Foundations of Portable Seismology: The Program for Array Seismic Studies of the Continental Lithosphere (IRIS-PASSCAL)

Anne Sheehan, University of Colorado Boulder

IRIS Workshop 2018

Outline

- Field Seismology Before PASSCAL
- Origins of PASSCAL
- Early PASSCAL experiments
- PASSCAL Science (a small sampling!)

Field Seismology in the 1980's –
still using helicorders for some experiments

Utah 1983, Denis Hatzfeld (*Craig Jones Photo*)

Sierra Nevada, CA, 1988, Anne Sheehan (*Craig Jones Photo*)

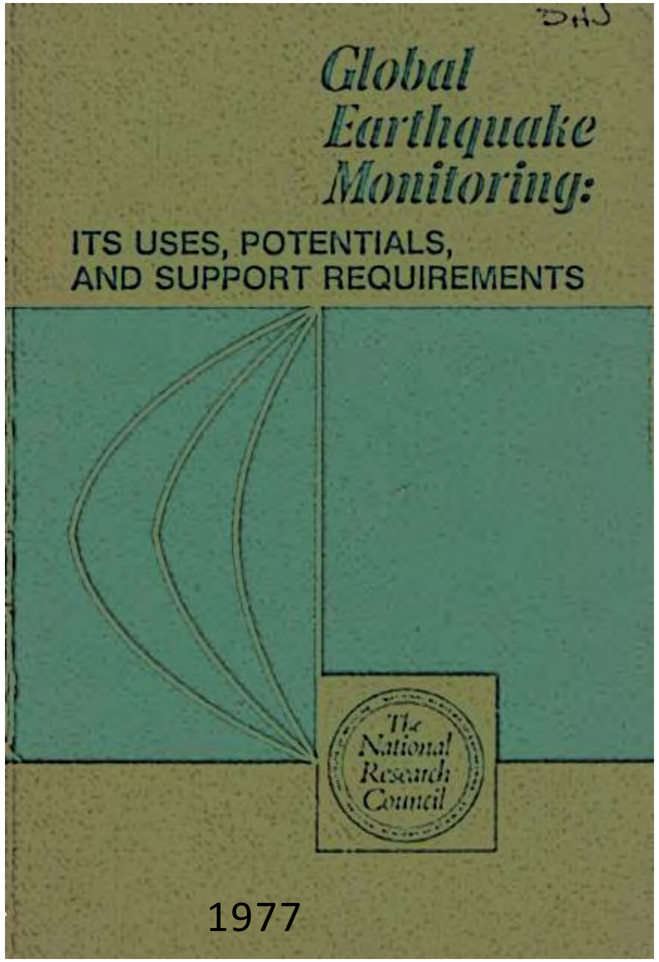
Sierra Nevada 1988, Tom Fairbanks (*Craig Jones Photo*)

Photo credit: Craig Jones

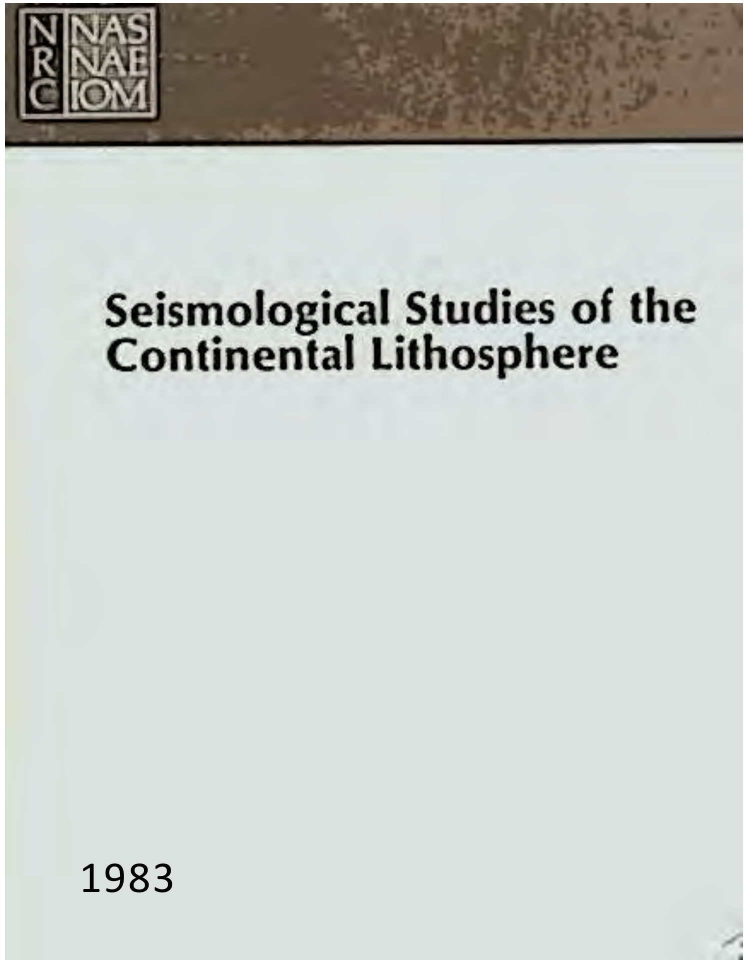
Photo credit: Craig Jones

Field Seismology in the 1980's –
Assortment of digital recording
Varying formats
Data not usually shared, archiving ad hoc
Limited recording capacity (event triggered)

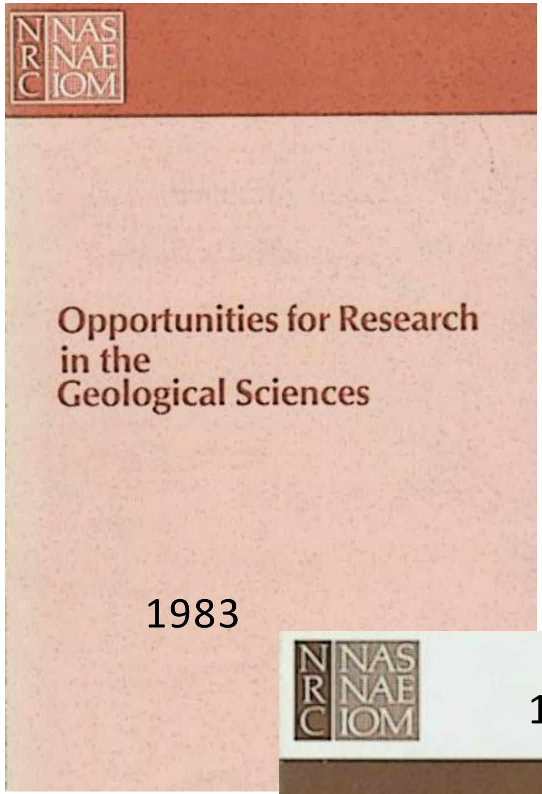
Late 1970's and Early 1980's - Reports from the National Academy helped lead to the development of the IRIS Consortium



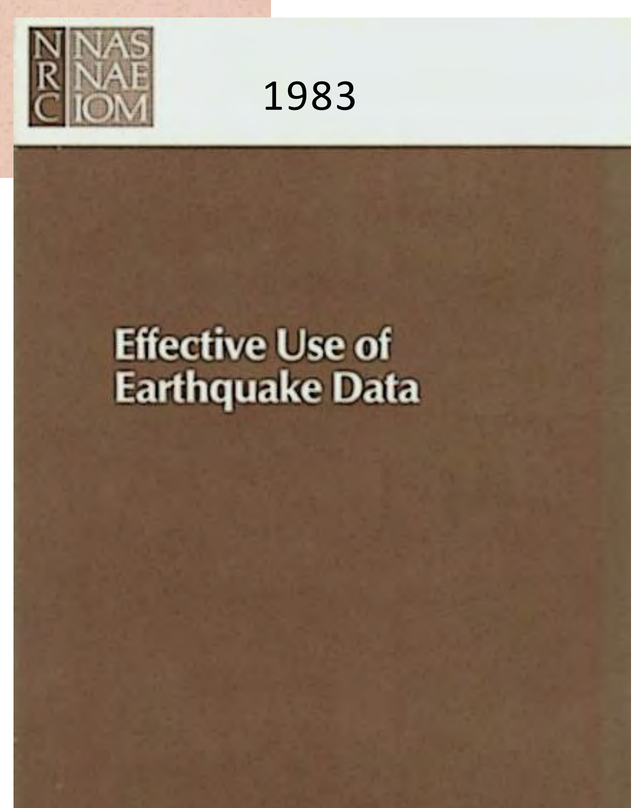
1977



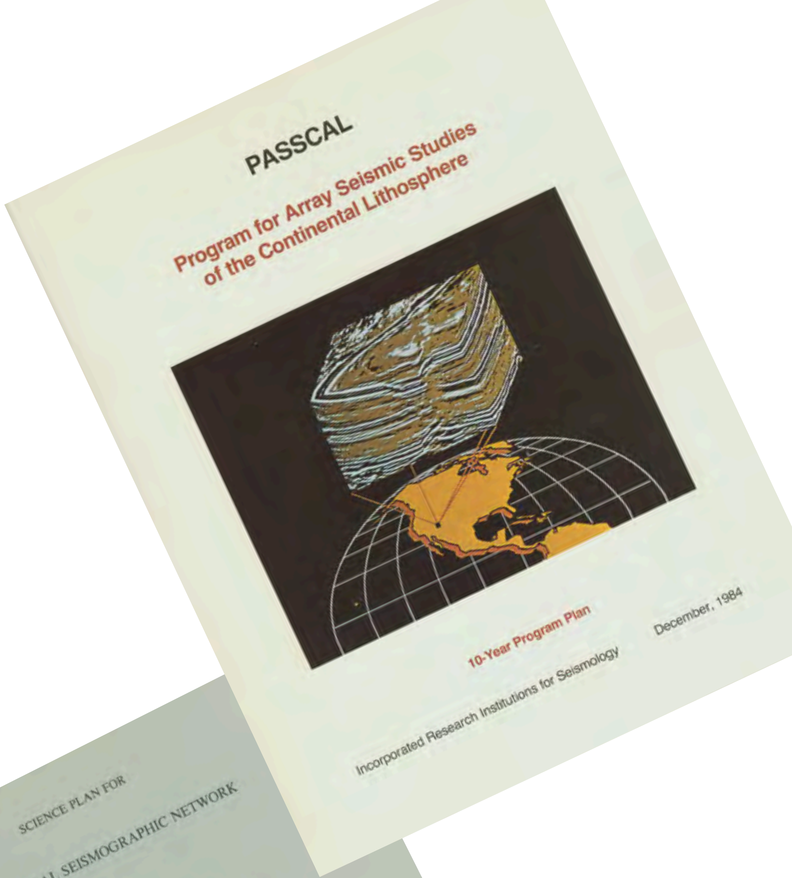
1983

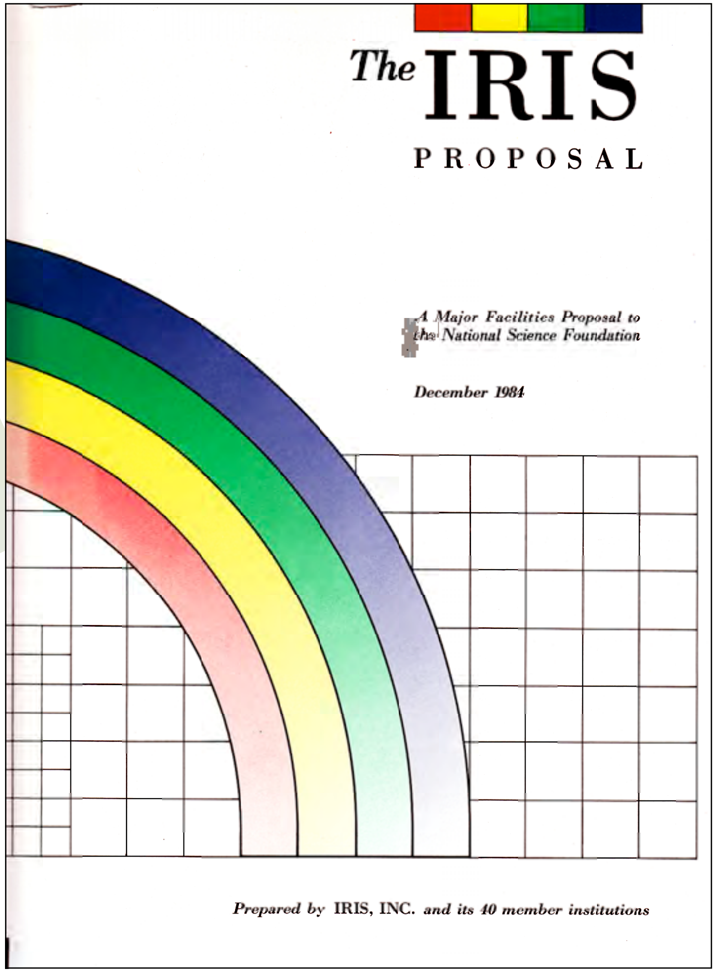


1983



1983





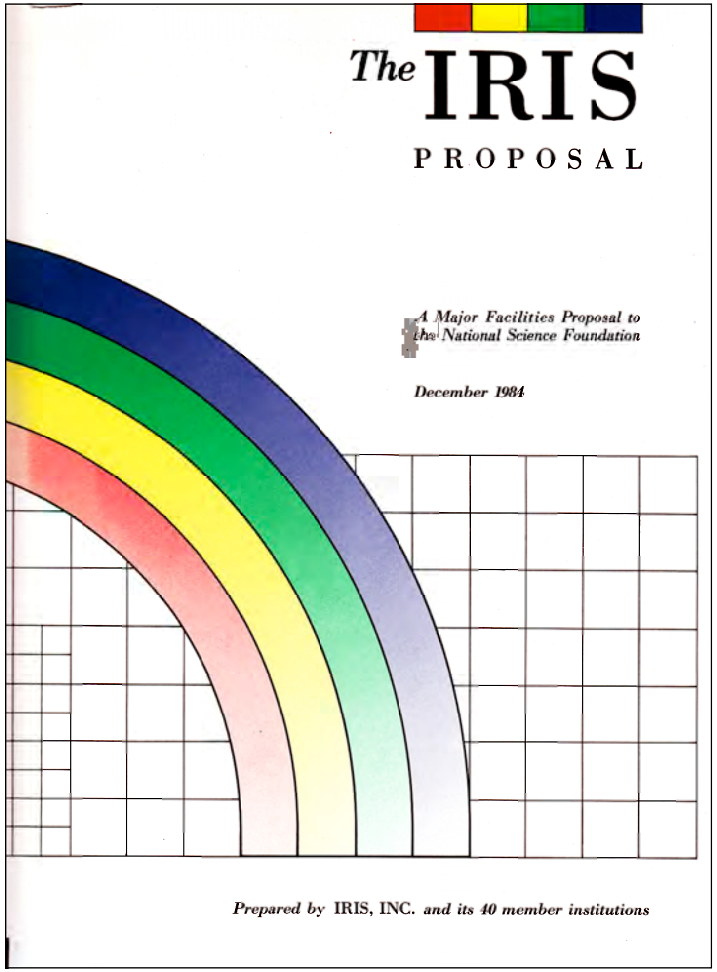
The Original IRIS Proposal to NSF (the 'Rainbow Proposal')

December, 1984

1984 IRIS 'Rainbow' Proposal

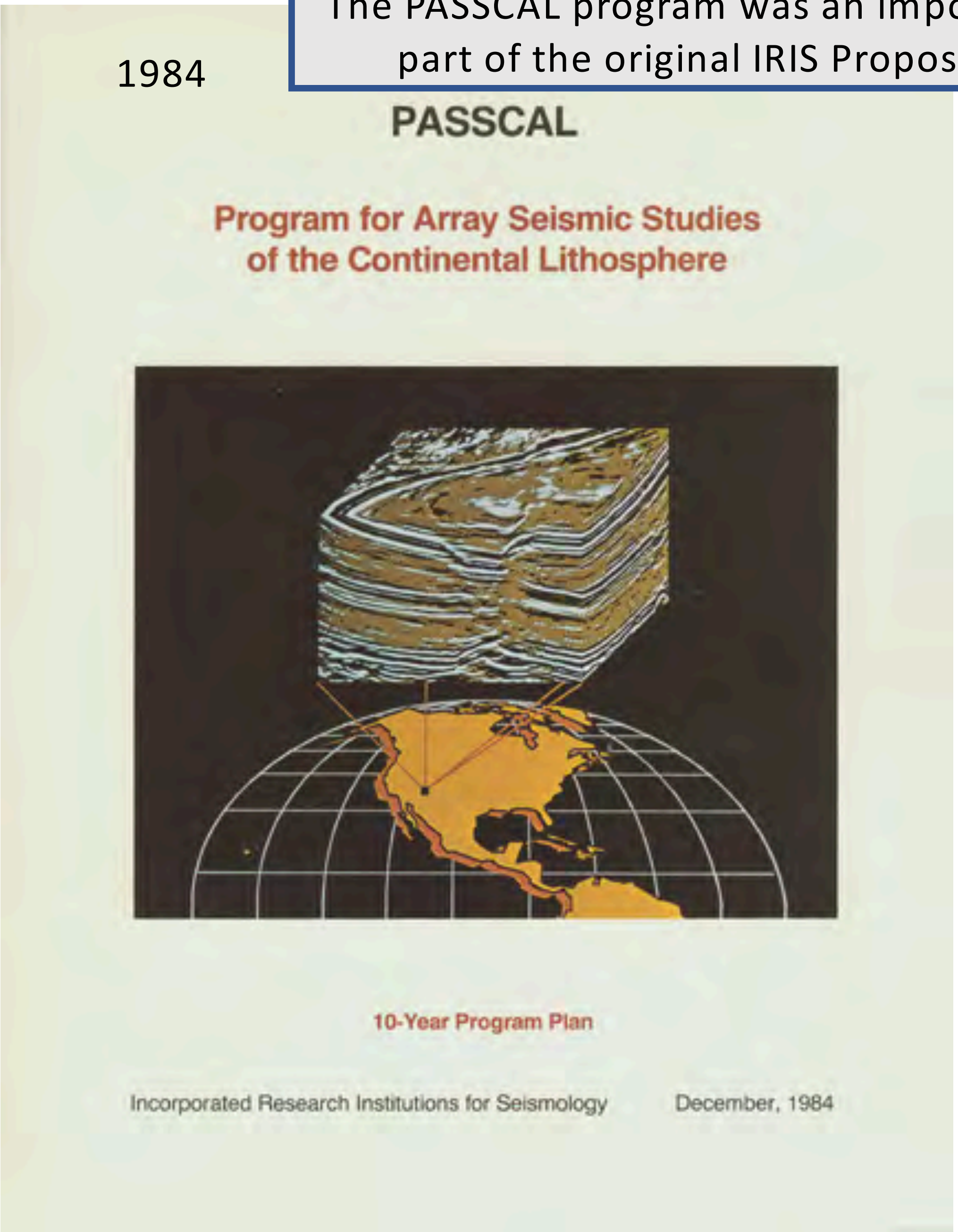
Proposal for a ten-year program for the implementation of four major national facilities for seismology:

- **A Global Digital Seismic Array**
  featuring real-time satellite telemetry from *one hundred* modern seismographic observatories
- **A Mobile Array**
  comprised of *one thousand* portable digital seismographs to be used for studies of the continental lithosphere
- **Central Data Management and Distribution Facilities**
  to provide rapid and convenient access to the data sets for the entire research community
- **A Major Computational Facility**
  capable of supporting the analyses of these new data



The PASSCAL program was an important part of the original IRIS Proposal

1984



Masters, G., T. Jordan, P. Silver, and F. Gilbert, Aspherical earth structure from fundamental spheroidal mode data, *Nature, 298*, 609, 1982.
Masters, G., J. Park, and F. Gilbert, Observations of coupled spheroidal and toroidal models, *J. Geophys. Res., 88*, 10285, 1983.
Nakanishi, I., and D. L. Anderson, World-wide distribution of group velocity of mantle Rayleigh waves as determined by spherical harmonic inversion, *Bull. Seismol. Soc. Am., 72*, 1185, 1982.
Nakanishi, I., and D. L. Anderson, Measurements of mantle wave velocities and inversion for lateral heterogeneity and anisotropy, 1, Analysis of great circle phase velocities, *J. Geophys. Res., 88*, 10267, 1983.
Nakanishi, I., and D. L. Anderson, Measurements of mantle wave velocities and inversion for lateral heterogeneity and anisotropy, 2, Analysis by the single-station method, *Geophys. J. R. Astron. Soc., 78*, 573, 1984*a*.
Nakanishi, I., and D. L. Anderson, Aspherical heterogeneity of the mantle from phase velocities of mantle waves, *Nature, 307*, 117, 1984*b*.
Nakanishi, I., and H. Kanamori, Source mechanisms of twenty-six large, shallow earthquakes ($M_S \geqslant 6.5$) during 1980 from *P*-wave first motion and long-period Rayleigh wave data, *Bull. Seismol. Soc. Am., 74*, 805, 1984.
Nataf, H.-C., I. Nakanishi, and D. L. Anderson, Anisotropy and shear velocity heterogeneities in the upper mantle, *Geophys. Res., Lett., 11*, 109, 1984.
Niazi, N., and H. Kanamori, Source parameters of 1978 Tabas and 1979 Qainat, Iran, earthquakes from long-period surface waves, *Bull. Seismol. Soc. Am., 71*, 1201, 1981.
Okal, E., and L. Stewart, A negative search for an ultra-slow component to the source of the Yunnan earthquakes of May 29, 1976, *Phys. Earth Planet. Inter., 26*, 208, 1981.
Parker, E. B., Micro earth stations as personal computer accessories, *Proc. IEEE, 72*, 1526, 1984.
Peterson, J., and E. E. Tilgner, Description and preliminary testing of the CDSN seismic sensor system, *U.S. Geol. Surv. Open File Rep. 85–288*, 1985.
Riedesel, M., D. Agnew, J. Berger, and F. Gilbert, Stacking for the frequencies and *Q*s of ${}_0S_0$ and ${}_1S_0$, *Geophys. J. R. Astron. Soc., 62*, 457, 1980.
Romanowicz, B., M. Cara, J. F. Fels, and D. Rouland, GEOSCOPE: A French initiative in long-period three-component global seismic networks, *Eos Trans. AGU, 65*, 753, 1984.
Savino, J. K., K. McCamy, and G. Hade, Structures in earth noise beyond twenty seconds, a window for earthquakes, *Bull. Seismol. Soc. Am., 62*, 141, 1972.
Tanimoto, T., and D. L. Anderson, Mapping convection in the mantle, *Geophys. Res. Lett., 11*, 287, 1984.
Tanimoto, T., and D. L. Anderson, Lateral heterogeneity and azimuthal anisotropy of the upper mantle: Love and Rayleigh waves 200–250 s, *J. Geophys. Res., 90*,1842, 1985.
Woodhouse, J., and A. Dziewonski, Mapping the upper mantle: Three-dimensional modeling of earth structure by inversion of seismic waveforms, *J. Geophys. Res., 89*, 5953, 1984.

IRIS: A Program for the Next Decade

PAGES 213–219

Stewart W. Smith
Incorporated Research Institutions for Seismology, Arlington, Va.

The Incorporated Research Institutions for Seismology (IRIS) Consortium has produced an ambitious plan for new seismological research facilities to be developed during the coming decade. The plan reflects a broad consensus among seismologists in this country with respect to both the need for improved data and the potential for significant scientific advances that can occur as a result. The three elements of this program are a 100-station broadband global network utilizing satellite telemetry, a 1000-station portable network of advanced digital seismographs, and a national center for management and distribution of the data generated by these networks to the research community. The purpose of this paper is to provide a hrief overview of the long-range plan and an update as to the progress made to date.

Introduction

In a major departure from the traditional single-investigator approach to research support, the seismological community came together in 1984 in a national grassroots movement to create a consortium of research universities for the purpose of implementing, through a cooperative approach including industry and government agencies, a set of initiatives for critically needed national facilities necessary to support seismological research in the coming decades. IRIS, the Incorporated Research Institutions for Seismology, a nonprofit corporation, was founded May 8, 1984.

The IRIS proposal [*McEvilly and Alexander*, 1984] that emerged from this effort represented the collective request from the U.S. seismological community for a set of modern research tools. The tools, or national facilities, will serve the earth sciences as primary data sources well into the next century. Replacement of the present vintage equipment with modern instrumentation and data management systems is a necessary step in achieving a major improvement in our ability to understand the earth's interior.

Our knowledge of the earth's interior is now limited by data quality and quantity. Theory and analysis techniques exist to improve our view of the subsurface substantially, beyond the thin skin accessihle to the drill. Important questions in geodynamics, resources, and geological hazards demand this improved understanding of our earth. This IRIS program will provide the next generation of geophysicists with the means to address these questions.

0096–3941/86/6716–0213$1.00

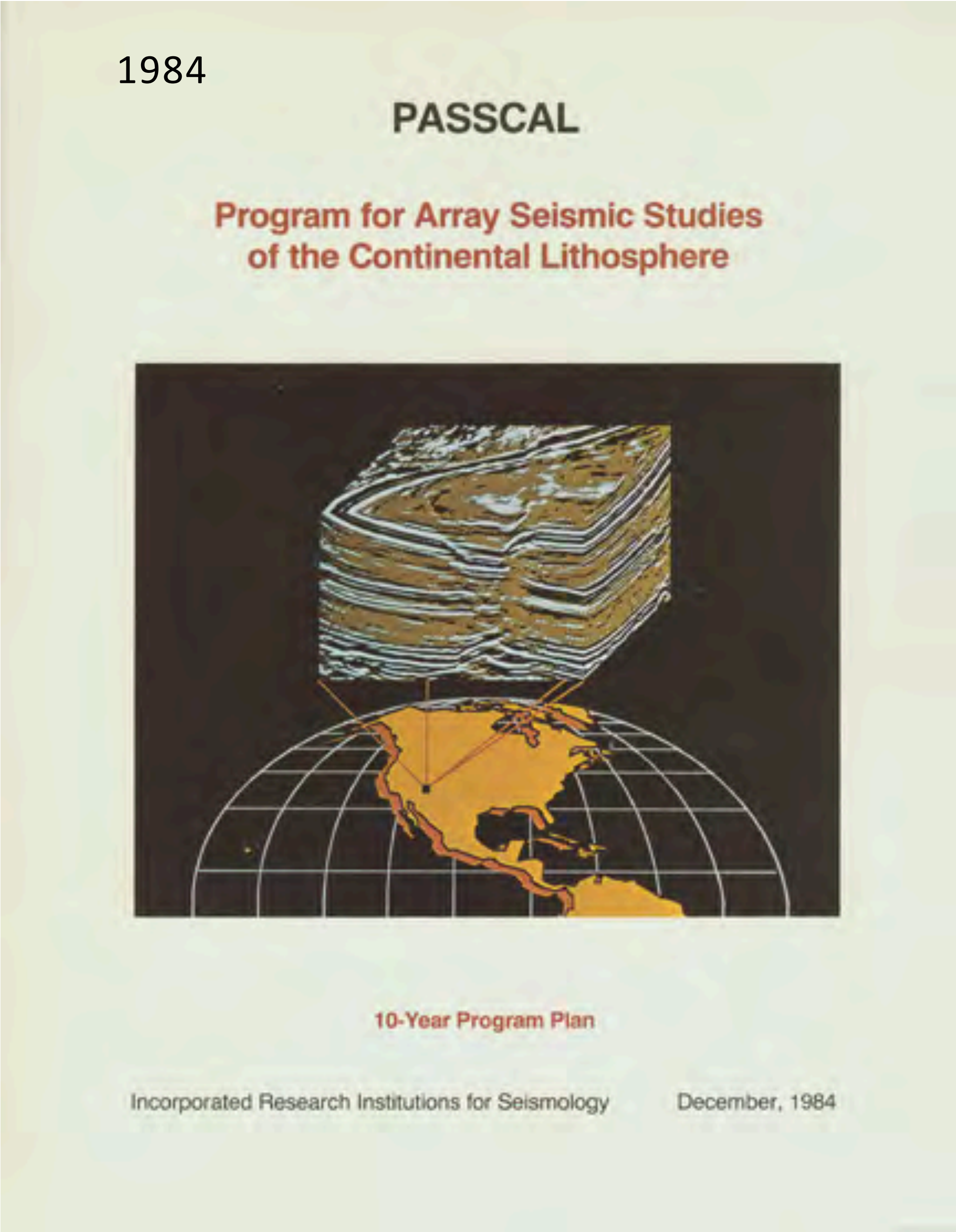
The 1986 AGU Spring Meeting marks the first anniversary in the operational life of the IRIS Consortium. It was a year ago that planning funds became available from the National Science Foundation (NSF) so that committee work could begin to be translated into action. It was also the first time that hard choices about allocation of limited resources among competing programs were faced. This report reviews tbe early experience in the operation of the consortium and the specific progress that has been made during the past year toward our long-range goals.

The Current IRIS Program

Until October 1985, the physical existence of IRIS was limited to a mail drop at the AGU headquarters building in Washington, D.C., a convenience for which we are grateful, and an electronic mail system that linked key members of committees across the country. Without the latter it is difficult to imagine how the enterprise could have functioned during those early days. Space was leased, furnished, and occupied during October 1985; a small staff was assemhled to begin operations at that time.

IRIS represents the first attempt by seismologists (of the dry land variety, anyway) to organize and operate such a consortium. There are, of course, a number of successful precedents in other disciplines to use as models, such as the University Consortium for Atmospheric Research (UCAR) and the Joint Oceanographic Institutions (JOI). As newcomers to this style of operation, we are just heginning to learn the kinds of things that are necessary to make it successful. As expected, one of the keys has been the sublimation of specific institutional and individual priorities in order to promote the larger goals of IRIS. That this seems to work is a result of the widespread effort that went into the early planning and development of the science plans [*IRIS*, 1984*a,b*]. With scientific goals and priorities so generally agreed upon in advance, the development of priorities for spe-

Smith, EOS, 1986


1984

PASSCAL

Program for Array Seismic Studies of the Continental Lithosphere

10-Year Program Plan

Incorporated Research Institutions for Seismology

December, 1984

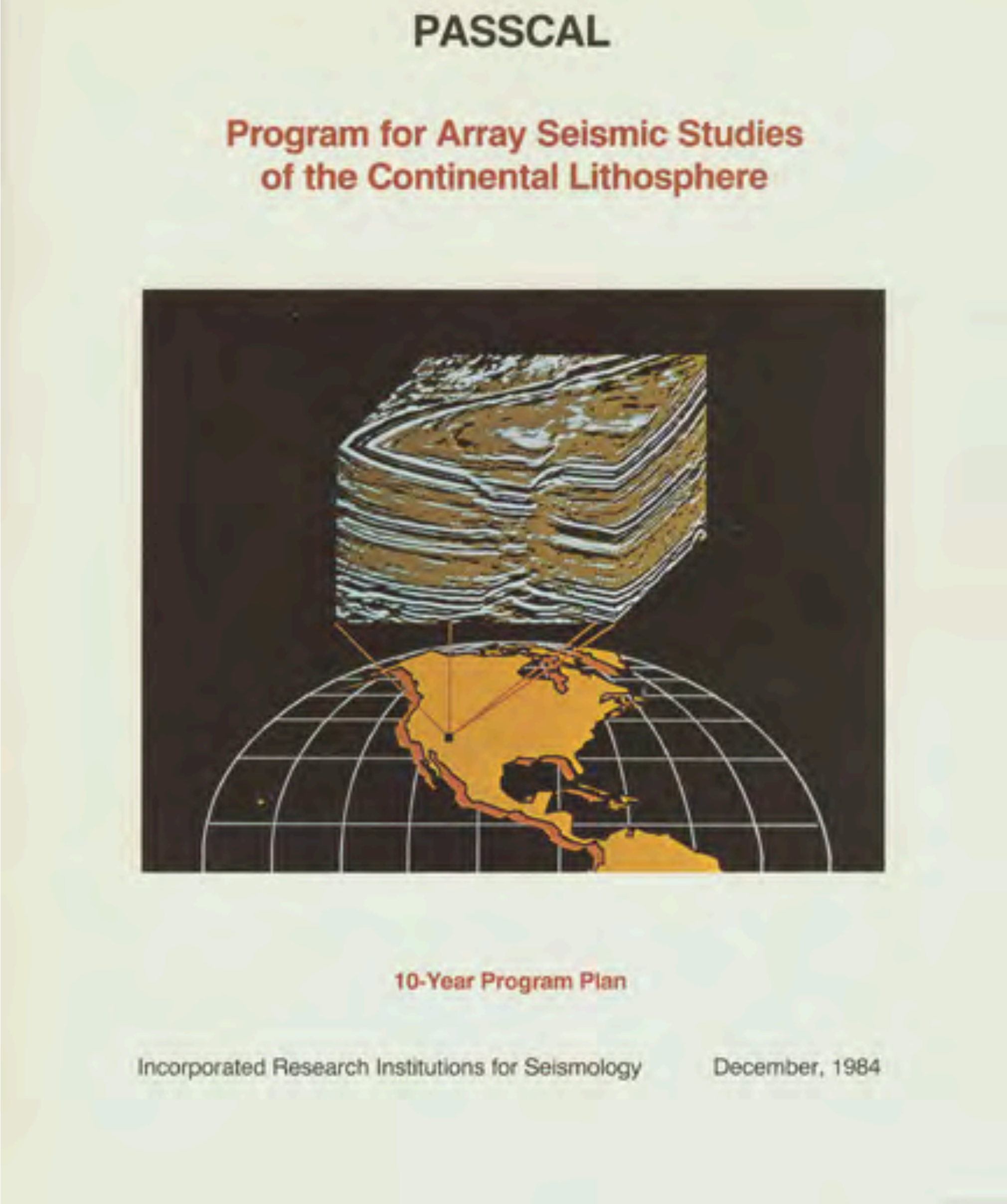
Portable Array Studies (PASSCAL)

Instrument Development

The PASSCAL Science Plan spelled out in detail the need for an advanced portable seismograph system. This system would be digital, with high dynamic range; it would be portable and micro-powered, and most importantly, it would be flexible and modular so as to be able to adapt to changes in technology that are likely to occur over the lifetime of the instrument. Since the plan is to make a major national commitment through the purchase of 1000 instruments, it is clear that we should not freeze in place the technology available at this particular point in history. The rapidly changing field of mass storage illustrates the most obvious example of this problem, but comparable changes in encoder technology, timing systems, and virtually every other part of the system are very likely over the next decade. To avoid this, a plan was made for a modular communications "bus" approach to design. With this concept the seismic instrument functions as a local

Smith, EOS, 1986

1984


PASSCAL

Program for Array Seismic Studies of the Continental Lithosphere

10-Year Program Plan

Incorporated Research Institutions for Seismology December, 1984


Photo credit: Craig Jones

Bob Phinney, First chair of PASSCAL Standing Committee

Photo from PASSCAL web page

Jim Fowler, founding manager for PASSCAL program. Started as IRIS Chief Engineer in 1984.

PASSCAL Timeline

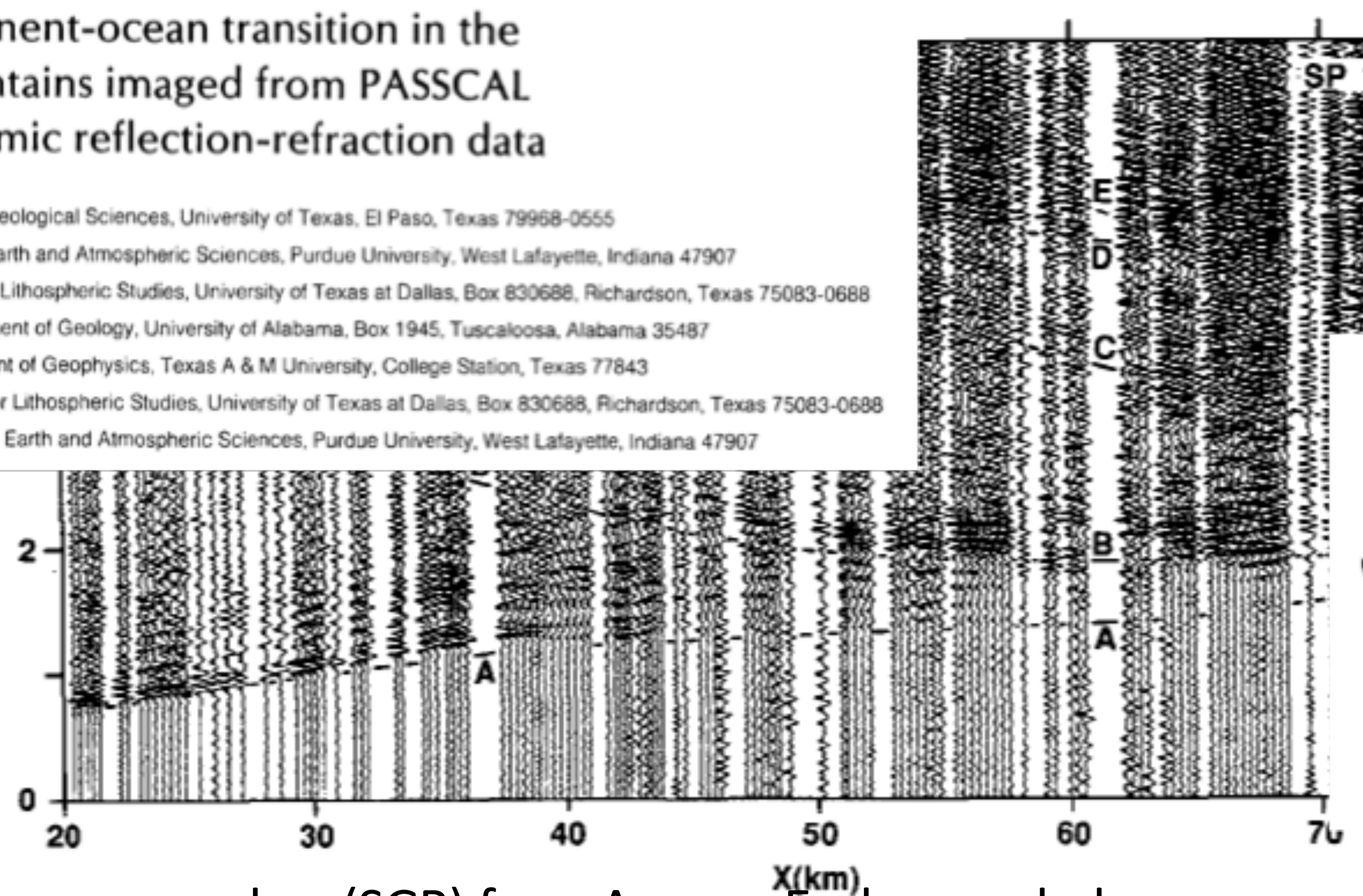
1984 – IRIS Incorporated
1986 – Ouachita Experiment
1986 – Basin and Range Experiment
1986 – Issue RFP for new instrument
1987 – Issue contract to develop a new instrument
1988 – Basin&Range Passive Experiment - 1st experiment with prototype instruments.
1989 – First PASSCAL instrument center opened at Lamont
1989 – Loma Prieta – first aftershock deployment (RAMP)
1990 – receive first broadband sensors

1991 – Tibet broadband experiment (1st BB experiment to produce SEED data)
1991 – Stanford PASSCAL instrument center established – active source and RAMP
1992 – Rocky Mountain Front experiment – first experiment with over 25 broadband
1995 – first GPS clocks on REF TEKs
1998 – New PASSCAL Instrument Center at New Mexico Tech, closed LDEO and Stanford instrument centers
1999 – first TEXAN instrument
2002 – new data acquisition systems developed
2003 – USArray starts

PASSCAL Oachita Experiment, 1986

Paleozoic continent-ocean transition in the Ouachita Mountains imaged from PASSCAL wide-angle seismic reflection-refraction data

G. R. Keller Department of Geological Sciences, University of Texas, El Paso, Texas 79968-0555
L. W. Braile Department of Earth and Atmospheric Sciences, Purdue University, West Lafayette, Indiana 47907
G. A. McMechan Center for Lithospheric Studies, University of Texas at Dallas, Box 830688, Richardson, Texas 75083-0688
William A. Thomas Department of Geology, University of Alabama, Box 1945, Tuscaloosa, Alabama 35487
Steven H. Harder Department of Geophysics, Texas A & M University, College Station, Texas 77843
Wen-Fong Chang Center for Lithospheric Studies, University of Texas at Dallas, Box 830688, Richardson, Texas 75083-0688
W. G. Jardine Department of Earth and Atmospheric Sciences, Purdue University, West Lafayette, Indiana 47907



400 seismic group recorders (SGR) from Amoco. Each recorded data from a string of geophones on digital cassettes. Overlapped COCORP line.

Keller et al, Geology, 1989

PASSCAL Basin and Range, 1986 & 1988

The 1986 PASSCAL Basin and Range Lithospheric Seismic Experiment

PAGES 593, 596–598

1986 PASSCAL Basin and Range Lithospheric

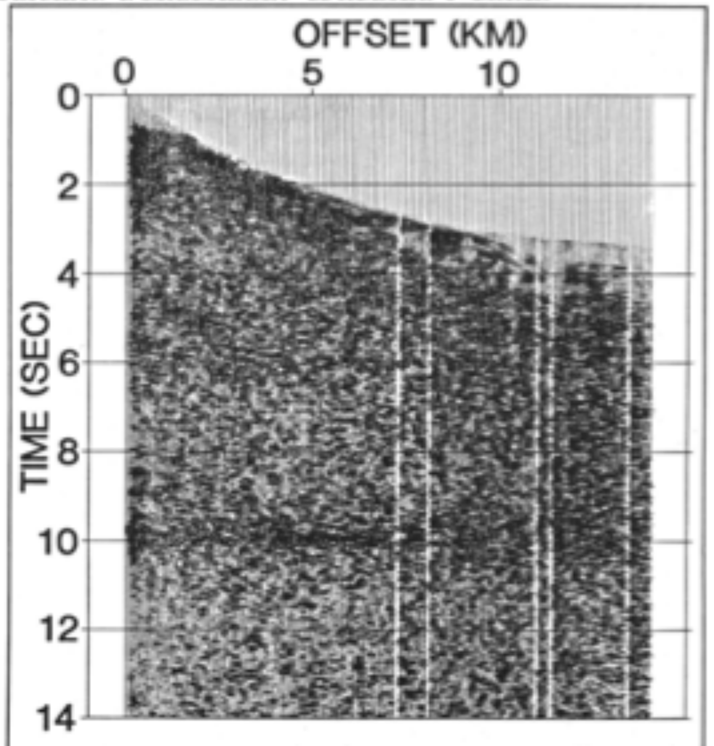
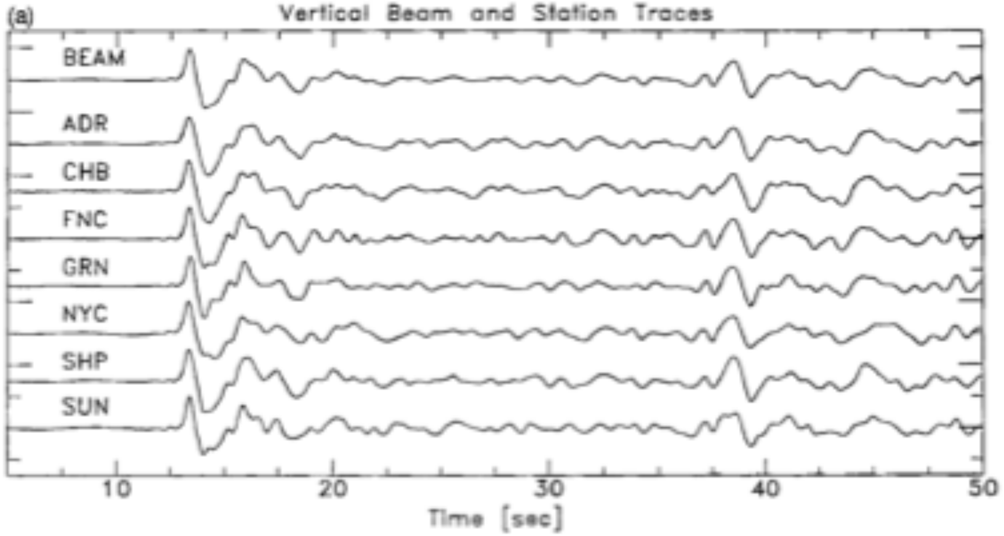


Fig. 4. A portion of the reflection spread shot gather from the center shot on the north-south profile. Note the laminated high-amplitude reflection Moho near 10 s two-way travel time and the decrease in crustal reflectivity near 7 s two-way travel time.

Catchings et al, 1988

Array analysis of the large-aperture array of the 1988–89 PASSCA Basin and Range Passive-Source Seismic Experiment

George E. Randall and Thomas J. Owens
Department of Geological Sciences, University of South Carolina, Columbia, SC 29208, USA



Randall and Owens, 1994

Lamont PASSCAL Instrument Center (PIC), 1989 - 1998

Art Lerner-Lam

Noel Barstow

Bob Busby

Paul Friberg

Loma Prieta 1989 – 1st RAMP (aftershock) deployment

Heidi Houston, Thorne Lay, Susan Schwartz, David Simpson and Ornella Bonamassa deploying PASSCAL instruments.

- This was the second overall deployment of the new PASSCAL equipment.
- Data collected in triggered mode using STA/LTA.

Photos from Susan Schwartz

Loma Prieta 1989 – 1st RAMP (aftershock) deployment

Bulletin of the Seismological Society of America, Vol. 81, No. 5, pp. 1737–1753, October 1991

EMPIRICAL GREEN'S FUNCTION ANALYSIS OF LOMA PRIETA AFTERSHOCKS

BY S. E. HOUGH, L. SEEBER, A. LERNER-LAM, J. C. ARMBRUSTER, AND H. GUO

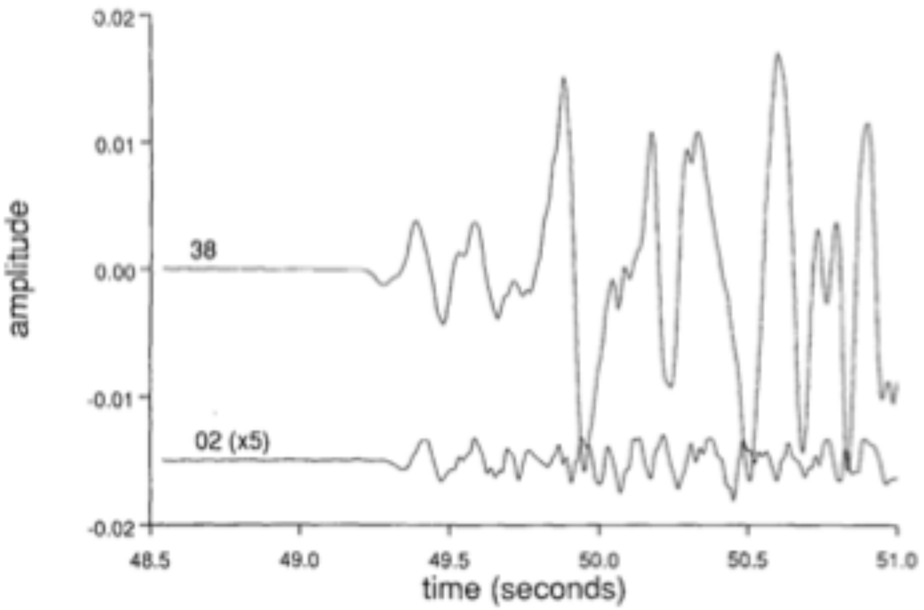
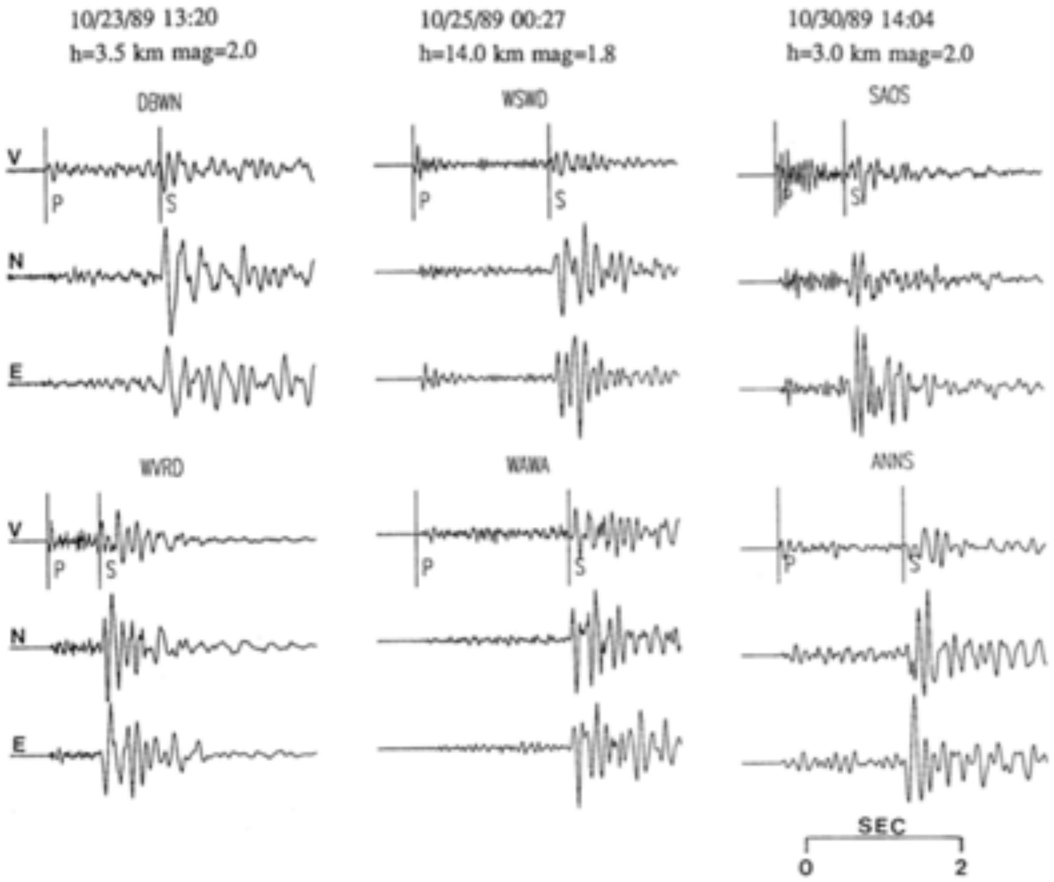


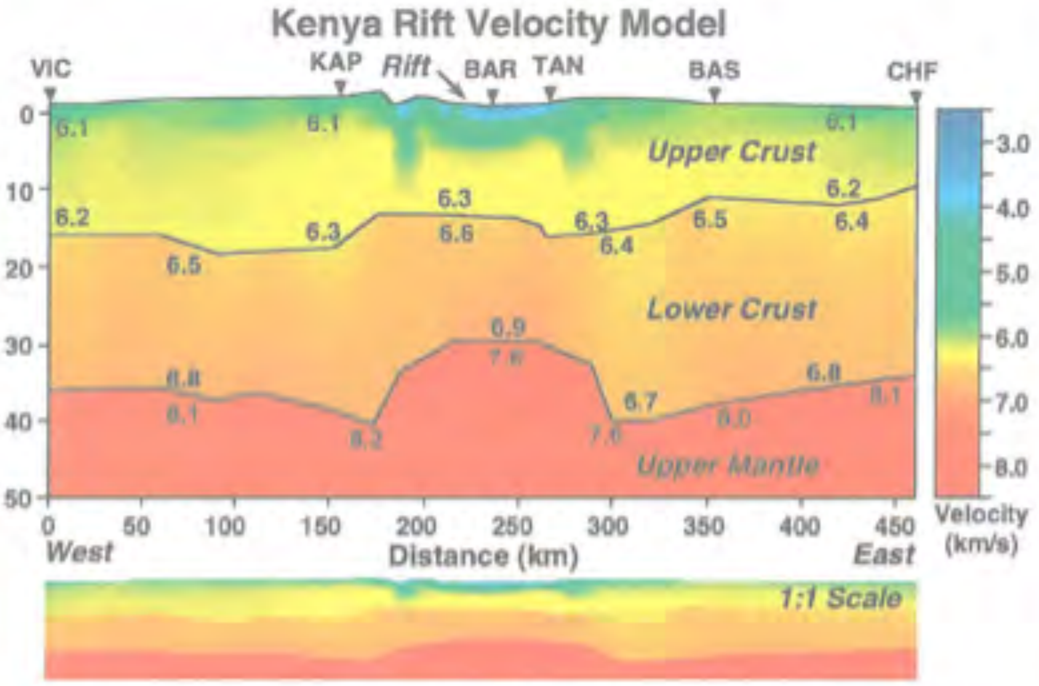
FIG. 2. Initial *P*-wave arrivals for events 38 and 02 recorded at station WAWA. The amplitude of the smaller event, which is used as empirical Green's function, is amplified by a factor of 5. The two events are observed to be significantly different in magnitude but to have very similar waveform complexity.

LOMA PRIETA AFTERSHOCK RELOCATION WITH *S-P* TRAVEL TIMES FROM A PORTABLE ARRAY

By Susan Y. Schwartz and Glenn D. Nelson, University of California, Santa Cruz



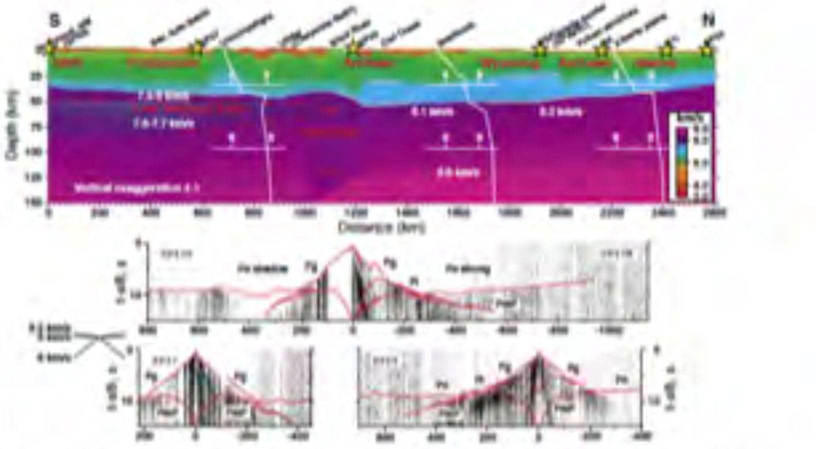
1991 Stanford PASSCAL Instrument Center Established – Active Source and RAMP



KRISP 90 velocity model derived by travel-time inversion (Braile et al., Tectonophysics 1994 KRISP Volume)

Probing the Archean and Proterozoic Lithosphere of Western North America

Timothy J. Henstock and Alan Levander, Rice University
Catherine M. Snelson, G. Randy Keller, Kate C. Miller, and Steven H. Harder, University of Texas at El Paso
Andrew R. Gorman and Ron M. Clowes, University of British Columbia, Vancouver
Michael J.A. Burianyk, University of Alberta, Edmonton
Eugene D. Humphreys, University of Oregon



Lithospheric P-wave velocity model along the Deep Probe corridor extending from southern New Mexico to Edmonton, Alberta. Three crustal domains and two mantle domains have distinct seismic velocity structure. The mantle structure beneath the Proterozoic terranes of the southern Rocky Mountains/Colorado plateau has low velocities similar to that of a spreading ridge, whereas the mantle beneath the Archean Wyoming and Hearne Provinces is somewhat faster than that of the North American craton as a whole. The transition from slow to fast velocity occurs over a distance less than 250 km in the vicinity of the surface contact separating Archean cratonic from Proterozoic island arc terranes at the Cheyenne Belt. The two Archean provinces have distinctly different crustal thicknesses and velocities. In particular the Wyoming province is characterized by a thick (~20-25 km) high-velocity (>7.0 km/s) lower crust.

Tibet – 1st major Broadband experiment 1991-92

Tom Owens and Francis Wu, PIs

Greg Wagner and Lupei Zhu

11 stations - 10 STS2, 1 Guralp CMG3-ESP
330 mb hard disks, data download by hard disk or exabyte tape
Data stream 1 – 5 sps triggered, Data stream 2 – 40 sps triggered, Data stream 3 – 1 sps continuous

OMEGA clocks

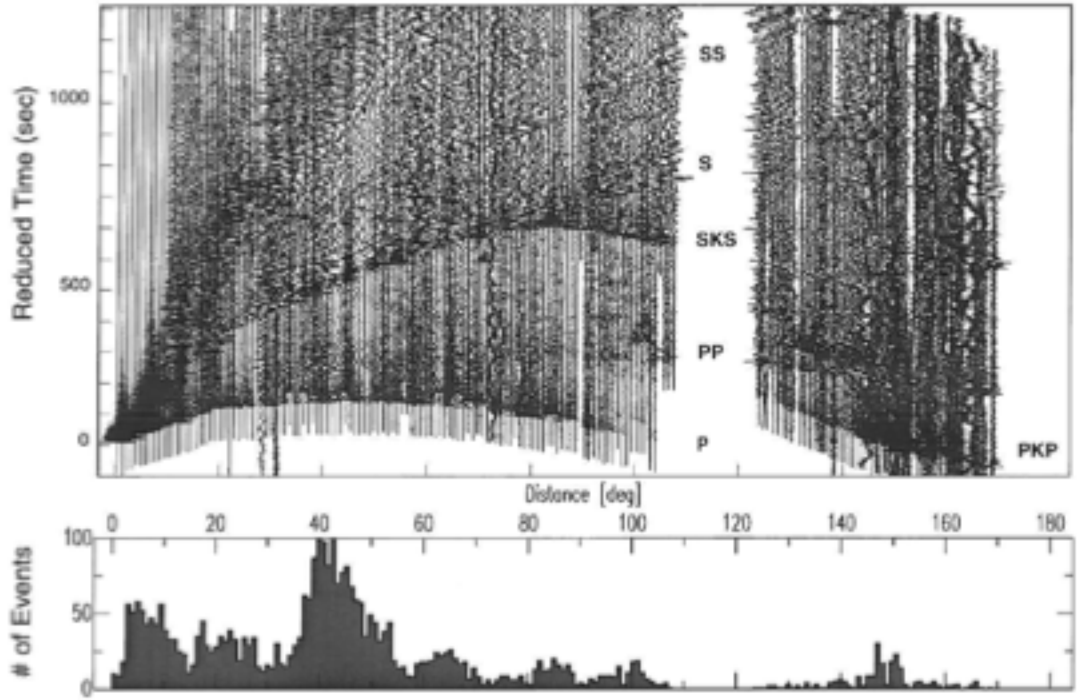
Demonstrated that very high-quality broadband data could be obtained at temporary sites in extreme environments.
Data of interest to scientists beyond the PIs on the project

Photo credits: Left, Francis Wu; Center Lupei Zhu.

Tibet – 1st major Broadband experiment 1991-92

PASSCAL Views the World from Tibet

T.J. Owens
University of South Carolina



Owens, Randall, Wu, Zeng, BSSA, 1993

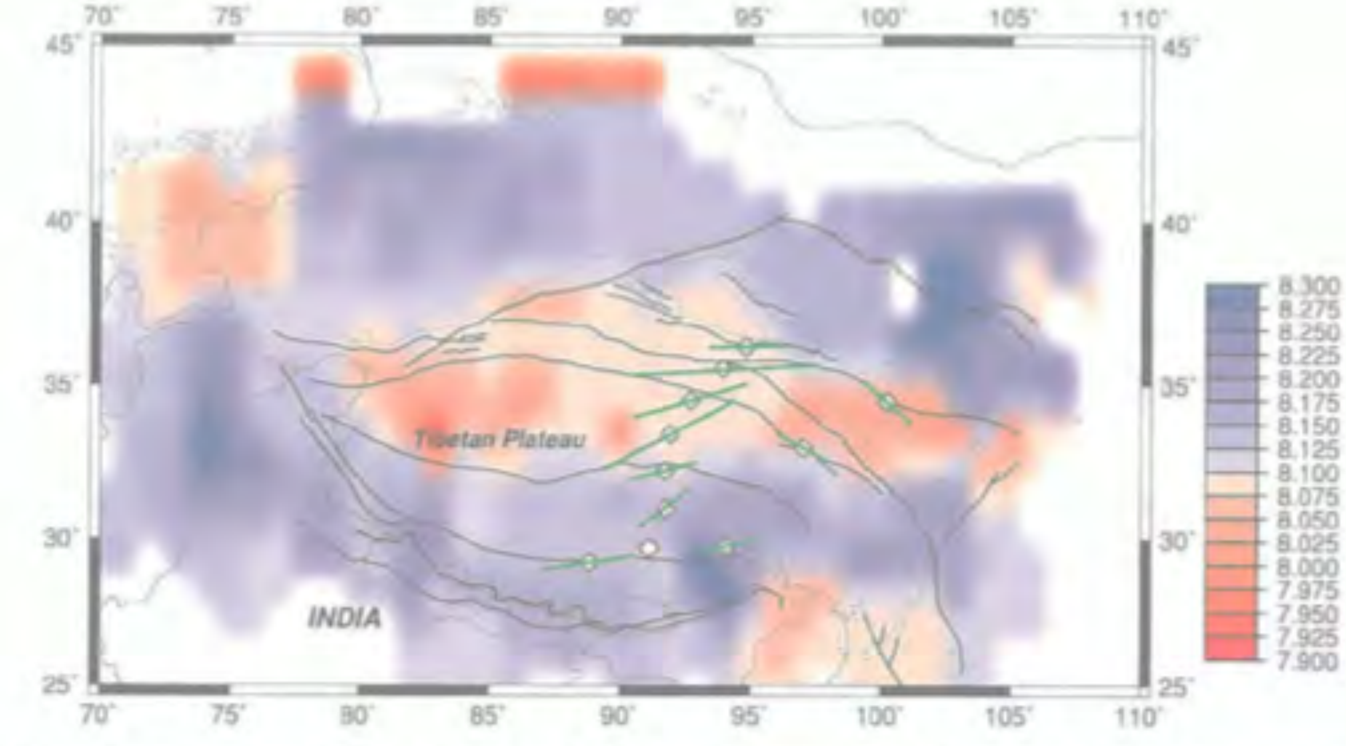
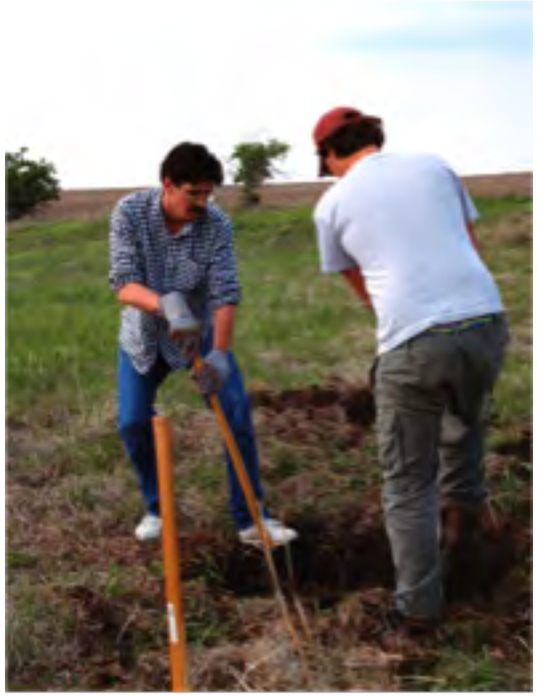


Figure: Summary results from the Tibetan Plateau Broadband Experiment. Color image shows Pn velocities from tomographic inversion of paths from both PASSCAL and ISC stations. White diamonds are the PASSCAL broadband sites. Green lines at each site show the orientation and magnitude of shear wave anisotropy beneath each site. For reference, the magnitude of the vector at the northernmost site is 0.9sec. Light dashed lines show the 4000m contour and solid black lines show large scale geologic features.

McNamara, Owens, Silver, Wu, JGR, 1994
McNamara, Walter, Owens, Ammon, JGR, 1997

Rocky Mountain Front 1992. 30 Broadband stations

Lerner-Lam, Humphreys, Grand, PIs



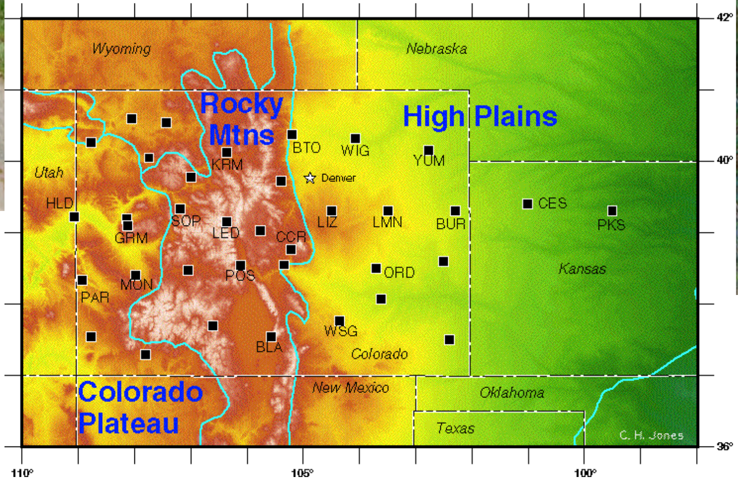
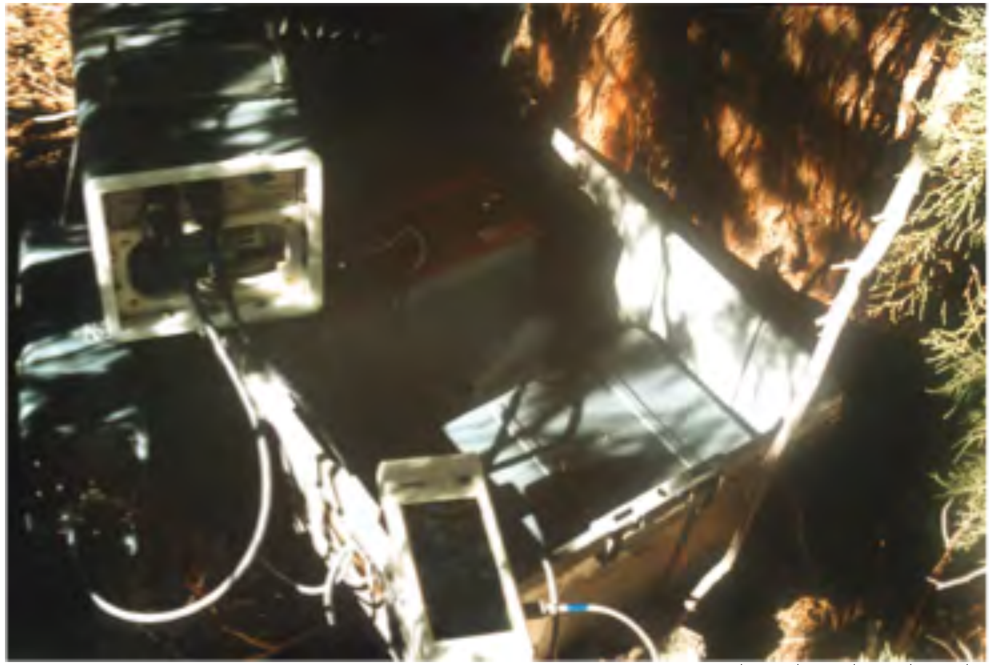


Photo credits: Anne Sheehan

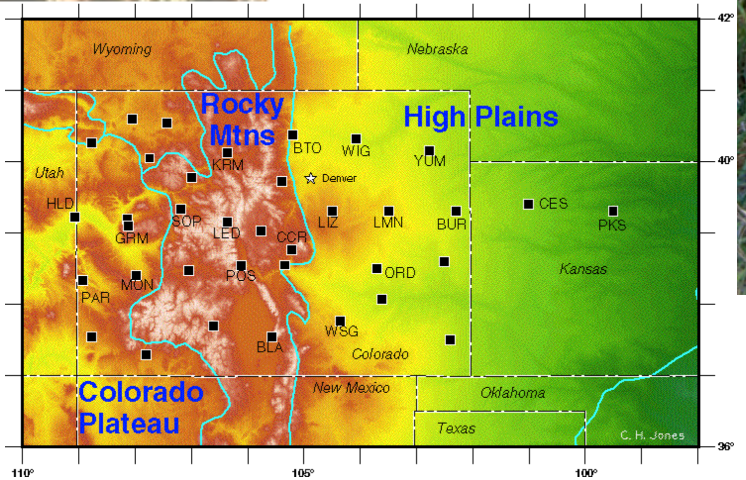
Omega clocks, 200 mb disks, triggered and low rate continuous

Rocky Mountain Front 1992. 30 Broadband stations

Lerner-Lam, Humphreys, Grand, PIs



Exabyte drive to download data to exabyte tape in the field. Epson controller for DAS.



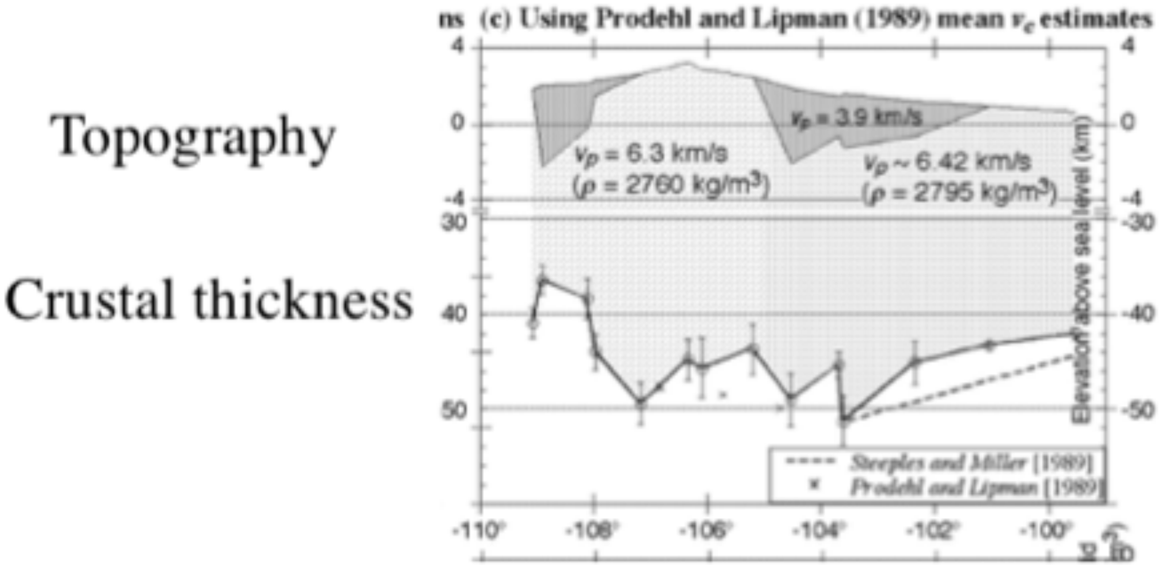
Omega clocks, 200 mb disks, triggered and low rate continuous

Photo credits: Anne Sheehan

Rocky Mountain Front 1992. 30 Broadband stations

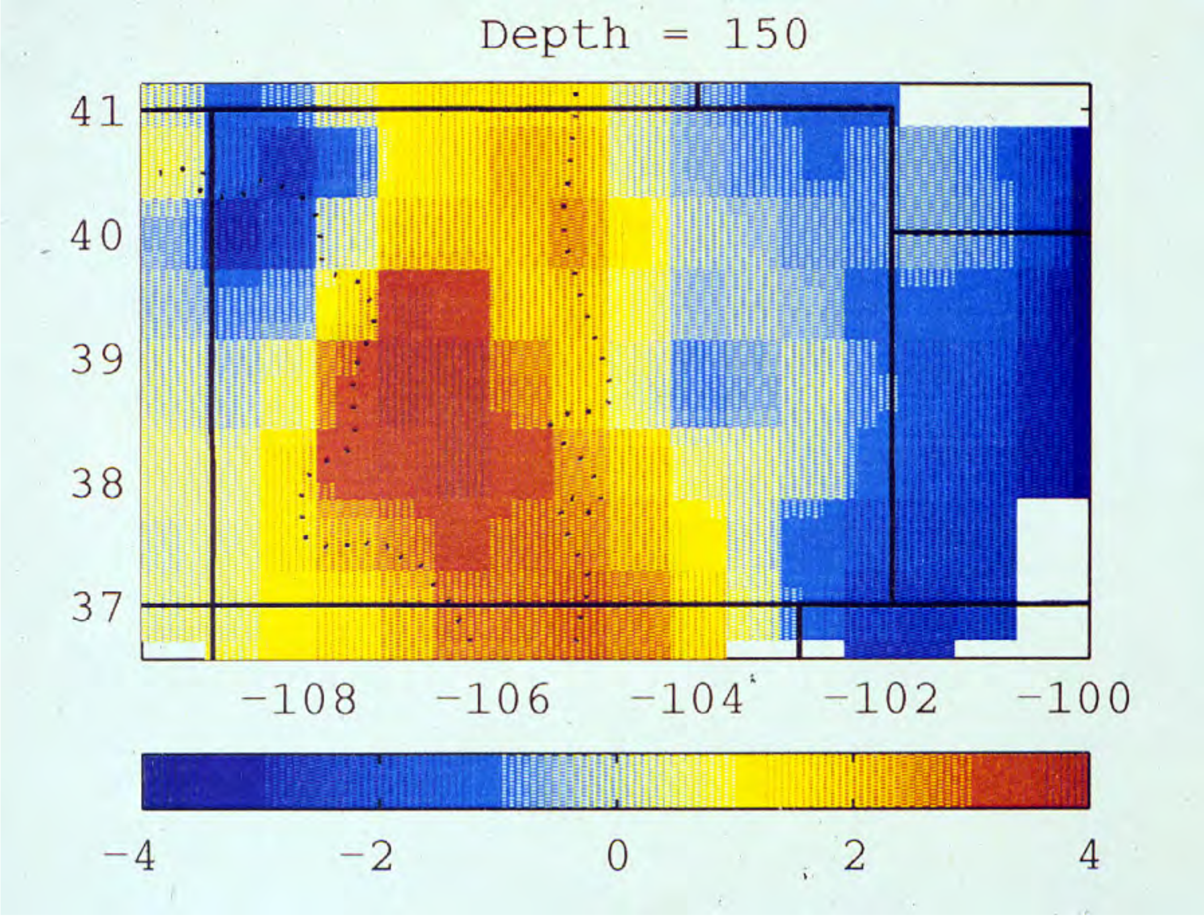
Found Rockies are not compensated by a simple Airy-type root, require significant compensation in the mantle

Crustal thickness from receiver functions



Sheehan, Abers, Lerner-Lam, Jones, JGR, 1995

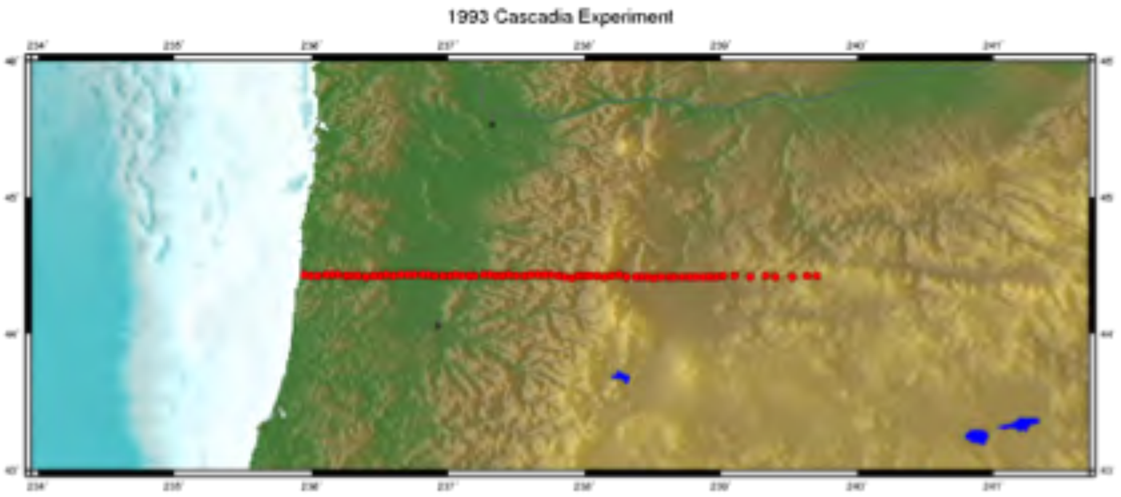
Mantle structure from teleseismic S-wave tomography



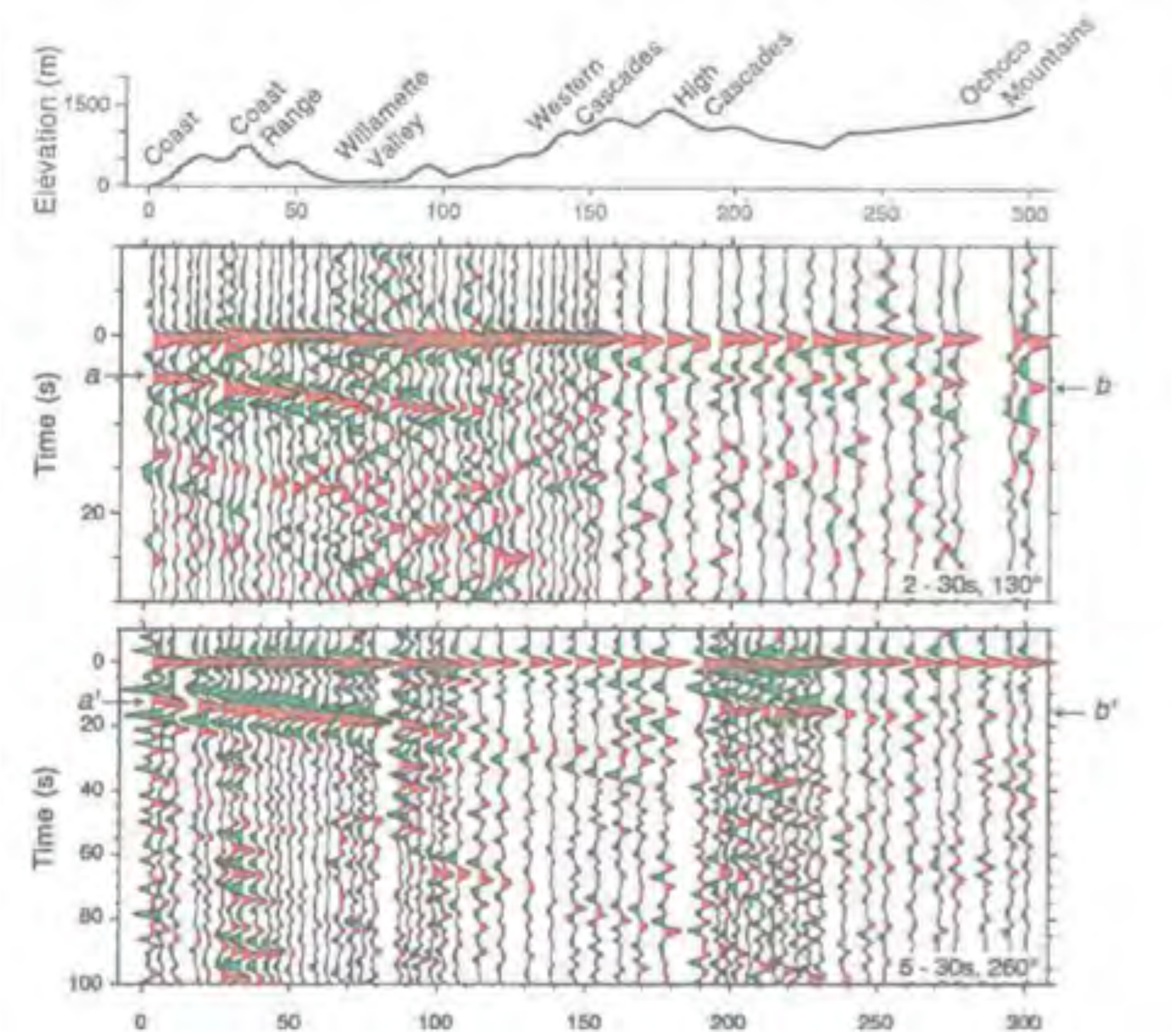
Lee and Grand, JGR, 1996

1993 Cascadia Experiment

PI Nabelek, OSU



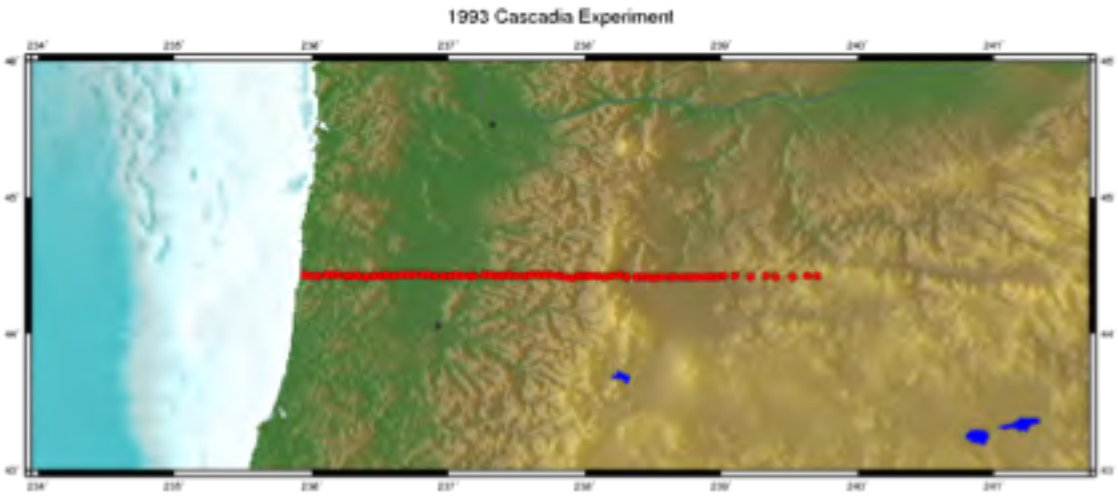
69 broadband sites
44 stations simultaneously
Spacing 4 km



Nabelek et al., One-pager from IRIS Proposal, 1995
Li and Nabelek, 1999

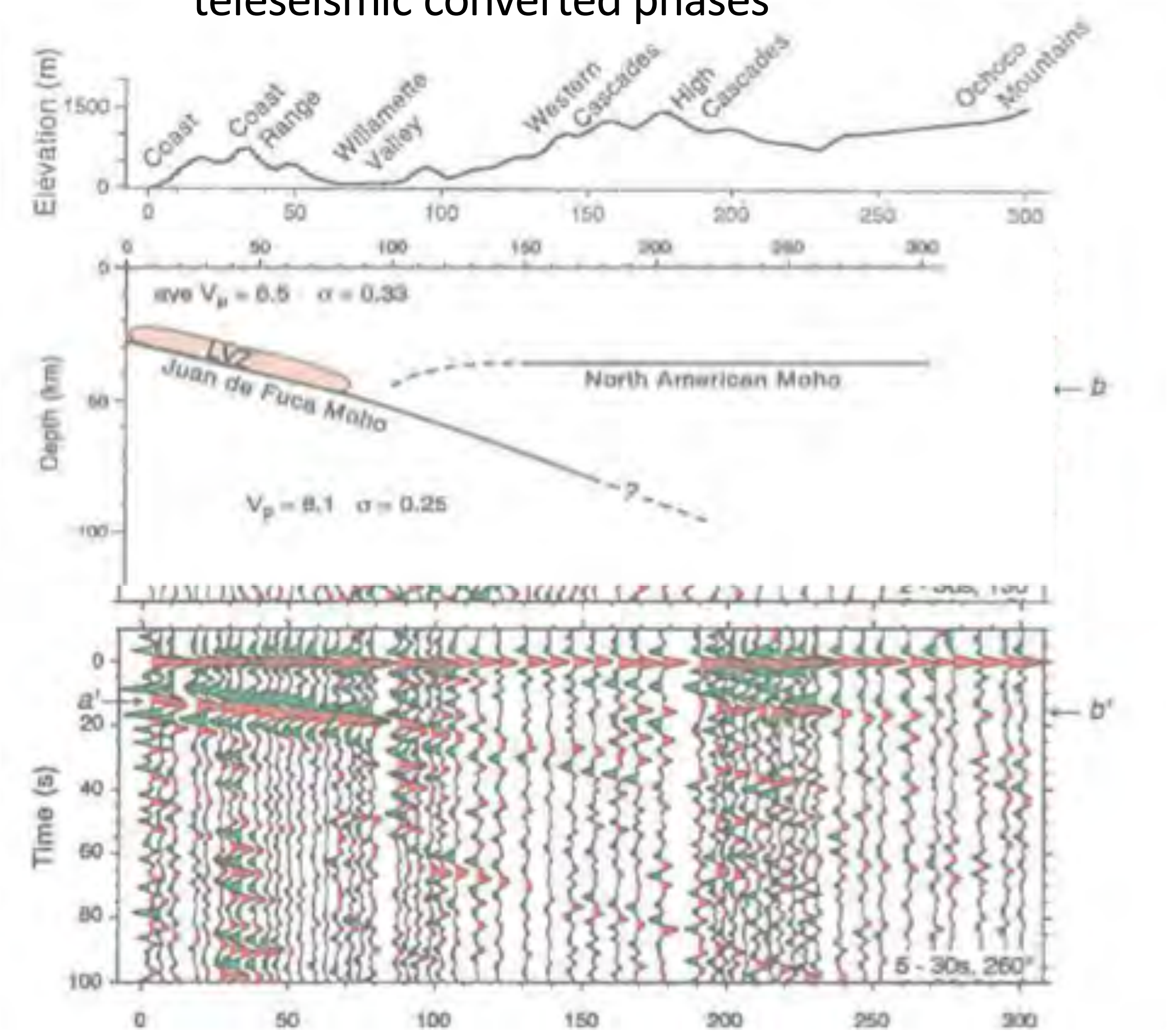
1993 Cascadia Experiment

PI Nabelek, OSU



69 broadband sites
44 stations simultaneously
Spacing 4 km

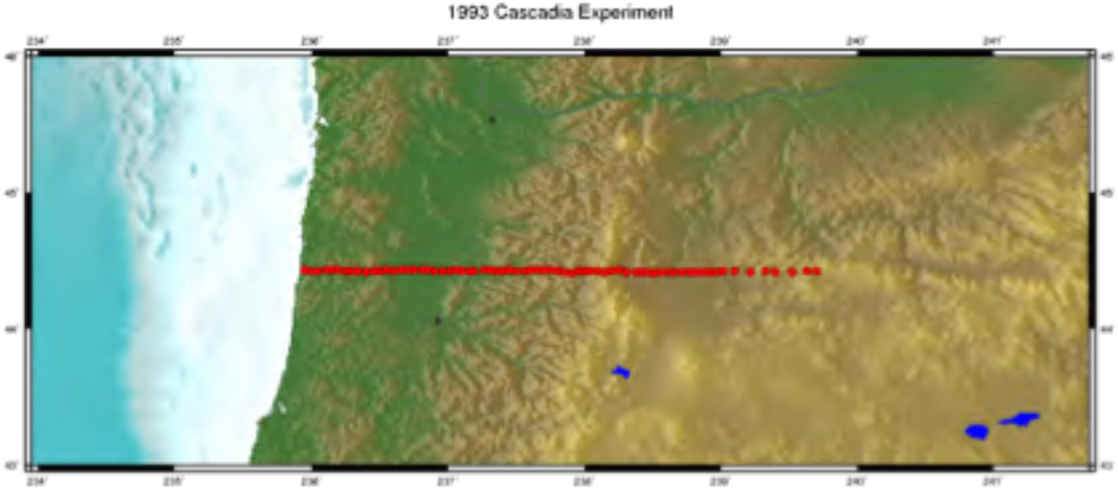
Image of Cascadia Subduction zone from teleseismic converted phases



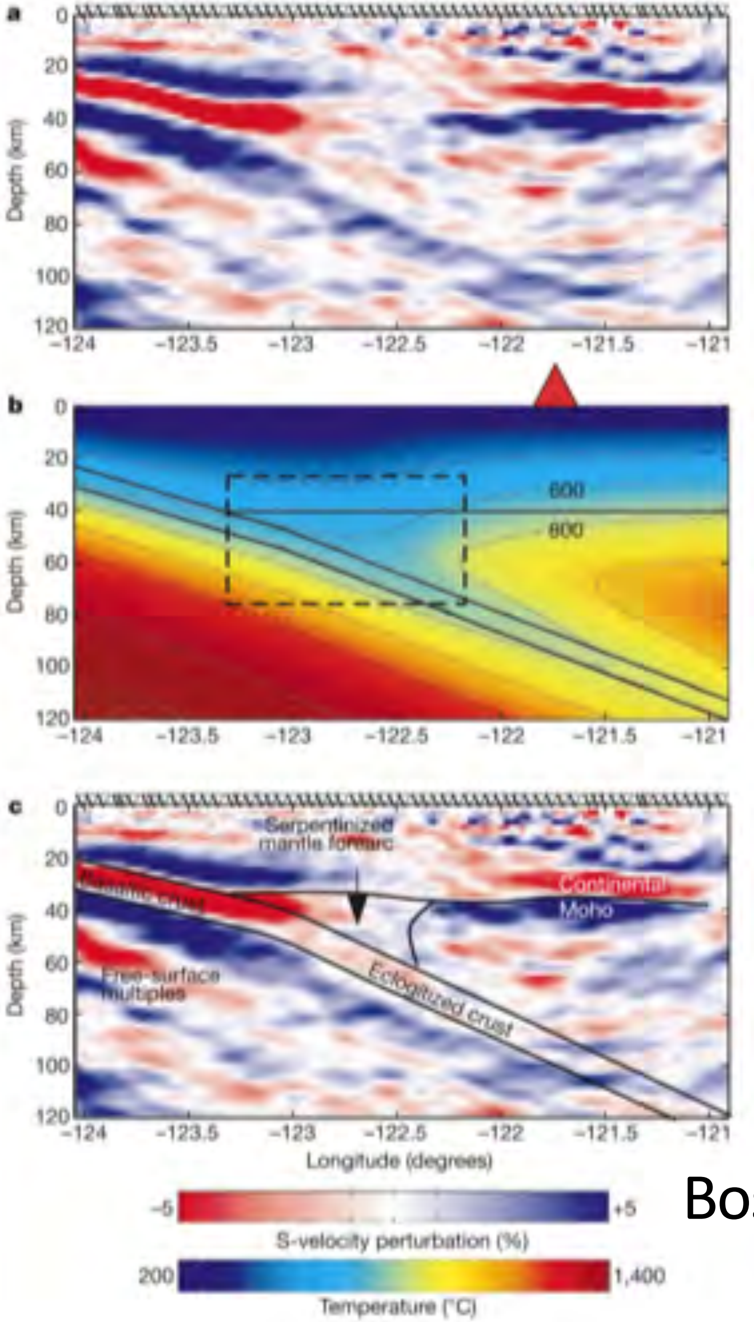
Nabelek et al., One-pager from IRIS Proposal, 1995
Li and Nabelek, 1999

1993 Cascadia Experiment

PI Nabelek, OSU



69 broadband sites
44 stations simultaneously
Spacing 4 km



Scattered wave image

Thermal model

The loss of signal from the continental Moho in the mantle forearc is attributed to mantle serpentinization by fluids released from the subducting plate.

Bostock et al., 2002

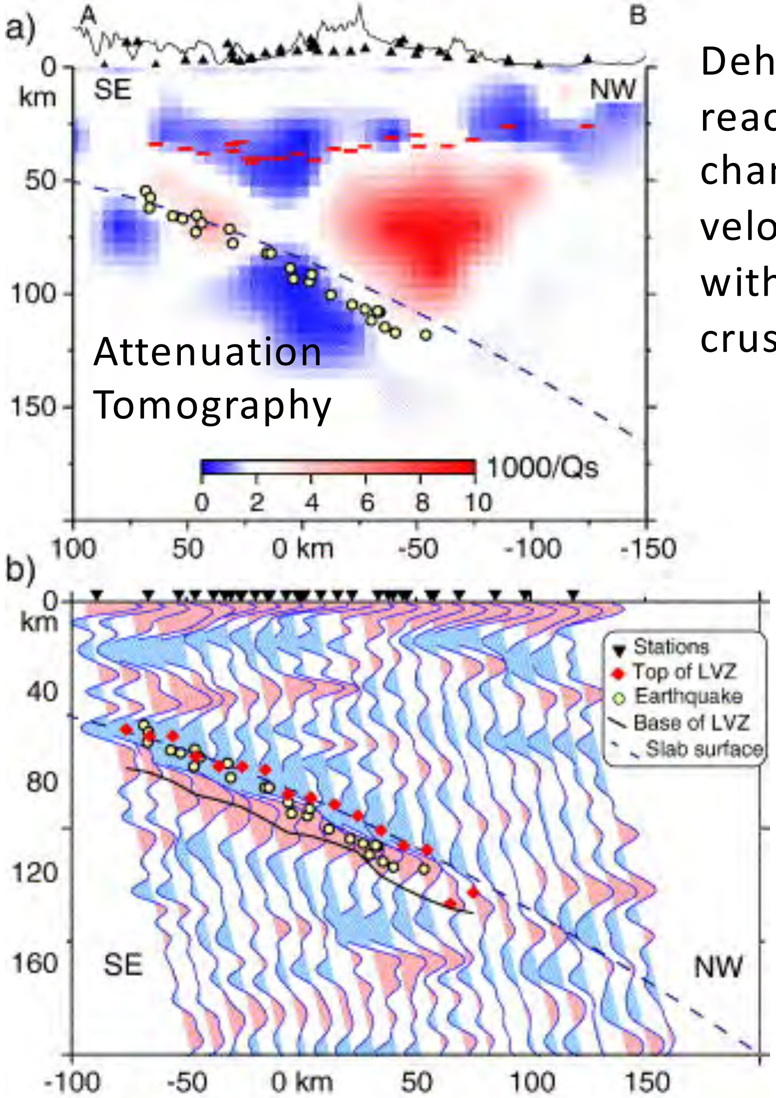
1998 New Mexico Tech PASSCAL Instrument Center Established

Mission:

Provide state-of-the-art, low power portable seismic instrumentation and deliver basic field expertise and data management tools in support of portable array seismic experiments worldwide

BEAAR, Alaska. 1999-2001.

Abers, Christensen, Hansen

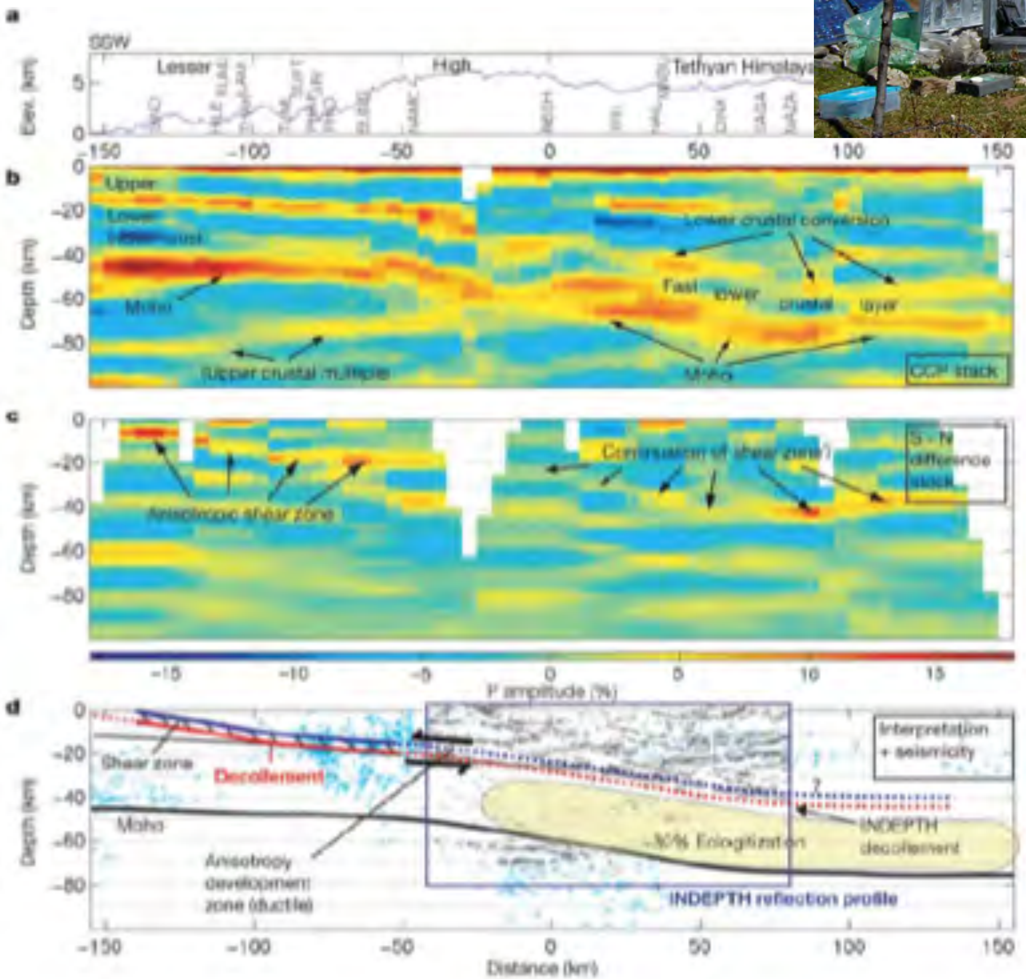


Dehydration reactions explain changes in seismic velocities seen within subducting crust

Abers et al., EPSL 2006

HIMNT, Nepal-Tibet. 2001-2002.

Sheehan, Wu, Bilham



Decollement at base of the Himalaya

Schulte-Pelkum et al., 2005

Studies of the Earth's inner core using PASSCAL data from BOLIVAR (Venezuela)

Observations of Antipodal PKIIKP Waves: Seismic Evidence for a Distinctly Anisotropic Innermost Inner Core

Fenglin Niu *(Department of Earth Science, Rice University)*, **Qi-Fu Chen** *(Institute of Earthquake Science, China Earthquake Administration)*

Studies of the seismic structure of the inner core using body waves that propagate through the inner core, such as PKIKP, are always hindered by contamination from mantle heterogeneities. A common approach in eliminating mantle anomalies is to use differential travel time or relative amplitude between PKIKP and a reference phase, which travels along a very close ray path to PKIKP in the mantle. Waves reflected at or refracted above the inner-core boundary (ICB), PKiKP and PKPbc, have been frequently employed to study the top ~400 km of the inner core [*e.g., Niu and Wen, 2001; Creager, 1992*]. On the other hand, no such reference phase has been identified as suitable for modelling the deeper part of the inner core [Breger et al., 2000]. As the result the seismic structure of the deeper ~800 km of the inner core is less constrained compared to the top ~400 km of the inner core. We found that PKIIKP is an ideal reference phase to PKIKP for deciphering seismic structure at the centre of the earth, as the two have very similar ray paths in the mantle (Figure 1a).

We found clear PKIIKP arrivals from two deep-focus

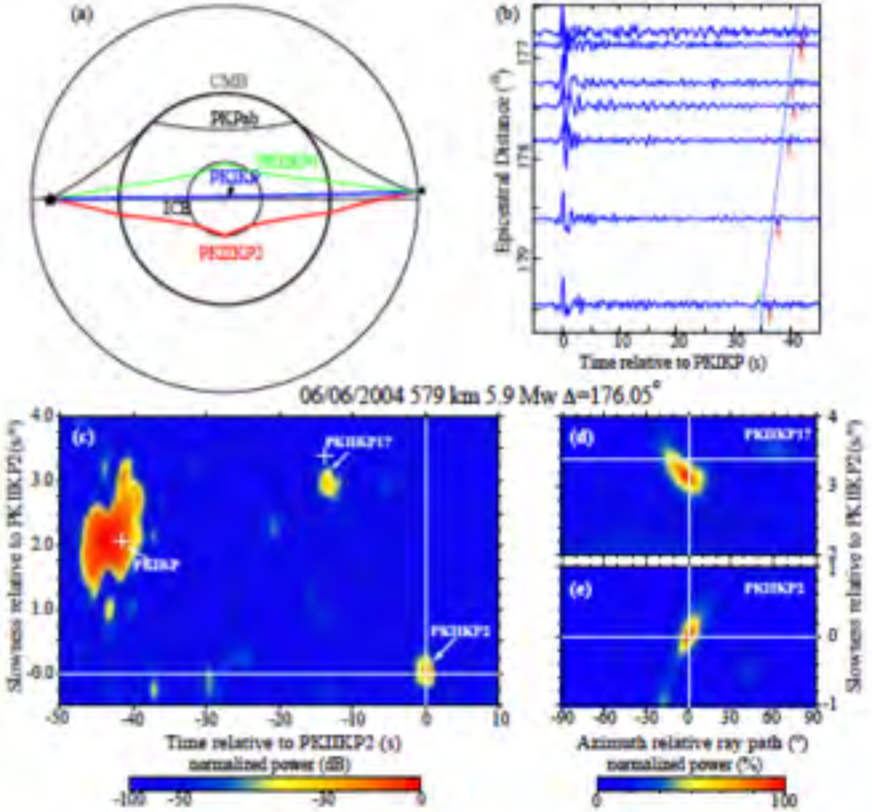
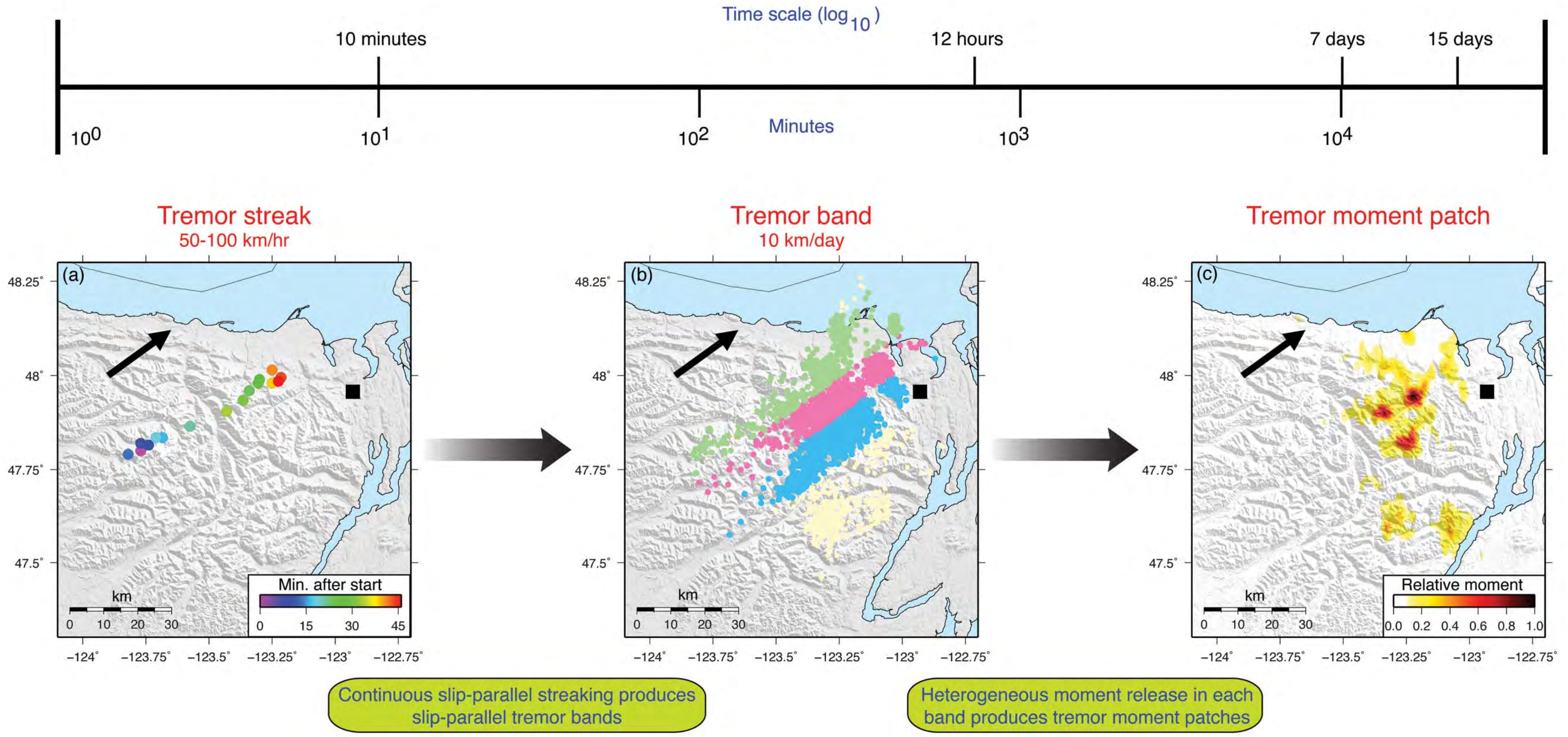


Figure 1. (a) Ray paths of the core phases: PKIKP (blue), PKPab (black), PKIIKP1 (green) and PKIIKP2 (red) at an epicentral distance of 178°. (b) Examples of seismograms recorded by the BOLIVAR array. (c) Color contour map of the vespa-

Niu and Chen, Nature Geo, 2008
Miller and Niu, EPSL, 2008

Details of Tremor Observed by a Dense Seismic Array

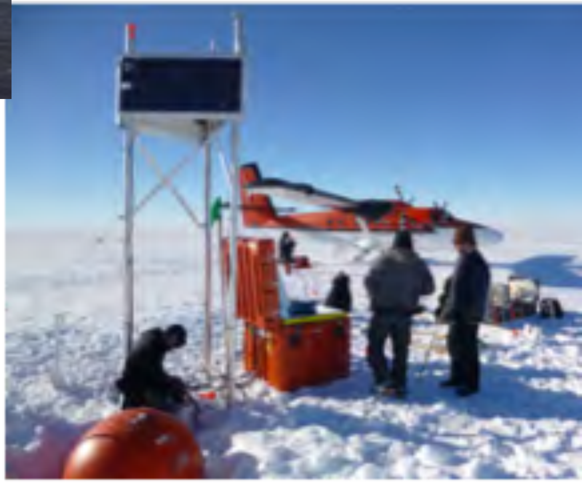


Ghosh, A., J. E. Vidale, J. R. Sweet, K. C. Creager, A. G. Wech, and H. Houston (2010), Tremor bands sweep Cascadia, Geophys. Res. Lett., 37, L08301.

PASSCAL Today

46 different experiments in 2017
48 different experiments in 2018

Examples of 2017/18 experiments –
Mexico RAMP
Alaska Amphibious Array
Education – Geophysics classes
Totten Glacier
Rutford Ice Stream
Induced seismicity – CO, TX, OK
Patagonia
Mongolia
SHIRE New Zealand
Seismic study of post-fire flash floods
FLUME 2.0
Dead Sea wide angle

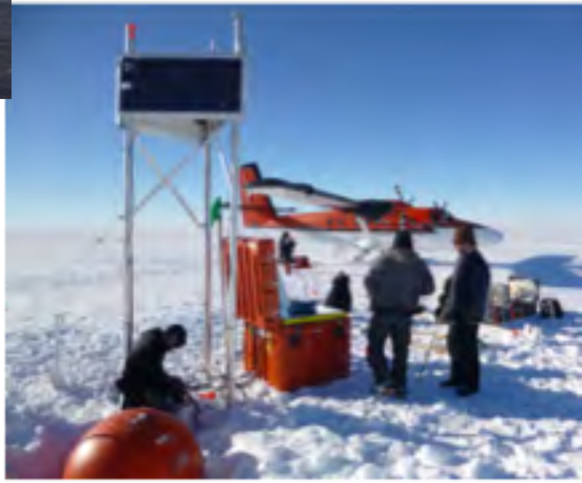


Summary –

PASSCAL has allowed us to do research on tectonic process on every continent, at every type of plate boundary, and a tremendously broad range of scales.

Much of what we now know about collisional processes in orogens, modes of rifting, and the cycling of melt and volatiles in subduction zones comes from PASSCAL experiments.

PASSCAL is guided by the community to address the major seismological science targets of today and tomorrow, even as those targets become more broad in nature.



Thank you to the many people who provided slides and information!

- Francis Wu
- Bob Busby
- Susan Schwartz
- Randy Keller
- Steve Harder
- Susan Beck
- Ken Creager
- Lara Wagner
- Art Lerner-Lam
- Paul Passmore
- Tom Owens
- Karen Fischer
- Steve Roecker
- Craig Jones
- Peter Molnar
- Kent Anderson
- Bob Woodward
- Marcos Alvarez









PASSCAL Inventory, 2018

Highlights: Calendar Quarter 1, 2018

SAGE, GLISN, & GEOICE: FY18, Y5, Q2

Equipment Inventory as of March 31, 2018

Table 6: Equipment inventory at the end of Q1, 2018

Inventory	Data loggers				All-in-one		Sensors						
	3-Ch Data logger	6-Ch Data logger	1-Ch “ Texan”	Multi-Channel	3-Ch/Broadband	3-Ch/Geophone	Broadband	Intermediate	Short Period	Geophone 3-ch	Geophone 1-ch	MC Geophone 1-ch	Accelerometer
PASSCAL	1221	81	2185	17		73	782	17	319	829	2416	817	30
RAMP		10						10					10
Polar	71	6					128	2					3
GLISN		14					10						
GEOICE	65					200	65						
TA	312	142					559						82
Total	1669	253	2185	17		273	1544	29	319	829	2416	817	125