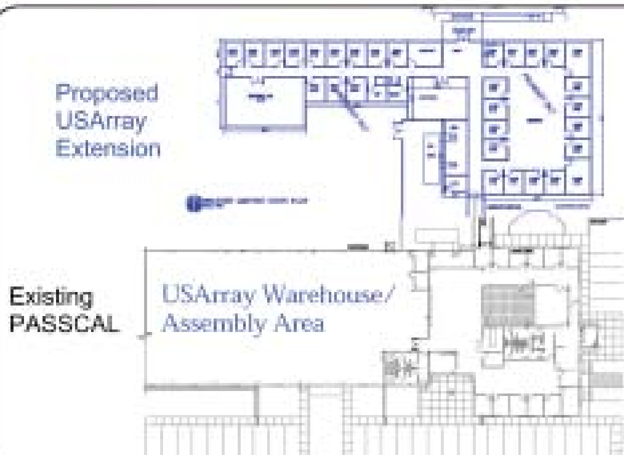
Sincerely,

Daniel H. López
President

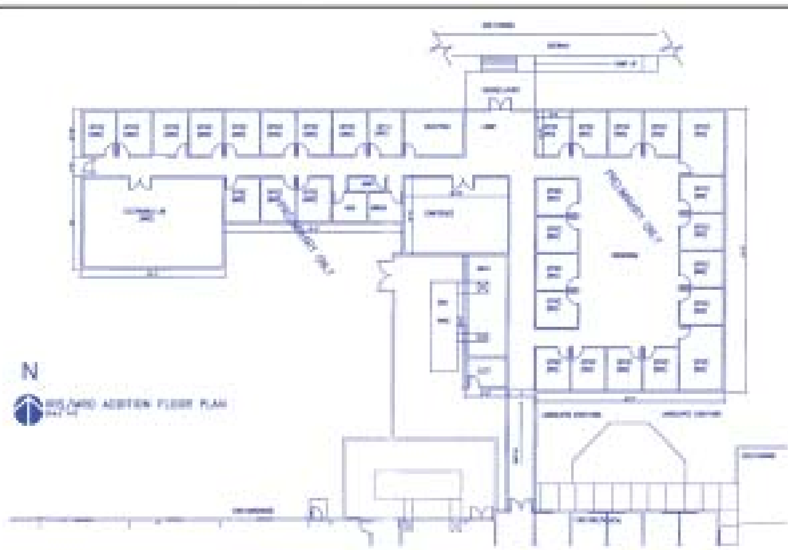
DHL/lc
Enc.

IRIS/PASSCAL Instrument Center (front view; looking west).

*Proposed extension is to the right of the photograph.*




Preliminary site plan showing location of proposed USArray extension, and warehouse/assembly area.




Proposed USArray extension (detail).

# 6. EarthScope-Related Web Links

## EarthScope General

www.earthscope.org

Internet portal for EarthScope. Contains links to background and detailed information on the four components of EarthScope, management and implementation plans, station deployment schemes, documentation on hardware, and links to meeting reports, etc.

www.earthscope.org/assets/es_proj_plan_lo.pdf
www.earthscope.org/assets/es_proj_plan_hi.pdf

The EarthScope Project Plan, published 10/2001, in both low and high-resolution .pdf formats. The report was compiled by the EarthScope Working Group, and contains background on the scientific needs, scope, budget and implementation plan for the EarthScope experiment.

www.earthscope.org/assets/es_wksp_mar2002.pdf

Report of a community workshop held in Snowbird, UT, 10/2001. Identifies scientific targets for EarthScope, the needs beyond the EarthScope Facility, and identifies the EarthScope Audience.

www.earthscope.org/assets/es_eando_lo.pdf
www.earthscope.org/assets/es_eando_hi.pdf

Report of the workshop held in Boulder, CO and Tucson, AZ, in 2002, and attended by many Earth scientists and educators. The report summarizes the workshop discussions and presents a plan for education and outreach activities in support of EarthScope and advancing public understanding of Earth.

www.nap.edu/books/0309076447/html

At the request of NSF, the NRC appointed a committee to review the science objectives and implementation planning of EarthScope. The committee concluded that EarthScope will have a substantial impact on earth science in America and worldwide. Their recommendations encompassing science questions, management, E&O and partnerships are presented in this document.

## USArray

www.earthscope.org/USArray_wtpaper.pdf

White paper developed from a workshop held in Albuquerque, NM in 1999, held to discuss the design and implementation of USArray. Prepared by the USArray Steering Committee, this document discusses the following USArray topics within the context of EarthScope: scientific challenges for USArray, define its technical and multidisciplinary components, discussed an operations and management scheme, and identifies ways in which USArray can best be used to advance Earth science research, education and outreach.

www.iris.edu

Home page for IRIS. Provides links to IRIS four main programs: the Global Seismographic Network, Data management System, Program for Array Seismological Studies of Crust and Lithosphere, and Education and Outreach. Also provides information on membership, organization and governance, news, data access tools, the Seismic Monitor and other outreach products.

www.iris.edu/manuals/DATutorial.htm

Tutorial to introduce users to the type of data archived at the IRIS Data management Center, and how to request it. A downloadable .pdf file is available at www.iris.washington.edu/manuals/acrobat/TUTORIAL/tutorial.tar which includes all the manuals for the tools mentioned in the tutorial.

www.iris.edu/cgi-bin/wilberII_page1.pl
WILBUR is the DMC's most popular web-based seismic waveform data request tool. This interface allows users to search and request data from SPYDER and FARM archives. Data are delivered in SEED, mini-SEED, SAC binary or SAC ASCII files.

www.iris.edu/SeismiQuery
SeismiQuery is a web tool that allows users to query the database for specific information about data availability as well as network, station and channel information. SeismiQuery is made up of several pre-formatted queries that focus on specific types of information and data requests. Users may also write their own queries in SQL (a primer is provided).

www.passcal.nmt.edu/iris/passcal/passcal.htm
Home page for the PASSCAL Instrument Center. Contains technical description and instructions for use of PASSCAL equipment, availability, application forms for loan of instruments, summaries of past deployments, links to PI pages.

www.anss.org
USGS site outlining the Advanced National Seismic System (ANSS), and provides catalogs, shakemaps, history of the CNS, meeting information, funding updates, and education and outreach material.

vortex.ucr.edu/emsoc
Home page for EMSOC, a national instrument facility for electromagnetic studies of the continents. Provides description of MT techniques, membership and association rules, details of equipment for loan and request procedures, deployment schedules, operating instructions, and portal to data.

## PBO

www.earthscope.org/PBOwhitepaper.pdf
A white paper providing the scientific rationale and deployment strategy for a Plate Boundary Observatory, presented by the PBO Steering Committee to the National Science Foundation. Based on input from the PBO Workshop held October 3-5, 1999.

www.earthscope.org/geo_pbo_wp.pdf
White paper contains the results of a workshop held May 22-25, 2001 on the community input to the geological component of PBO. Provides community consensus on the data required to meet Geo-PBO objectives, and a preliminary budget.

www.unavco.org
Home page for UNAVCO, Inc., with information on membership, organization and governance, news, science products and current proposals. This will be the primary operational resource for PBO, purchasing, integrating and providing oversight for installation of PBO instrumentation.

www.unavco.org/research_science/publications/proposals/pbo/pbo.html
Draft PBO proposal. Contains detailed budgets, installation strategies, monumentation designs, plans for integration with USArray facilities and stations, description of Geo-PBO, and overall management by UNAVCO, Inc.

www.unavco.ucar.edu
Home page for the UCAR UNAVCO facility in Boulder, Colorado.

www.unavco.ucar.edu/data_support/data/gsac/gsac.html
Introductory page to the GPS Seamless Archive Centers (GSAC). Contains a FAQ, list of data providers, links to retailer web clients, data structures and exchange formats, and several Perl modules.

www.unavco.ucar.edu/data_support/data/data.html

Access portal to campaign or permanent GPS stations as accessed through UNAVCO's Oracle RDBMS.

www.scign.org

Home page for SCIGN. Contains complete list and maps of contributing stations, meta-data, time-series for major networks, information on SCIGN organization and governance, news, meeting calendar.

sopac.ucsd.edu

Data processing and portal for SOPAC data archive.

www.unavco.ucar.edu/tech_highlights/socorro/socorro.html

Documents the design and installation of a prototype collocated PBO permanent GPS station with a USArray Transportable Array station. This site serves as a systems integration test platform on which alternative power and communications technologies can be examined.

quake.wr.usgs.gov/research/deformation/minipbo

Documents the installation of several prototype borehole strain-meter systems in the Bay Area. Sites to measure deformation include borehole strain-meters, seismometers and accelerometers, and Global Positioning System (GPS) receivers.

## SAFOD

www.icdp-online.de/html/sites/sanandreas/index/index.html

Home page for SAFOD. Contains general SAFOD project information, outline of pilot hole goals and science plan, daily images and progress reports posted during drilling of the pilot hole using the ICDP Drilling Information System, and information for scientists wishing to conduct research as a part of the project.

www.icdp-online.de/html/sites/sanandreas/objectives/proposal.html

A detailed discussion of the scientific rational and operation plan for SAFOD, extracted from a proposal submitted to NSF on August 30, 1998. Provides detailed information on scientific hypotheses to be tested with SAFOD (including extensive literature citations) and summary work plans from allied proposals submitted by project scientists to NSF, USGS and other agencies in 1998.

quake.wr.usgs.gov/research/parkfield/index.html

Home page for USGS Parkfield Earthquake Experiment. Contains discussion of scientific and technical background for long-term monitoring at Parkfield, recent scientific advances at Parkfield, general issues related to earthquake prediction, and relationship of SAFOD to overall Parkfield Experiment.

quake.usgs.gov/research/parkfield/overview.html

Internet portal for Parkfield data networks, including summary maps, technical discussions, results and bibliography from a variety of data networks (seismic, deformation, electromagnetic) currently being operated by the USGS and other agencies along the segment of the San Andreas Fault that last ruptured in the 1966 M=6 Parkfield earthquake.

quake.geo.berkeley.edu/hrsn/hrsn.overview.html

Home page for the Univ. California at Berkeley High Resolution Seismic Network (HRSN), an array of intermediate-depth (200-300 m) borehole seismometers installed along the Parkfield segment of the

San Andreas Fault. Includes information on sensors and telemetry, station locations and data access, and annual reports from the HRSN.

gretchen.geo.rpi.edu/roecker/
paso_home.html
Home page for the Parkfield Area Seismic Observatory (PASO). Includes discussion of installation and maintenance of the PASO instrumentation network, preliminary scientific results, and data reports.

www.eos.duke.edu/Research/seismo/
parkfield.htm
Information on Duke University's NSF-sponsored Parkfield field camp, conducted in October 2000 of as part of continuing education and outreach efforts related to SAFOD.

icdp.gfz-potsdam.de
Home page for the International Continental Scientific Drilling Program (ICDP). Provides information on scientific drilling projects from around the globe supported by the ICDP, including scientific background, data from real-time drilling information system for each project, role of participating institutions, and a searchable index of ICDP projects and personnel.

# 7. Acronyms

ACC ................. Analysis Center Coordinator
AEDS ................ US Atomic Energy Detection System
AKDA................ Alaska Deformation Array
ALSM ................ Advanced laser Swath Mapping
AMS ................. Accelerator Mass Spectrometry Laboratory
AND ................. Azimuthal Neutron Density
ANF.................. Array Network Facility
ANSS................ Advanced National Seismic System
AOF ................. Array Operations Facility
ARI .................. Academic Research Infra-structure
ASL.................. Albuquerque Seismological Laboratory
ASTER ............. Advanced Space-borne Thermal Emission and Reflection
BARD ............... Bay Area Regional Deformation Network
BINEX.............. Binary Exchange format
BLM ................. Bureau of Land Management
BOP ................. Blow Out Pressure
BSM ................. Borehole Strain Meters
BUD ................. Buffer for Uniform Data
CAMS............... Center for Accelerator Mass Spectrometry
CGPS ............... Continuous GPS
CORBA ............ Common Object Request Broker Architecture
DAAC............... Distributed Active Archive Center
DCN ................. Data Concentrator Node
DDBM .............. Deep Drilled Braced Monument
DHI .................. Data Handling Interface
DIS................... Drilling Information System
DMC................. Data Management Center
DMS ................. Data Management System
DOE ................. Department of Energy
DOSECC.......... Drilling, Observation and Sampling of the Earth's Continental Crust
DST.................. Drill Stem Test
E&O ................. Education and Outreach
EBAR ............... Eastern Basin and Range Network
EFEC ............... EarthScope Facilities Executive Committee
ESEC ............... EarthScope Science and Education Committee
FARM ............... Fast Access Recovery Method
GDS ................. Gyroscopic Directional Survey
GeoPBO ........... Geologic and paleoseismological component of PBO
GPS.................. Global Positioning System
GSAC............... GPS Seamless Archive Center

GSN .................. Global Seismographic Network
HRSN ................ U.C. Berkeley High Resolution Seismic Network
IAC ................... Individual Analysis Centers
ICDP ................. International Continental Drilling Program
IDD ................... Internet Data Distribution
IDL.................... Interface Description Language
IGS ................... International GPS Service
IMS ................... International Monitoring System
InSAR ............... Interferometric Synthetic Aperture Radar
IRIS................... Incorporated Research Institutions for Seismology
KTB................... Kontinentales Tiefbohrung
LDM .................. Local Data Manager
LIDAR............... Light Detection and Ranging
LSM .................. Laser Strain Meters
LWD.................. Logging While Drilling
MD .................... Measured Depth
MEMS ............... Microelectromechanical Systems
MREFC ............. Major Research Equipment and Facilities Construction
MRI ................... Major Research Infrastructure
MT .................... Magneto-telluric
MWD ................ Measurements While Drilling
NASA ................ National Aeronautics and Space Administration
NBAR ................ Northern Basin and Range Network
NEHRP.............. National Earthquake Hazards Reduction Program
NEIC ................. National Earthquake Information Center
NOSAMS........... National Ocean Sciences Accelerator Mass Spectrometry Facility
NSF ................... National Science Foundation
NSN................... National Seismic Network
NSRL ................ Nuclear Structure Research Laboratory
O&M ................. Operations and Maintenance
ODP .................. Ocean Drilling Program
PANGA.............. Pacific Northwest Geodetic Array
PASO ................ Parkfield Area Seismic Observatory
PASSCAL .......... Program for Array Seismic Studies of the Continental Lithosphere
PBO .................. Plate Boundary Observatory
PBO-AC ............ PBO Analysis Center
POLARIS .......... Portable Observatories for Lithospheric Analysis and Research Investigating Seismicity
PRIME............... Purdue Rare Isotope Measurement Laboratory
QC .................... Quality Control
R&RA................ Research and Related Activities
RAB .................. Resistivity At Bit
RAID ................. Redundant Array of Independent Disks
RFP ................... Request For Proposals
RINEX............... Receiver Independent Exchange format

RTDN................ Real-Time Data Node
SAF................... San Andreas Fault
SAFOD.............. San Andreas Fault Observatory at Depth
SBAR................ Southern Basin and Range Network
SCEC................ Southern California Earthquake Center
SCIGN.............. Southern California Integrated Geodetic Network
SDBM................ Short Drilled Braced Monument
SEED................ Standard for the Exchange of Earthquake Data
SEG-Y............... Society of Geophysics - Y format
SINEX............... Solution Independent Exchange format
SIO/IGPP.......... Scripps Institute of Oceanography/Institute of Geophysics and Planetary Physics
SNR................... Signal to Noise Ratio
SOPAC.............. Scripps Orbit and Permanent Array Center
TCP/IP.............. Transmission Control Protocol/Internet Protocol
TD..................... Total Depth
TVD.................. Total Vertical Depth
UNAVCO........... University Navstar Consortium
USArray............ United States Seismic Array
USGS................ United States Geological Survey
USI.................... Ultrasonic Cement Imaging
VSAT................ Very Small Aperture Terminal
VSP................... Vertical Seismic Profile
WILBER............ Web Interface to Lookup Big Events for Retrieval
XML.................. eXtended Markup Language

# Part IV. Supporting Documentation

## Biographical Sketches, NSF 1030 Forms, Current and Pending Support, and Institutional Resources

1. IRIS - USArray
2. PBO - UNAVCO, Inc.
3. SAFOD - Stanford
4. IRIS - EarthScope Facility Office

earth scope

WWW.EARTHSCOPE.ORG