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 08-1		FOR NSF USE ONLY
NSF 04-512	11/15/08	NSF PROPOSAL NUMBER
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EAR - CONTINENTAL DYNAMICS PROGRAM		

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Stanford University	651 Serra Street, Room 220 STANFORD, CA 94305-7211
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IS AWARDEE ORGANIZATION (Check All That Apply) (See GPG II.C For Definitions) ☐ SMALL BUSINESS ☐ FOR-PROFIT ORGANIZATION ☐ MINORITY BUSINESS ☐ WOMAN-OWNED BUSINESS ☐ IF THIS IS A PRELIMINARY PROPOSAL THEN CHECK HERE

TITLE OF PROPOSED PROJECT **Test of 3C recording with 1C instruments in association with High Lava Plains field program, for crustal shear-wave velocity, anisotropy, and lithology.**

REQUESTED AMOUNT	PROPOSED DURATION (1-60 MONTHS)	REQUESTED STARTING DATE	SHOW RELATED PRELIMINARY PROPOSAL NO. IF APPLICABLE
$ 49,976	12 months	07/01/08	

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

- ☐ BEGINNING INVESTIGATOR (GPG I.G.2)
- ☐ DISCLOSURE OF LOBBYING ACTIVITIES (GPG II.C)
- ☐ PROPRIETARY & PRIVILEGED INFORMATION (GPG I.D, II.C.1.d)
- ☐ HISTORIC PLACES (GPG II.C.2.j)
- ☒ SMALL GRANT FOR EXPLOR. RESEARCH (SGER) (GPG II.D.1)
- ☐ VERTEBRATE ANIMALS (GPG II.D.5) IACUC App. Date ______ PHS Animal Welfare Assurance Number ______
- ☐ HUMAN SUBJECTS (GPG II.D.6) Human Subjects Assurance Number ______ Exemption Subsection ______ or IRB App. Date ______
- ☐ INTERNATIONAL COOPERATIVE ACTIVITIES: COUNTRY/COUNTRIES INVOLVED (GPG II.C.2.j) ______
- ☐ HIGH RESOLUTION GRAPHICS/OTHER GRAPHICS WHERE EXACT COLOR REPRESENTATION IS REQUIRED FOR PROPER INTERPRETATION (GPG I.G.1)

PI/PD DEPARTMENT	PI/PD POSTAL ADDRESS
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Project Summary

Stanford University and IRIS (Incorporated Research Institutions for Seismology) will collaborate to utilize the "Texan" RT-125 recording facility operated by PASSCAL for three-component (3C) recording of a series of borehole detonations planned for September 2008 during the funded NSF-CD-EAR program "High Lava Plains" (HLP) program (formally "Collaborative Research: Understanding the Causes of Continental Intraplate Tectonomagmatism: A Case Study in the Pacific Northwest"). We will collect data of scientific interest to the funded CD program, but we also aim to demonstrate the technical feasibility of using three one-component (1C) recorders in parallel at a single site to record 3C data. Success in the latter aim will open a path to fuller utilization of the PASSCAL and Earthscope Texan recording facility, more complete recording of the waveforms generated by NSF-funded controlled-source experiments, and extraction of additional scientific results from future experiments.

We request funding to deploy these equipment in Oregon. If this SGER proposal is funded, a Stanford graduate student will process the resulting data at no charge to NSF during academic 2008-2009. If this SGER proposal is funded, IRIS will arrange fabrication of 300 "harnesses" to connect 900 existing 1C recorders (Texans) in groups of 3 to 300 existing 3C 4.5 Hz geophones, at no charge to this proposal.

This is an SGER proposal because of the urgency of our request: the funded CD experiment on which we are piggybacking takes place in September 2008, before any regular proposal could be reviewed and funded. Although the HLP controlled-source experiment was funded in 2006, that experiment was designed to utilize the entire PASSCAL Texan pool. Additional Texans needed for this 3C experiment could only be committed to CD-funded science after proposals to utilize these instruments for Earthscope-funded programs were declined in 12/07. Additionally, a 4-month lead-time is required for PASSCAL fabricate the 300 three-Texan-to-one-geophone "harnesses" that S-wave recording will require, so that an urgent approval is needed if we are to be ready for recording in September 2008.

This is also an SGER proposal because it is exploratory and innovative, to use an instrument facility designed only for single-component recording, and to operate it to acquire three-component data. Our work represents a new approach to a research topic (crustal S-wave seismology) that has languished due to lack of available equipment, and is likely to catalyze change in the way the PASSCAL facility and the Flexarray component of EarthScope's USArray are utilized. Building the necessary connecting "harnesses" and implementation of a successful field test will allow acceptance and adoption of this methodology by the community.

We will collect high-resolution (100 m spacing, 1 ms temporal sampling) P- and S-wave profiles at multiple azimuths in south-eastern Oregon. We will process the data to make any necessary time-corrections to permit joint analysis of 3C data recorded on three separate 1C instruments, then sub-sample and analyse the data for anisotropy and S-wave velocity, utilising the high spatial resolution. We seek to measure additional crustal elastic properties and thereby demonstrate an improved ability to interpret crustal lithology and tectonic history. Although some preliminary observations of crustal anisotropy have been made in the USA it has not normally been possible to localize their depth extent, because passive observations are typically made at far lower frequencies (coarser resolution) than active-source measurements. Hence the need to make 3C active-source measurements to complement the now standard 3C passive-source receiver-function methods. If we are successful, our results, in conjunction with the existing CD-funded explosive-source refraction velocity model and receiver function images, will help estimate the relative roles of magmatic intrusions and crustal flow in maintaining crustal thickness in SE Oregon.

Broader Impacts:

We will test a method to use existing equipment to collect 3C data, thereby impacting costs and strategies for future instrument purchases funded by NSF. The harnesses built for this project will be available for future projects, allowing acquisition of seismic information not yet routinely acquired. We will train Stanford undergraduates in field geophysics methods during our experiment.

Project Description - Project Motivation

PASSCAL and the Earthscope FlexArray represent major infrastructure investments by NSF to enable the seismological community to carry out its research. A significant gap in the current facility is instrumentation to record full-waveform controlled-source data: whereas the modern passive-seismic experiment typically utilizes a few tens of three-component sensors, the active-source community has focused on increasing the density of recording by deploying typically more than a thousand sensors in each experiment. This led to a conscious decision by PASSCAL in the 90s to purchase a cheap single-channel recorder with a single vertical geophone (the Reftek RT-125 "Texan" recorder), a decision that was followed by Earthscope in the design of its FlexArray. But just as the frontier in teleseismic analysis is in deriving ever more sophisticated material properties from 3C earthquake recordings, so an open scientific frontier is developing similar recordings at higher frequencies. Although our reliance on explosive sources means that we cannot routinely promise to generate S-waves, at the present time by not providing the opportunity to record them we are limiting the science we can do if S-waves are generated. By building additional connectors we can utilize the existing 1C Texan recorders with existing Mark Products 4.5 Hz 3C geophones. PASSCAL has built a prototype harness, and is able to arrange fabrication of 300 harnesses prior to the September 2008 experiment.

Because of the worldwide paucity of suitable equipment, a review by Meissner et al. (2006) only identified three examples of credible crustal shear-wave anisotropy experiments (two in Germany, one in FSU) (Figure 1a), to which we may add one in Nevada (Figure 1b) (Satarugsa & Johnson, 2000) and one offshore-onshore experiment in Greenland (Clement et al., 1994). Thus although basic analysis methodologies exist, we have barely begun to understand what data of this type may offer in understanding the crust. The one US study shows the difficulties faced by investigators in this area thus far: Satarugsa & Johnson (2000) used five different recording systems, and five different geophone types, in their experiment, and were unable to deploy more than 86 3C recorders in a single profile. We hope to deploy 420 3C recorders, a five-fold increase.

Project Description – Work Plan

Jim Fowler and Marcos Alvarez at PASSCAL Instrument Center have designed a "harness" to connect 3 Texans to 1 Mark L28 3C geophone, and – if NSF funds this SGER request to utilise such equipment – will arrange for fabrication of 300 of the harnesses. The 14-week build time, plus time for contracting, shipping and testing means that a positive response to this proposal is required in early April to allow readiness for the early September planned experiment. The Earthscope FlexArray also includes 120 RT-130 instruments that are designed to use existing 3C L-22 seismometers, and these will be deployed simultaneously to increase the volume of S-wave data recorded and to provide a quality check on our new approach to recording 3C data with 1C Texans.

Randy Keller (OU) and Steve Harder (UTEP) are funded to deploy all the PASSCAL Texans at c. 800m spacing along two profiles intersecting near Burns, OR, and to detonate 13 large seismic shots in early September 2008. This proposal seeks funds to ship 1320 Earthscope FlexArray Texans to Burns, OR, at the same time, together with 120 FlexArray RT-130 3C recorders and L-22 seismometers. We also request funds for 8 students in 4 deployment vehicles to deploy the equipment over 3 days; assist with shot firing and shot-hole remediation for two intervening days, and retrieve the equipment over 3 days, total 8 field days plus 2 days travel. One additional project manager (Klemperer) and one additional PASSCAL technician will be required in Burns during the project. We emphasize that this work plan is cost effective because the CD program has already funded the shot-hole drilling and explosive purchase, so this SGER experiment will leverage on the much larger overall proposal. Following the fieldwork, a Stanford graduate student funded by a Stanford departmental fellowship will work with PASSCAL staff to format the data into source gathers, and begin analysis.

We have designed our experiment within the limitation of the existing equipment resource:

300 3C 4.5Hz geophones, requiring 900 Texan recorders; leaving an additional 800 Texans in the FlexArray pool. Based on study of the data recorded by Satarugsa & Johnson (2000), and by Rabbel & Lüschen (1996) and Rabbel et al. (1998), we believe 100m is an appropriate instrument spacing to give us reasonable assurance of ability to correlate split phases from trace to trace. 300 3C sensors, plus 120 RT-130 3 at 100-m spacing, will instrument 42km of profile at 100m spacing. Similarly, we note that the previous experiments recorded the best shear-wave data at offsets from 10 to 100 km, and we designed an experiment to capture as many ray-paths as possible at these offsets, therefore based at the crossing point of the two wide-angle profiles (Figure 2). We will split the recorders into two separate 21-km segments of 210 sensors each; because these segments are separated by about 20 km from each other, and by about 20 km from the next nearest shot-points, we will also deploy 420 single instruments (in conjunction with the already planned instruments to be deployed by Keller and Harder) at 100-m spacing to link the S-wave recording to the shot-points, so that we collect single-fold in-line reflection data with offsets no greater than 50 km to provide structural context for our 3C data (and of course, additional geological information about the Harney Basin and Caldera in the central part of the main north-south HLP refraction profile). Our 3C recorders (Figure 2) will each record 4 in-line shots at offsets of c. 20 to 100 km, and 4 shots at an approximately orthogonal azimuth at offsets of c. 60 to 120 km. Each segment will also record 5 longer-offset sources, which may not provide useful S-wave data – we shall see – but will certainly provide additional ray-paths for Keller's primary refraction interpretation of the two profiles.

Harder (UTEP) has already located all the shotholes and contracted drillers and loaders. Keller has already located an instrument center capable of handling 2500 Texans, and programming them over 3 days. Keller will work with Klemperer to provide target deployment positions of all the Texans, and road/deployment logs for the Stanford students, based on his previous scouting of the profiles. Klemperer will recruit 1 graduate student and seven undergraduates and travel with them to Oregon for the 8-day survey in September, in 4 rented deployment vehicles (panel vans). One additional PASSCAL tech will be required to staff the additional 1320 Texans and 120 RT-130 with the same program as all the other Texans on the main refraction profiles, though with 1ms sample rate for the 3C instruments to allow for correction of timing offsets between channels, if necessary.

Following the experiment we will work with IRIS/PASSCAL to prepare shot gathers for all instruments, and carry out checks of the time stability of the groups of three instruments by cross-correlating first-arrivals on the three components. This step is not necessary on traditional purpose-built 3C instruments, and may or may not be necessary in this application of the Texan 1C instruments. We will then carry out additional pre-processing following Satarugsa & Johnson (2000): spherical-divergence corrections and normal-moveout corrections based on $Vp/\sqrt{3}$, corresponding to s of 0.25; rotation of the horizontal components (recorded as magnetic N and E) into true radial and transverse components (SV and SH) relative to the average azimuths of the profile segments; bandpass filters, f-x deconvolution, and f-k filters to enhance S/N ratio. Crustal velocities will be derived by forward and inverse modeling using now-standard 2-D ray-tracing and ray-inversion codes (Zelt and Smith, 1992), by Keller's group at OU for P-arrivals and by Stanford/OU for S-waves. Poisson's ratios will be derived as the ratio of these velocity models. Presuming that we see shear-wave splitting (fast and slow waves on the SV and SH components – Figure 1), we will carry out cross-correlation (Bowman and Ando, 1987) and particle-motion (hodogram) analyses (Crampin, 1985) to determine the polarization direction. Because Sg (Figure 1a) propagates sub-horizontally but SmS (Figure 1b) and intra-crustal reflections propagate sub-vertically we have the opportunity to explore all orientations of anisotropy. A low degree of splitting in the lower crust will support the view that this segment of crust is Cenozoic magmatic additions. A high degree of anisotropy would support a pre-existing crust deformed by continental margin processes. These analyses will be carried out by a Stanford graduate student supported by a university fellowship at no cost to NSF, in the twelve months following the field work.

Project Description – Technical & Scientific Results Envisioned

The work plan above will provide a full test of the utility of the PASSCAL and Earthscope Texan facilities for 3C recording as well as their design 1C capability. We anticipate one full scientific paper about the S-wave results and geological implications for crustal evolution of the High Lava Plains, and possibly also a short technical note on the new equipment and recording methodology.

Broader Impacts

This project will exploit synergies between NSF's existing PASSCAL equipment facility, and newly completed Earthscope MRE, and if successful will have technical implications for both programs. Even if only minimally successful in a technical sense, the project will yield valuable additional seismic ray-paths for the HLP controlled-source experiment, doubling the total number of seismograms recorded in that experiment.

This project will include seven Stanford undergraduates on the field crew (from geophysics, geology and engineering, likely including women and possibly minorities), who will be exposed to research in the field and then to data processing at Stanford. Klemperer has a record of involving undergraduates in his seismic field programs as their first introduction to research. He has recently funded three undergraduates (two physics majors, one engineering major; two of the three are female) through NSF REU grants, two of whom have now published peer-reviewed papers on their results from previous experiments, and all of whom have now been inspired to attend graduate school.

Results from Prior NSF Support

SIMON KLEMPERER EAR-0208475 (Continental Dynamics) — $784,499 9/02-8/08

Collaborative Research: US-EAGLE (Ethiopia-Afar Grand Lithospheric Experiment): Modification of Lithospheric Structure During Continental Break-up

Our international Ethiopia-US-UK team collected new active and passive seismic data to image the Main Ethiopian Rift as it approaches the transition from rifting to spreading. Multiple data-analysis methods at Stanford (wide-angle seismic tomography, SKS-splitting, and combined surface-wave/receiver-function velocity analysis, provide observations of a narrow zone of rifting in the mantle, with a minor signature of local melting, and an equally narrow zone in which the old continental crust is affected by rifting, in which we image en-echelon gabbroic intrusions occupying the middle crust, show how the rifting focuses at continental break-up, but does not propagate smoothly or continuously along a single rift axis (Abdelsalam et al., 2004; Bendick et al., 2006; Gashawbeza et al., 2004; Keranen et al., 2004; Keranen & Klemperer, 2008; Klemperer & Cash, 2007; Les et al., 2004; Maguire et al., 2006; Walker et al., 2004; plus numerous papers not co-authored by Klemperer and abstracts at national meetings (most recently Gashawbeza et al., 2007; Keranen et al., 2007). Stanford results will appear in three PhD theses (Gashawbeza (tentatively 08/08, Keranen (03/08), Walker (01/04). Two female US undergraduates (Cash, Les) received their first research experience; both have now entered graduate school. The experiment was widely reported (BBC and print media). Numerous Ethiopian scientists participated and received training during our fieldwork, and in one 3-month study visit to Stanford. All data have been archived with IRIS-DMC.

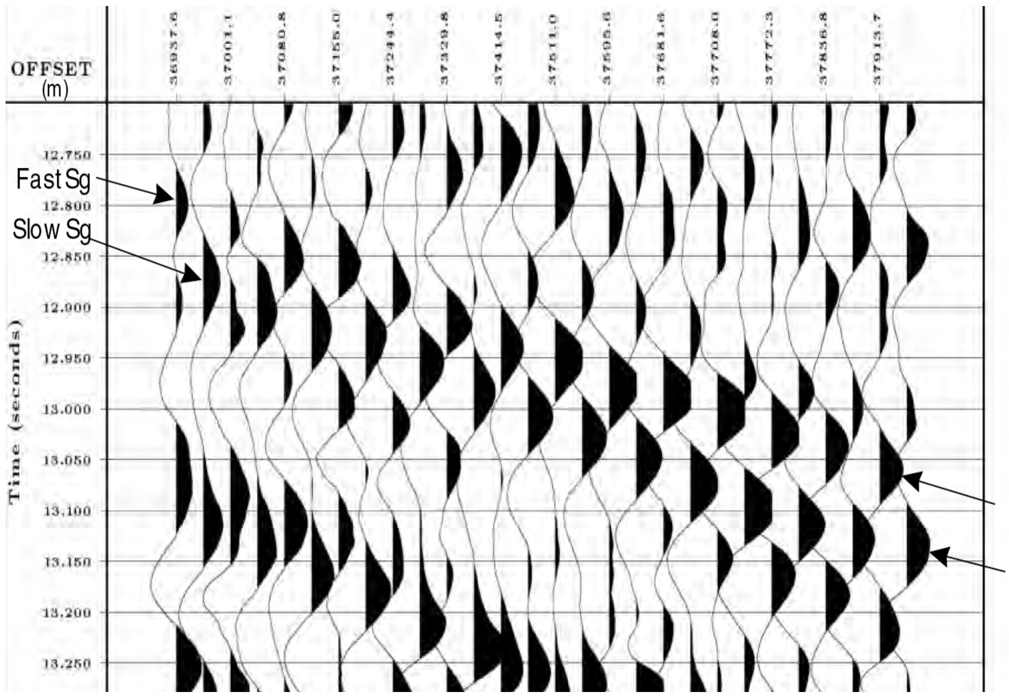
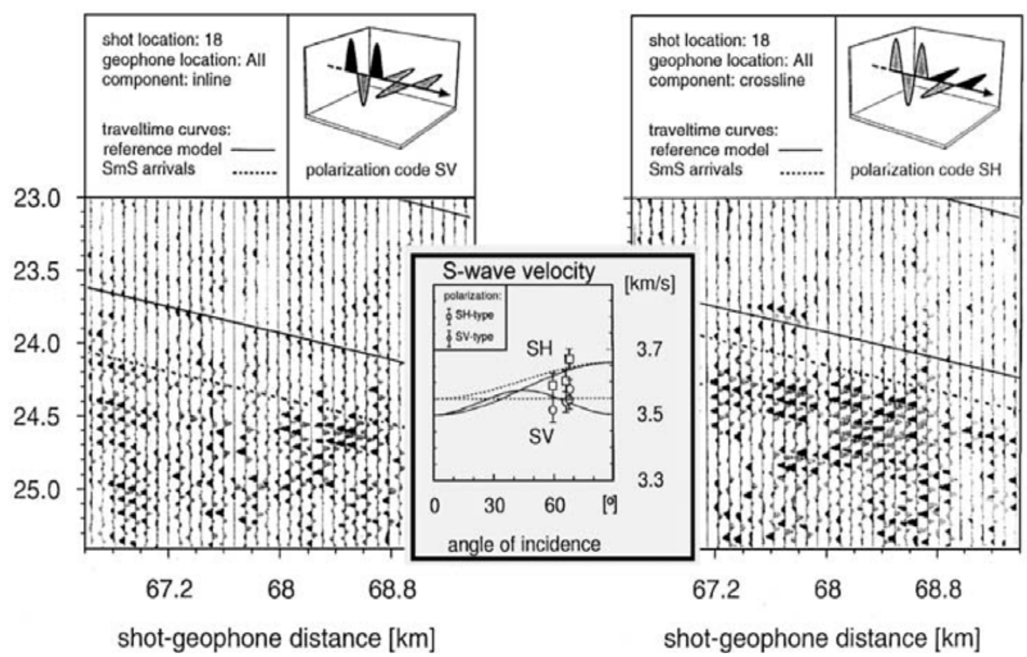


Figure 1a:
anisotropy of upper-crustal refraction at offsets of 35-40km, Ruby Range, Nevada, probably indicating aligned cracks in upper crust
(Satarugsa & Johnson, 2000)

Figure 1b:
anisotropy of Moho reflection at offsets 65-70km, Urach, SW Germany: SH-waves arriving 250 ms earlier than SV-waves, probably indicating flow in the lower crust
(Rabbel et al., 1998; Meissner et al., 2006)



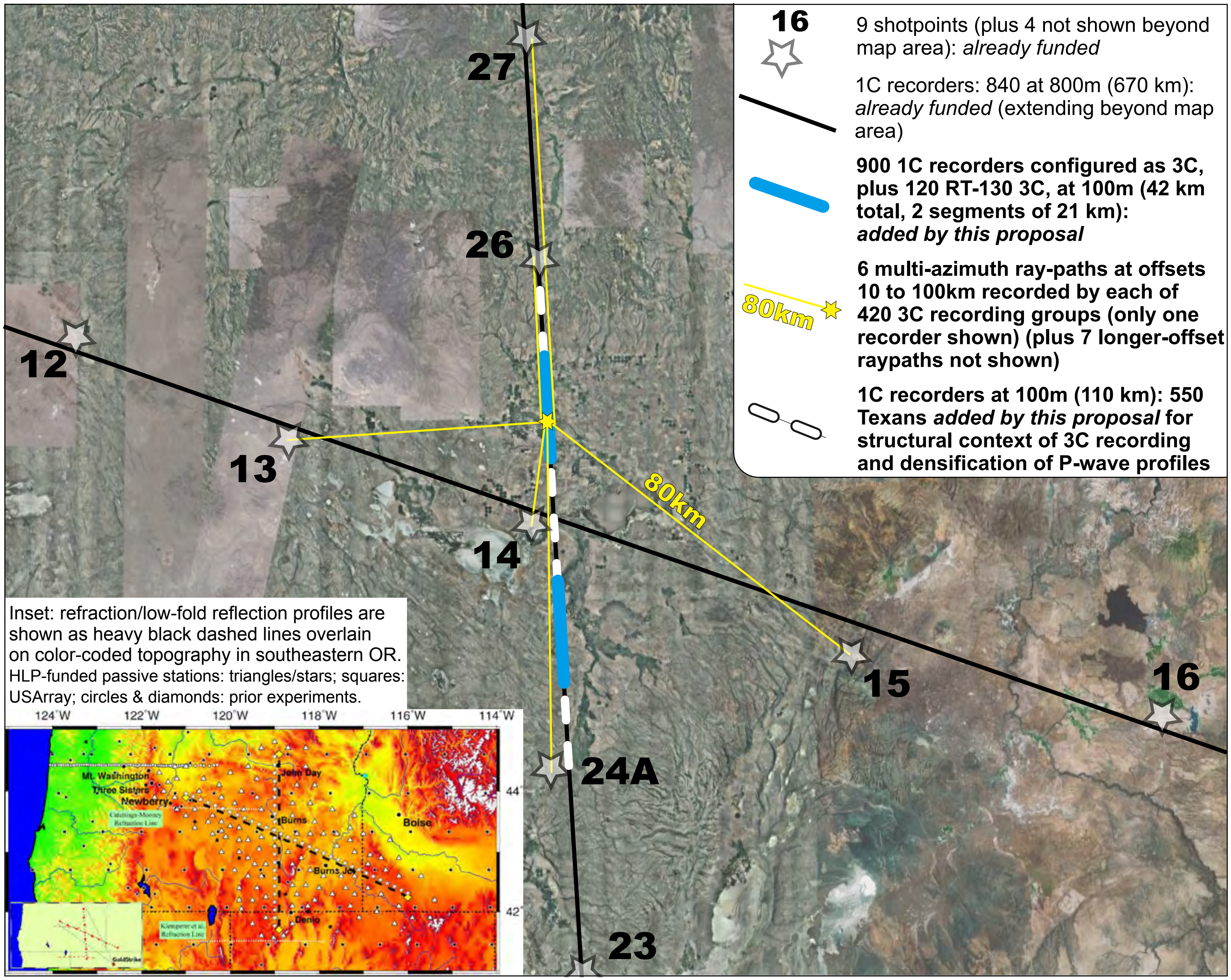


Figure 2 : proposed recording geometry within context of funded CD HLP proposal

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BIOGRAPHICAL SKETCH

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EDUCATION

1980 B.A. Natural Sciences (Mineralogy & Petrology), Cambridge University
1985 Ph.D. Geophysics, Cornell University (advisors: Jack Oliver, L. Brown, D. Karig)

PROFESSIONAL EXPERIENCE

1985 Research Associate, Consortium for Continental Reflection Profiling (COCORP), Cornell University (advisor: Jack Oliver)
1985-87 Research Associate, British Institutions' Reflection Profiling Syndicate (BIRPS), Cambridge University (mentor: Drum Matthews)
1987-90 Royal Society University Research Fellow, Cambridge University
1990 on Professor, formerly Associate Professor, of Geophysics, Stanford University
Professor, formerly Associate Professor (by courtesy), Geological and Environmental Sciences
Director, IRIS-PASSCAL Instrument Center at Stanford, 1992-1998
Director, Stanford Earth Sciences GIS Laboratory, 1994-1999
1999 on Visiting Professor of Geology, Royal Holloway University of London

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*advisee of Klemperer. **Over 100 additional publications.**

Stanford University Budget Justification

A, B, C. PERSONNEL
One week salary support is requested for PI Klemperer to participate off-campus in the seismic fieldwork and as token support during supervision of the data analysis throughout 2008-2009. The budgeted salary amount consists of the direct effort for the project plus 8.8% vacation accrual/disability sick leave (DSL) for exempt employees and 7.4% for non-exempt employees, per our negotiated rate agreement with the Office of Naval Research. These amounts do not exceed total salary. The vacation accrual/DSL rates will be charged at the time of the salary expenditure. No net salary will be charged when the employee is on vacation, disability or worker's compensation. We request no support for the graduate student who will work up these data and who will be funded by an internal fellowship. The fringe benefit cost is 27.9% for faculty.

D. EQUIPMENT
None requested.

E. TRAVEL
Domestic: Field work:
We budget rental of 4 deployment vans at $50/day and $0.32 per mile for 10 days and 1800 miles, plus gas at 12mpg and $3.50/mile; plus one personal vehicle from Stanford to Burns, OR, plus one RT air fare from Socorro, NM to Boise, ID, and rental car, for the PASSCAL technician. We budget 6 motel rooms for 8 students, 1 technician and 1 field manager (Klemperer) at $80/day for 9 days, and food at $35/day.

F. PARTICIPANT SUPPORT
None requested.

G.1. MATERIALS AND SUPPLIES
We budget shipping of equipment from Sonorro, NM to Burns, OR at $1.20/kg each way, for 1450 Texan seismographs@2kg, 120 RT-130@9kg, 120 L-22 seismometers@6.25kg, 300 3C L-28@1.5kg and 450 1C phones@0.5kg, plus 200kg computers and miscellaneous supplies, total 4215kg. We budget 2 D-cells for each of 1450 Texans at $1/cell ($2900), gel-cells for 120 RT-130 at $13/cell ($1560), miscellaneous supplies for each of 970 deployment sites (bags, flagging, stakes) at $1/site, and miscellaneous supplies for 4 deployment teams (hand-tools, etc.) at $40/team. All materials and supplies will be utilized off-campus.

I. INDIRECT COSTS
The standard Stanford University overhead rates of 30% off-campus are applied to all costs.

J. TOTAL DIRECT & INDIRECT COSTS
We request a one-year budget of $49,976.