Controlled-Source Seismology: An Essential Tool in the Geosciences

A White Paper Resulting from a Series of EarthScope Sponsored Workshops in 2007and 2008

1. Executive Summary

EarthScope represents a transformative vision of the way in which Earth Sciences can explore our continent, and offers a framework in which to re-assess the role of our highest-resolution geophysical tool, controlled-source seismology. This tool is effective in near surface studies that focus on the upper 100 m of the crust to studies that focus on Moho structure and the lithospheric mantle. IRIS has now existed for over two decades and has transformed the way in which passive-source seismology in particular is carried out. Progress over these two decades has led to major discoveries about continental architecture and evolution through the development of three-dimensional images of the upper mantle and lithosphere. Simultaneously the hydrocarbon exploration industry has mapped increasingly large fractions of our sedimentary basins in three-dimensions and at unprecedented resolution and fidelity. Thanks to EarthScope, a clear scientific need and opportunity exists to map, at similar resolution, all of the crust - the igneous/metamorphic basement, the non-petroliferous basins that contain the record of continental evolution, and the seismogenic faults and active volcanoes that are the principal natural hazards we face.

Controlled-source seismology remains the fundamental technology behind exploration for all fossil fuels and many water resources, and as such is a multi-billion-dollar industry centered in the USA. Academic scientists are leaders in developing the algorithms to process the most advanced industry data, but lack the academic data sets to which to apply this technology. University and government controlled-source seismologists, and their students who will populate the exploration industry, are increasingly divorced from that industry by their reliance on sparse spatial recording of usually only a single-component of the wavefield, generated by even sparser seismic sources. However, if we can find the resources, the technology now exists to provide seismic images of immense scientific and societal value that play a key role in fulfilling the ambitious mission of EarthScope.

This White Paper sets out a road map for the US controlled-source community to self-organize, and lays out fundamental needs to sustain that scientific community as a resource for all earth scientists.

2. The Role of Controlled-Source Seismology in Exploration of the Continents

In most situations, controlled-source seismology is highest resolution tool available for studies of the crust and uppermost mantle. For example in the past 20 years, controlled-source studies have: a) imaged faults at many scales and orientations (even vertical), b) mapped and characterized discontinuities and the velocity structure (Vp and often Vs) throughout the crust and uppermost mantle, c) delineated the structure of major features such as rifts, orogens, and subduction zones that are ancient or active today, d) detected fluids and magma in the crust, and e) played a key role in seismic hazard analysis and characterization of sites proposed for key facilities. Examples of some of these results are presented in the figures at the end of this paper.

3. Timeline of Meetings and Organization of Community Structure

This “White Paper” addresses the conclusions and actions resulting from a series of meetings of the U.S. Controlled-Source Seismology (CSS) group. These meetings were catalyzed by a small gathering during the 2006 Fall AGU meeting and began with a larger formal focus group gathering (~30 attendees) during the EarthScope National meeting in 2007, a 2-Day EarthScope-sponsored workshop on “The Role of Controlled-Source Seismology in the EarthScope Project” that preceded the Society of Exploration Geophysicists meeting in San Antonio (29 attendees) that was followed by a focus group gathering (~40 attendees) during the 2007 Fall AGU meeting and a focus group gathering during the 2008 IRIS workshop (~20 attendees). Together, these meetings included almost every member of the U.S.

Controlled-Source Seismology (CSS) community including numerous students with many individuals attending more than one meeting. In addition, these efforts have coordinated closely with an IRIS initiative to increase the level of cooperation between the petroleum industry and academic communities.

In the short-term, the most tangible results of these meetings were; (1) the emergence of a clear sense of community that spans interests from the near surface, to industry-scale, to the deep crust, to the lithospheric mantle, and (2) formation of an IASPEI U.S. National Committee on Controlled-Source Seismology to facilitate the scientific goals of this field. At the 2007 Fall AGU meeting, we elected officers and agreed to accept the IASPEI mandate to create a community structure that will:

* facilitate controlled-source experiments and their interpretation;
* promote controlled-source capabilities and integration with other scientific communities;
* develop innovative experiment designs; a knowledge base of best practices for fieldwork; software development and sharing; and a forum for discussions of needed technological developments;
* enable access to industry data and expertise, facilitate academic - industry interactions;
* develop plans for national field project support (i.e., manpower and equipment);
* support of the U.S. research-and-education community, with an emphasis on continental controlled-source seismology;
* be open to anyone wishing to support these goals, and provide information regarding current progress that is easily accessible through a web site.

4. Existing and historical infrastructure for controlled-source seismology

The controlled-source community has worked together to pool resources (primarily instrumentation) to conduct refraction/wide-angle reflection experiments for many years, and this practice continues on an international basis. These data are archived in the IRIS Data Management System.

The use of industry seismic crews in studies of the study of the deep crust of the continental lithosphere was lead by the Consortium for Continental Reflection Profiling (COCORP) that "pioneered the use of multichannel seismic reflection profiling for the systematic exploration of the continental lithosphere". "COCORP's success spawned an entire generation of national programs cored by deep reflection profiling, notable examples being BIRPS in Britain, DEKORP in Germany, LITHOPROBE in Canada, ECORS in France, and the efforts of AGSO in Australia. Although the last formal COCORP survey was completed in 1992, the COCORP dataset remains a unique and valuable resource for ongoing studies at Cornell and elsewhere". (http://www.geo.cornell.edu)

Today, the only source facility that is presently available for controlled-source studies is the RV Langseth that conducted its first seismic experiment early in 2008. Obviously, this resource is only useful for studies very near oceans.

http://www.ldeo.columbia.edu/res/fac/oma/langseth/index.html

There have been issues about the potential for harmful effects of air guns on marine mammals that effect on-shore/off-shore experiments. However, a report about Sperm whales in the Gulf of Mexico and seismic surveys with air guns concluded that marine seismic surveys and these whales can co-exist:

Jochens, A., D. Biggs, K. Benoit-Bird, D. Engelhaupt, J. Gordon, C. Hu, N. Jaquet, M. Johnson, R. Leben, B. Mate, P. Miller, J. Ortega-Ortiz, A. Thode, P. Tyack, and B. Würsig. 2008. Sperm whale seismic study in the Gulf of Mexico: Synthesis report. U.S. Dept. of the Interior, Minerals Management Service, Gulf of Mexico OCS Region, New Orleans, LA. OCS Study MMS 2008-006. 341 pp.

A history of U. S. instrumentation for controlled source seismology

Prior to 1984 – After a series of experiments conducted by the U. S. Geological Survey in the 1960's, the 1970's were a time when relatively few experiments were conducted primarily because of a lack of instrumentation. Thanks to cooperation between the U. S. Geological Survey, university researchers, colleagues from foreign countries, and national laboratories, the pace of field experiments increased in the late 1970's and continued into the 1980's at a modest pace. The development of the

SCR (Seismic Cassette Recorder) by the U. S. Geological Survey answered the need for a set of matched instruments even though they recorded on analog tape. Otherwise, experiments were conducted with a bewildering mix of recorders and seismometers with varying characteristics.

1984-1990 – The founding of IRIS in 1984 and the Canadian LITHOPROBE project brought renewed energy to the controlled source community in North America during this time, and many significant experiments were conducted. As part of LITHOPROBE, the Geological Survey of Canadian acquired 200+ digital instruments (PRS-1) that they helped design. However, a PASSCAL instrument that was truly suitable for controlled source work was unavailable from the IRIS pool during its early years of existence. The U. S. Geological Survey continued to conduct experiments with the SCR instruments and to regularly collaborate with the LITHOPROBE group so that experiments employing over 300 instruments could be conducted. In many cases, university and international groups participated in these experiments making more instruments available. In the mid-1980's, AMOCO donated 200 Seismic Group Recorders (SGR) to Stanford, and with support from IRIS/PASSCAL and the USGS, these instruments were modified for use in large-scale experiments and soon become the workhorse instrument for the U.S. community. The U. S. Geological Survey crustal studies group in Menlo Park provided much of the infrastructure needed to operate and maintain these instruments.

Although new instruments that could be provided by PASSCAL were yet to be developed, PASSAL supported its first two controlled source experiments in 1986. An experiment focused on the Ouachita orogenic belt used the AMOCO research crew that operated 800 SGR instruments. A large experiment in northern Nevada, employed the SGRs, and virtually all of the other instruments that the academic community could muster.

The Pacific to Arizona Crustal Transect (PACE) began in 1985, but it's later phases (1987, 1989, and 1992) evolved into PASSCAL experiments as the SCR's, SGRs and enough PASSCAL instruments became available to be helpful.

The KRISP experiments in 1985 and 1990 solidified an international partnership for controlled source seismology between the U. S., United Kingdom, Germany, Denmark, and Ireland that endures to today. The SGRs were the main instruments employed in the KRISP 90 and ultimately the KRISP 94 experiments.

1991-1998 –The SGR became a workhorse instrument for the community thanks to cooperation between Stanford University, the U. S. Geological Survey, and PASSCAL. Recognizing the controlled source community's need for a simple instrument for their experiments, PASSCAL worked with RefTek to design a 3-component version of the main RefTek instrument that was called the RefTek Jr. by some. However, this instrument required heavy batteries, external GPS clocks for many applications, and was far from simple.

By pooling various combinations of the Canadian instruments, the RefTek Jrs., the SGRs, and the SCRs, a number of large experiments were carried out. The SSCD (Southern Sierra Continental Dynamics), DELTA FORCE and DEEP PROBE experiments were the last to use the SCRs.

A new generation of recorders designed primarily for use in controlled source experiments became available in 1999. The RefTek 125 (Texan) instrument became was developed via a combination of grants to the University of Texas at El Paso (UTEP). The initial grant was from the Texas Higher Education coordinating board and funded a collaboration between UTEP and RefTek to design this instrument. Broad input from the international community and PASSCAL was sought during this process. Thanks to an MRI grant from NSF, 440 instruments were available by mid-1999, and during this year, 5 large experiments (3 with 400 instruments) were undertaken.

2000-2008 – PASSCAL quickly purchased an additional 400 Texan instruments bringing number in the PASSCAL/UTEP pool to 840. By collaborating with international colleagues, it became commonplace for 1000 Texan instruments to be fielded during experiments. After many successful deployments, an updated design (RefTek 125A) for the Texan instrument was finalized in 2004. PASSCAL and the EarthScope program began to purchase these models immediately, and the UTEP group focused on an upgrade path for the existing instruments so that as of mid-2008 some 2700 new or updated instruments are available for experiments. The first experiment deploying virtually all of this instrument pool is being undertaken in September of 2008.

5. Key issues that emerged from the workshops

5.1 Perceived high cost of experiments

A common myth is that Controlled Source Seismology (CSS) experiments are always expensive. The biggest expense is usually the sources (see discussions below), and just as with earthquakes, more is better. A LITHOPROBE-like effort with many 100's of km of contracted seismic reflection data, while highly desirable, would indeed be expensive. However, the Texan instruments afford us great flexibility to do experiments at many scales and with diverse array geometries. We have broadly shared a number of experiment designs and cost estimates that mostly emerged from EarthScope workshops, which show that significant experiments can be conducted with data acquisition costs in the $250K - $500K range. Using the participant support classification to budget for the travel expenses of undergraduate volunteers and having access to a source facility (see discussion below) can make even ambitious experiments cost-effective. The Texan instruments also have considerable potential for attracting funding to address important scientific problems in the growing fields of hydro-, environmental, economic and engineering seismology. **We therefore recognize that developing a broad base of support for Controlled-Source Seismology is important for the long-term health of the field**.

5.2 The role of the former U. S. Geological Survey crustal studies group

Over a period spanning approximately 1980 to 1997, the U. S. Geological Survey had a robust program in crustal studies based primarily in Menlo Park, CA with which the academic community cooperated regularly. This arrangement was simply ideal and benefited all involved via pooling of ideas, expertise, and resources, and a wide range of important scientific results were achieved. Although the funding for this activity within the U. S. Geological Survey has largely evaporated, this group remains viable and funds its self by focusing on near-surface studies. The possibility of funding some USGS participation in university-led experiments through IRIS and EarthScope has been discussed in many forums. In both the meetings that are the focus of this white paper and a recent meeting between the USGS Menlo Park seismic group and the IRIS Planning Committee, their participation in experiments has been a major point of discussion. The encouraging message from these meetings is that the USGS controlled-source group has been distributed and has experienced some retirements, but they are alive and well. They work with academic colleagues regularly but at a greatly reduced level compared to the 1980's and 1990's.

This current situation has left the academic community with the real difficulty that far too few of its members are licensed to handle explosives, and this community has on many occasions pointed out that permitting, drilling, and explosives handling were much easier when there was a higher level of direct participation from the U. S. Geological Survey. **A clear consensus is that a major effort to establish an expanded USGS CSS effort is needed, as is a more formal framework for cooperation.**

5.3 An NSF-funded source facility is needed

Some academic members of the CSS community have been conducting explosion seismic experiments without USGS support for some time, which proves this is possible. On the other hand, the groups that have done this are few in number, relatively established and possess considerable infrastructure. Thus, there is in essence an experience and infrastructure threshold that freezes out many capable members of the CSS community.

While USGS participation in experiments would be a positive factor, a major hurdle is cost. For example funding one USGS FTE requires ~$100,000/yr. Another option is to seek an agreement with the USGS in which they would work on an "as needed" and "cost recovery" basis the way they have in the past. **Thus, we should pursue a memorandum of understanding with the USGS as soon as possible so the CSS community can write proposals knowing that there would be someone to help them estimate the costs and do the experiment, in the event that they are funded. There are many indications of a spirit of cooperation**

between NSF and the USGS and this would be a timely low-cost, high impact activity that could have a major impact on EarthScope in particular.

As discussed above, CSS proposals are weakened by the budgetary need to include the source costs in the budget, making them expensive if they are ambitious efforts. **Our community feels that it is time to consider a source facility within IRIS, analogous to NSF support of ships in the marine community.** This facility could be distributed and consist of the following elements:

a) A shooting support facility that would consist of the UTEP group and the USGS as discussed above.

b) A near-surface source facility is not an expensive endeavor (e.g.,. a Mini-vibe and shotgun sources). However, it does require technical support in the form of staff. In addition, a Mini-vibe is capable if penetrating to depths approaching 1 km in good conditions and is thus a source capable of addressing many significant geological questions. In addition, the Vibroseis sources that are available from the NEES facility are credible (but fairly costly) sources that have been successfully employed in an EarthScope crustal-scale study.

c) For larger surveys, the best way to provide sources is to contract drill rigs and explosives and/or an industry Vibroseis crew through IRIS. It is not cost-effective for IRIS to own this equipment, plus contracting insures valuable state-of-the-art quality. We propose that NSF should set aside funds for contracts for drilling, explosives, and industry seismic reflection acquisition that would be overseen by IRIS. A $2.0 million dollar per year budget would support several wide-angle reflection/refraction experiments and the acquisition of deep seismic reflection data over carefully selected targets. Proposals could then be reviewed on their scientific merit rather than cost, and only approved proposals could use this fund.

Another major concern is the liability for damages caused by explosions. While our community has never caused injury to a person or damaged a structure with our controlled-sources, this possibility, however small, worries many. Using the USGS to permit and handle explosives largely avoids this problem, but even if a memorandum of understanding is reached with the USGS, they cannot help conduct all experiments. Commercial seismic and explosive contractors carry large liability policies, but coverage via these policies must be explicitly stated in the contract. Another problem is that many states frown on state employees buying liability insurance for their job. Some states even make it illegal. Our approach has always been to be very sure about what we are doing and to supervise operations carefully. However as we move toward more shots on private property, property owners will raise questions about liability insurance more often. **Thus, we request that IRIS consider acquiring a blanket liability policy that would cover PASSCAL experiments.**

5.4 How many instruments are enough?

Another common perception has been that the CSS community is not capable of deploying large numbers in an experiment. We have many examples of 1200-1300 instrument deployments even in remote places and difficult terrain, and experience shows that two modestly field-worthy people can deploy 50-to-100 instruments a day in a typical experiment, depending on driving time. **Thus, a two-day deployment by 20 crews fields 2000 to 4000 instruments.** For example, the High Lava Plains experiment conducted in Oregon in September of 2008 involved the deployment of over 2600 instruments by 23 crews. A portion of the deployment took three days because new 3-C recording with Texan instruments was being tried for the first time, and this deployment crossed a large mountain range. The CSS community has a tradition of helping each other in experiments, and geologic colleagues and their students are also anxious to help. Thus, gathering a crew this size is relatively easy for an experiment that takes 10-14 days, but longer experiments are admittedly a bigger challenge.

Our community appreciates the funding realities at NSF today, but 3-D and 4-D studies are a major focus in many research documents. In the seismic industry, 3-D crews often field ~10,000 instruments in order to achieve good 3-D coverage in sizeable areas. As we are pushed to and aspire to propose 3-D surveys, it is important to realize that the existing ~2700 instruments only constitute a 52x52 array. At an industry-standard instrument spacing of 50 m, this array would only cover 2.6 km x 2.6 km. At an instrument spacing of 500 m, this array would only cover area that is 26 km x 26 km. Thus, a crustal-scale 3-D experiment is indeed a major challenge logistically that would involve “rolling the array” several times to cover a large area, requiring several times the number of controlled-sources, already the most expensive element of our operations.

5.5 Manuals of "Best Practices"

During our meetings creating manuals of "Best Practices" arose in regard to a number of situations. For example, the real issue in regard to using large numbers of Texans in experiments is not the actual deployments, but rather the metadata that must be carefully collected, entered into a database in the field, and subjected to rigorous quality control. There is an exponential relationship between the number of instruments deployed and the number of possible mistakes that can be made in creating the required metadata. For instance the mistakes in a 200-instrument DASfile (a file matching the recorder serial number with a recording site number) can be corrected in minutes, while the mistakes in a 1000-instrument DASfile can take days or weeks. We've given a great deal of thought and some experimentation on how to change our management strategy to avoid this exponentially increasing complexity. First we suggest breaking large experiments into several smaller experiments (<200 instruments each), which are each managed separately throughout the entire quality control phase and only combined when the quality control has been completed on the smaller experiments. Second, we suggest assigning individual instruments to specific station numbers, rather than allowing deployers to decide which instrument is deployed at each station. The deployers would only verify that they deployed a particular instrument at a specific station. We have tasked individuals within our community to begin the hard work of gathering together the contents of such manuals, for inclusion on our community web page.

Obtaining permits is another areas where information would be useful because many believe that Controlled-Source Seismology experiments are always hard to permit for deployment and drilling. All types of field investigations are having more trouble with permitting than in the past, and the CSS community has had some difficulties. **However, we have had more cases of permitting being relatively easy than being problematic.**

In a similar vein, it is widely believed that using explosives must be very difficult since 9/11. **In fact, there has been no significant change in official procedures because quarrying operations exist in every state and country, which insures the existence of clear and reasonable regulations for the purchase and handling of explosives.** In addition, seismic exploration efforts have also resulted in regulations that often provide a framework for CSS operations. However, there are many ways to be clumsy about permitting that can greatly complicate the process, and pitfalls vary from area to area and with land ownership. This is another area where a manual of "Best Practices" would be very valuable. Such a manual could also be useful in passive array deployments.

5.6 Industry Issues

Working with industry, the petroleum industry in particular, is a natural activity for members of the CSS community. Many students go to work in this community, and the seismic reflection database in the petroleum industry is massive in the U. S. alone, and much of it would be a huge resource for EarthScope research. On an individual basis, many members of the CCS community have managed to obtain the release of significant amounts of data for their research and teaching programs. However, this approach is hit or miss and seldom produces data that can be made widely available. Various organizations have tried to push the release of industry data forward but with only modest success. Our subgroup working on this issue raised the following questions:

1. How do we find out where there is existing data for key EarthScope targets?

   Does this information reside in one, several, or many locations?

2. What are the existing umbrella's for accepting/archiving oil-industry data?

   Do we need a special EarthScope umbrella?

3. Should we consider piggyback recording, using portable EarthScope instruments, of oil-industry shoots? This might be mutually beneficial because of the wide-offset data our experiment could provide, and we would save some mobilization and source costs in our own experiment.

   Is it possible to deal with short notice opportunities in requesting NSF funding?

4. Should we expand EarthScope targets to include offshore regions (margins)?

   There is much available offshore data that would provide a quick start for EarthScope integrated studies

5. Will EarthScope welcome proposals to analyze non-EarthScope (industry) data?

One clear message is that better interactions with industry are highly desirable and that industry seismic reflection data is a huge potential resource for EarthScope researchers, but a good method to obtain its release for wide distribution remains elusive. The CSS group is coordinating with IRIS in regard this issue.

The one large breakthrough in regard to this is issue is the release of a large volume of data from Chevon for offshore California to the USGS and the American Geological Institute (http://soundwaves.usgs.gov/2005/06/). These data and data from several other contributors are available through the USGS National Archive of Marine Seismic Surveys (NAMSS) http://137.227.239.66/NAMSS/index.html. We can certainly use this success as a model for the release of land data.

5.7 Software

The software subgroup recognized the need to: **1) formulate a strategy for providing the EarthScope community with a "toolbox" to analyze seismic and other geophysical data using existing and emerging software, accessible through one web site; 2) develop a knowledge base of best practices for software development and sharing, and 3) provide community access to all types of academic software (data formatting, processing, modeling, imaging, inversion)**

1. Some key issues that this group identified were:
   - Identify software that is widely in use, or could be of use
   - Identify software gaps, including format exchange utilities between different codes

- Develop a design and maintenance plan for a web site with links to all software
- Identify and address reasons why software is not released such as:

    Fear that code is used incorrectly

    Creation of a beta version (including manual) is time consuming

    The algorithm is not published (yet)

    Release might give up a competitive advantage

    Lack of interest/time to maintain the software

    Not enough credit is given for software development

    Code writing is not considered “science”

2. Some steps that were identified that could provide a way forward:

- Identify incentives to encourage researchers to provide their software
- Provide guidelines for publishing/releasing software (<u>different levels</u>)
- Encourage funding agencies to support and reward software release as well as development
- Urge users to appropriately acknowledge the use of codes (<u>ideally a peer-reviewed citation</u>)
- Provide a peer-review system for software

3. Some thoughts about a plan for hosting, design and maintenance of web site

The host needs considerable experience with database and software serving.

The design should:

- Make it easy to post any type of software
- Include software, modules, subroutines, reformatting codes
- Allow different levels of release and support
- Include an author statement and user comments
- Include citations for published articles about the software
- Allow of updates and version tracking
- Low threshold for inclusion, “Buyer beware”

- Have one good example in place to serve as model with documentation, installation instructions, example input/out files, plots of output, references to the original application of code or the code itself (software journal), plus other applications of the code
- Include an electronic forum (testimonials, tips, warnings)
- Be largely self-maintaining

4. Other Issues

Unlike data, software is intellectual property

Develop benchmarking standards

Take advantage of similar and complementary efforts.

Probably need a 0.5 to 1FTE funded person to design and the create web site.

A broad committee is needed to oversee the web site, identify available software, and encourage further releases.

Workshops for software training and state-of-the-art software development techniques are needed.

6. Scientific opportunities

6.1 Innovative experiment designs and integration of multiple techniques

The seismological community around the world regardless of the scale of operation seeks to conduct surveys that have high resolution at the scale of the scientific target. The desire is to couple good spatial resolution in images or models aimed at mapping structures with the ability to determine velocities well enough to infer physical properties. With a total of 2700 Texan instruments in the PASSCAL/EarthScope combined pool, the possibility of contracting industry reflection crews, and access to sources, we have the opportunity to achieve much better resolution. However, new approaches to experiment designs are needed. Our integration and experiment design subgroups focused on the following points:

Better Resolution!

- Compared to the industry we don’t have the resolution we and the scientific community want and need.
- We presently lack some of resources and the knowledge base of industry in imaging in 3D and with 3 components.
- We need to improve interaction with geologists to interpret small-scale features in a large-scale context.
- Enhanced resolution of the whole-crustal and upper-crustal depths increases the accuracy of passive-source results.
- New/innovative experiment designs:
  - “2.5D”, 3D, swath 3D
  - 3D VSP imaging for steep structures
  - Non-traditional source-receiver geometries
  - Value-added (combined) experiments
- Take advantage of the full wave field via 3 component recording
- Hybrid multi-scale acquisitions that not simply use different receivers but also different sources (e.g. a densely sampled full-aperture wide-angle reflection/refraction survey that uses Vibroseis and explosive sources.

Challenges

- Sources: we need more and different kinds of sources (integrate different sizes of explosives and P/S-wave vibrators)

- More 3C instruments and/or better use of the existing equipment (i.e., implement the 3C configuration originally envisioned for the Texans)
  - HSVS technology for sensors
  - Anisotropy, multi-azimuth studies
  - Ambient noise tomography
- We need better communicate the strengths of CSS vs. passive-source methodologies in a constructive way that leads to better scientific results
- A source facility is badly needed (or said another way the facilitation of sources)

Possible Ways Forward

- Design an integrated "super experiment" to show how to take advantage of different CSS and passive methodologies in a single acquisition
- Piggy-back with industry during their acquisitions
- Take advantage of marine sources where possible (lakes, rivers, offshore/onshore)
- Take advantage of existing and funded projects. Requires improved communications within our community A website is a good starting point.
- Interact regularly with the geology community (have sympathetic geologists collaborate on our proposals and engage in interpretations)
- Work on shear wave attenuation problems
- Work with the passive source community to design formal schemes for the integrated analysis of CSS and passive source data.

6.2 Some near-term action items we identified and their status

•**Establish a website.** This has been done and the address is: ***http://www.usccss.org/***

•**Revisit the 2005 IRIS proposal item of one FTE at the USGS for sources and permitting.** This issue has been raised several times

•**Convene a source workshop.** Pending

•**Obtain a blanket insurance policy.** This subject has been raised with IRIS.

•**Actively pursue interactions with industry.** This effort is being pursued in cooperation with IRIS and on an individual basis.

•**Take advantage of funded project to organize piggyback experiments and innovate.** The High Lava Plains experiment scheduled for September of 2008, now includes two piggyback experiments for which funding has been obtained.

•**Create a formal organization for the CSS community.** We have formed the IASPEI U.S. National Committee on Controlled-Source Seismology and elected officers. This committee is intended to serve all members of the CSS community including those interested in near-surface studies.

7. Summary of long-term goals

Establish a source facility.

Establish a website and infrastructure to support the development, maintenance, and evolution of software.

Develop manuals of best practices for the key elements of CSS experiment such as planning and execution of experiments and software development.

Explore new technologies for instrumentation.

Develop new data analysis methodologies (e.g., material property tomography)

Generally explore what will improve the way we do science in our field.

Identify the missing gaps in information that colleagues want and we could provide with our evolved approaches.

Identify what scientific topics can we significantly contribute to or drive that will engage other disciplinary communities.

Work to find solutions for **grand challenges** such as:

•Answering the question, where does that fault go from the surface?"

•Deriving earth material properties beyond Vp,Vs, rho.

•Developing 3D anisotropic tomography capability

•Developing innovations in source technology

- creative new sources
- propagate 100 Hz to the Moho and back

•Developing joint inversion schemes for diverse data sets.

- Developing experiment designs that produce cost-effective 3D data sets.
- Developing a robust two-way interaction with industry groups.

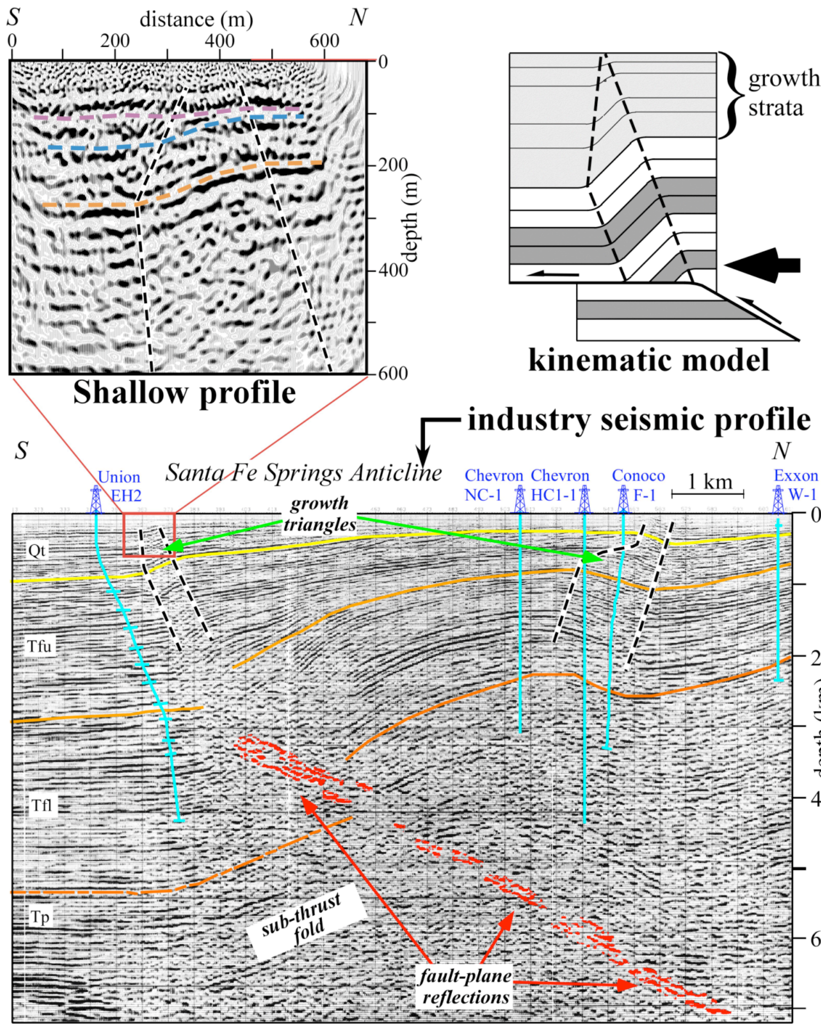
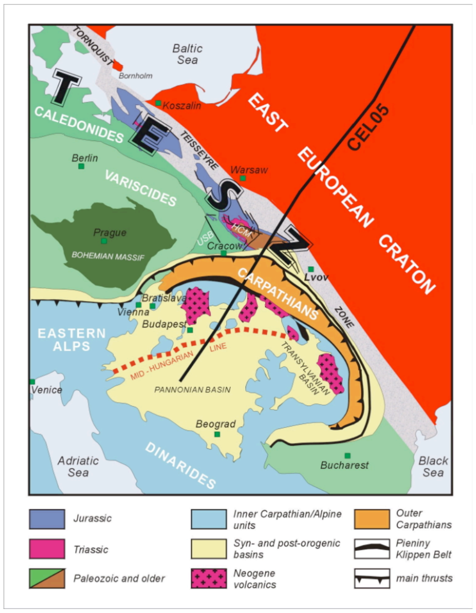


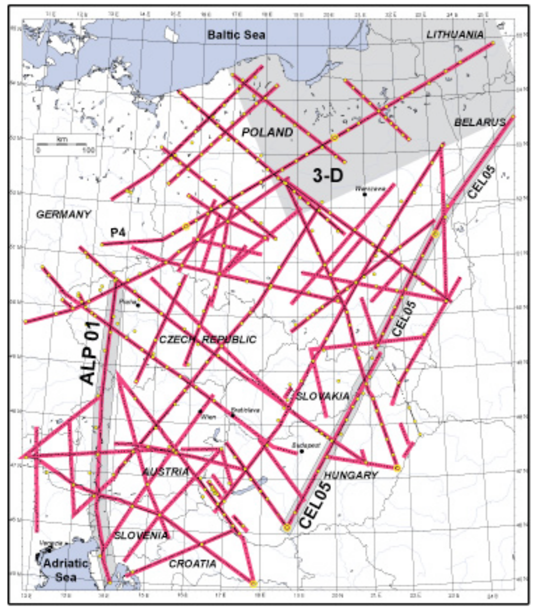
Figure 1: Seismic reflection profiles across the Puente Hills blind thrust fault, Los Angeles. Industry seismic reflection data were used to identify the major structures, and shallow seismic reflection profiles acquired with weight drop, Mini-Sosie or vibrator sources were employed to delineate the shallow expression of the folds above the blind thrust faults. Shallower profiles using sledgehammer sources were used to trace the folds to within 20 m of the surface, where cores can be taken or where a trench can be excavated to view the most recent folding. A kinematic model of the growth fold is shown in the upper right. Figure modified from Pratt et al. (2002).

Pratt, T. L., Shaw, J. H., Dolan, J. F., Christofferson, S., Williams, R. A., Odum, J. K., and Plesch, A., 2002, Shallow seismic imaging of folds above the Puente Hills blind-thrust fault, Los Angeles, California, *Geophysical Research Ltrs*, v. 29, p. 18-1 – 18-4 (May 8, 2002).

Figure 2

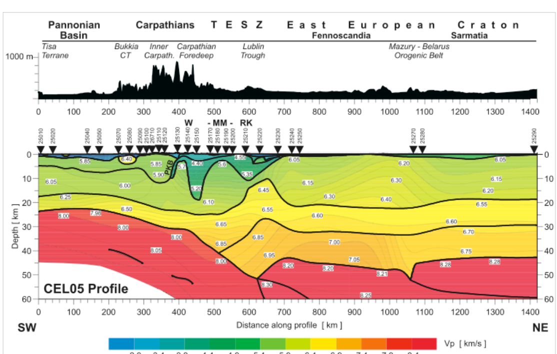


A

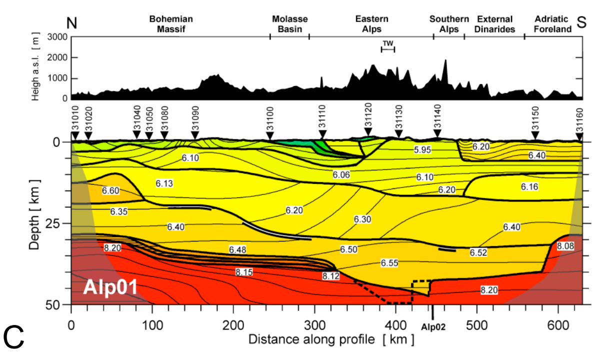


B

Central Europe has experienced a complex tectonic history that is dominated by the accretion of terranes to the rifted margin of Baltica (East European Craton) that extends through central Poland (TESZ – Trans-European Suture Zone) and formation of the Alps, Carpathians, and Pannonian basin (Fig. 2a). Beginning in 1997, Central Europe has been covered by an unprecedented network of seismic refraction experiments (Fig. 2b). These experiments (POLONAISE'97, CELEBRATION 2002, ALP2002, and SUDETES 2003) produced ~19,000 km of seismic profiles and extensive 3-D coverage and could have only been possible through a massive international cooperative effort. They along with the BOHEMA and ALPASS teleseismic experiments are providing exciting new insights into the structure and evolution of the lithosphere in this complex region. The velocity model derived from the CEL05 profile that extends from Baltica across the Carpathians into the Pannonian basin is shown in Fig. 2c, and the model for the ALP01 profile is shown in Fig. 2d.



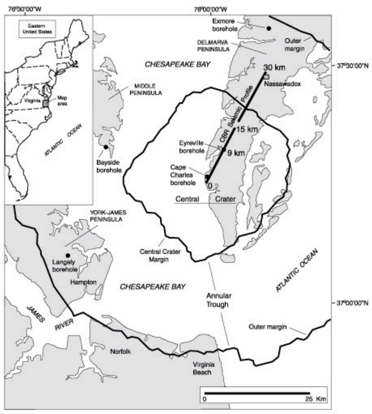
C

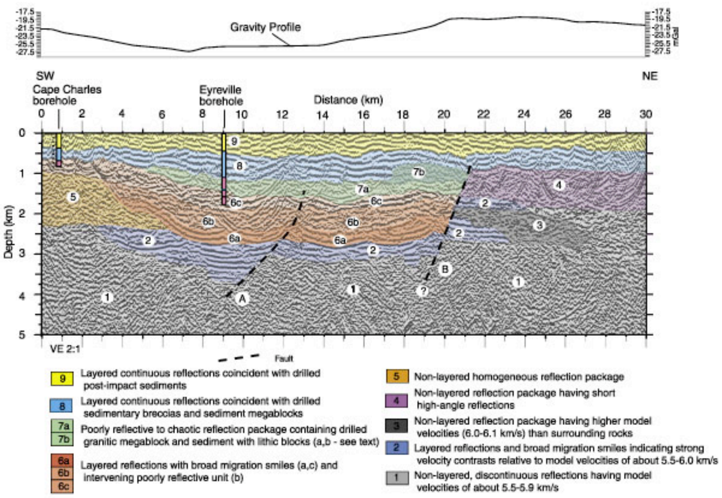


D

Brückl, E., F. Bleibinhaus, A. Gosar, M. Grad, A. Guterch, P. Hrubcova, G. R. Keller, M. Majdanski, F. Sumanovac, T. Tiira, J. Yliniemi, E. Hegedüs, H. Thybo, 2007, Crustal structure due to collisional and escape tectonics in the Eastern Alps region based on profiles Alp01 and Alp02 from the ALP 2002 seismic experiment: Journal of Geophysical Research, v.112, B06308, doi:10.1029/2006JB004687.

Grad, M., A. Guterch, G. R. Keller, T. Janik, E. Hegedűs, J. Vozár, A. Ślączka, T. Tiira, and J. Yliniemi, 2006, Lithospheric structure beneath trans-Carpathian transect from Precambrian platform to Pannonian basin: CELEBRATION 2000 seismic profile CEL05: Journal of Geophysical Research, v.111, B03301, doi:10.1029/2005JB003647.





Interpreted reflection image with tomographic velocities in color

A 30-km-long, radial seismic reflection and refraction survey completed across the northern part of the late Eocene Chesapeake Bay impact structure (CBIS) (Fig.1) confirms that the CBIS is a complex central-peak crater (Catchings et al., 2008). A tomographic P wave velocity model and low-fold reflection images, constrained by data from two deep boreholes, were used to interpret the structure and composition of the upper 5 km of crust. The seismic images (Figs. 2, 3) exhibit well-defined structural features, including (with increasing radial distance) a collapsed central uplift, a breccia-filled moat, and a collapsed transient-crater margin (which collectively constitute a 40-km-wide collapsed transient crater), and a shallowly deformed annular trough. These seismic images are the first to resolve the deep structure of the crater (>1 km) and the boundaries between the central uplift, moat, and annular trough. The images show 350 to 500 m of postimpact sediments above the impactites. The imaged structure of the CBIS indicates a complex sequence of events during the cratering process that will provide new constraints for numerical modeling.

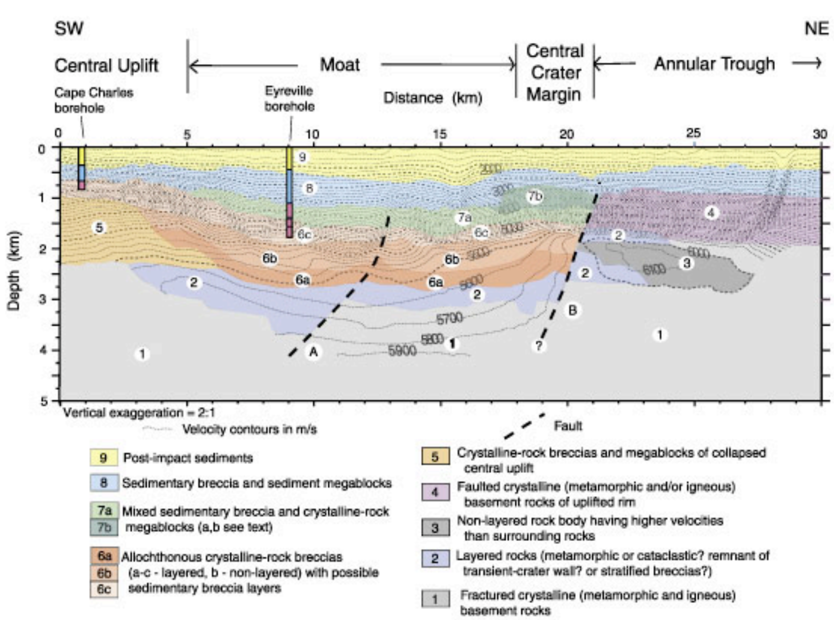


Figure 3: Integrated geological and geophysical interpretation.

Catchings, R. D., D. S. Powars, G. S. Gohn, J. W. Horton Jr., M. R. Goldman, and J. A. Hole (2008), Anatomy of the Chesapeake Bay impact structure revealed by seismic imaging, Delmarva Peninsula, Virginia, USA, J. Geophys. Res., 113, B08413, doi:10.1029/2007JB005421.