

**BACKGROUND MATERIALS TO ACCOMPANY THE REPORT
OF THE SAFOD ENGINEERING SUBCOMMITTEE OF THE
ADVISORY COMMITTEE FOR GEOSCIENCES
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BACKGROUND

The San Andreas Fault Observatory at Depth (SAFOD) was constructed as a component of the EarthScope Program of the National Science Foundation between 2003 and 2008. The facility includes a 10,500 ft borehole (measured depth along the well trajectory) that terminates inside of the active trace of the San Andreas Fault at a true vertical depth of 2.6 km. The scientific rationale for installing an observatory of seismic, pressure and deformation sensors within the actively deforming San Andreas Fault zone has been presented previously in the 2003 EarthScope MREFC Proposal and the 2007 EarthScope O&M proposal. In brief, the SAFOD observatory offers the unique opportunity to observe variations in deformation, fluid pressure, microseismicity and radiated seismic energy within and adjacent to recurring earthquake rupture patches over multiple earthquake cycles. Acting in concert with studies on recovered samples, SAFOD monitoring will thus make it possible to observe directly a number of time-dependant processes related to earthquake nucleation, propagation, and arrest, including: (1) the possible role of temporal variations in fluid pressure within the fault zone in controlling earthquake periodicity and rupture propagation and arrest, (2) the interplay between aseismic and seismic fault slip in the nucleation process for repeating microearthquakes, (3) the time scales and physical processes through which stress and strain interactions occur between nearby earthquakes, and (4) the manner in which earthquake energy is partitioned among seismic radiation, frictional dissipation, grain-size reduction, and chemical reactions.

The scientific experiment being conducted at SAFOD is unique. Never before have detailed measurements of the seismic and aseismic fault movement and related processes been attempted under the temperature, pressure and other physical conditions encountered inside of a major plate boundary fault at the depth where earthquakes nucleate. The challenge would be to build and install a robust system directly within the fault and operate it continuously at temperatures of ~125 °C and fluid pressures of 30 MPa. The MREFC proposal had a budget of \$2.56 M for all monitoring activities. This included: \$0.53 for development and testing of seismometers, MEMS accelerometers, tiltmeters, etc. (Stage 1); \$0.34 for behind casing instrumentation (Stage 2); and \$1.69 M for the observatory (Stage 3). Multiple deployments of seismic and tilt instruments were made in both the main hole and pilot hole between 2004 and 2007 in Stage 1. The optical fiber strain meter, designed by Mark Zumberge of UCSD was installed behind casing in 2005 in Stage 2.

After the completion of the Phase II drilling in 2005 we found that the wellbore fluid was saturated with natural gas and light weight hydrocarbons coming from the sedimentary formations either within or northeast of the San Andreas Fault. The presence of gas and light hydrocarbons in the wellbore fluid proved to create major problems in the Stage 1 deployments of instruments. We attempted to isolate the source of the hydrocarbons from the areas of greatest interest for instrumentation by installing a bridge plug and cement in the casing in 2006. This operation was unsuccessful, probably due to a poor

quality cement job done by the contractor when the casing was run in at the end of Phase II drilling.

The standard industry procedure for instrumenting wells with gas isolates all components and control lines from contact with the wellbore fluid. This is done by eliminating all O-rings from the design of the pressure vessels and using only metal-metal seals or welds. Control lines are protected by encapsulating them in stainless steel tubing. Connections between the control lines and the pressure vessels are made using metal-metal seals (Swedge Lock or equivalent). Following the advice of our principal contractor for the design and fabrication of the SAFOD observatory, Pinnacle Technologies, we adopted their recommendation for an array of instruments encapsulated within a 2nd pressure vessel (“pod”) with welded or metal-metal seals that were connected together by power and signal lines encapsulated in stainless steel tubing.

We also obtained advice on the proposed instrumentation system from the SAFOD Monitoring Instrumentation Technical Panel, experts associated with IODP and International Continental Scientific Drilling Program (ICDP), as well as the Geothermal Research Instrumentation Group at Sandia National Laboratories. Issues considered included the potential longevity of the SAFOD permanent instrumentation systems and recommend the following practices, which were implemented for the SAFOD observatory:

1. Employ instrumentation that allows long-term operation at elevated temperature and pressure in a corrosive environment. Replace polymer O-ring seals with metal-metal seals. Use only high-temperature, qualified electronic components. Encapsulate electrical conducting cables and optical fibers inside seamless stainless steel tubes that will be connected to the instrumentation pods through welded or metal-to-metal seals.
2. Plan for the SAFOD monitoring instrumentation system to be replaced every three years.
3. Deploy instrumentation on 2-3/8-in-diameter tubing to facilitate installation and retrieval. This tubing will also be used to install a bridge plug that will isolate pressure at the bottom of the hole for long-term monitoring of fluid pressure within the fault zone.

The observatory installed at the conclusion of the MREFC project in September 2008 used the best design and equipment that fit within a Stage 3 budget that was much smaller than originally planned. The reason for this is simple to understand: Drilling in Phase III in the summer of 2007, when the core from the San Andreas Fault was obtained, cost far more than had been anticipated when the MREFC proposal was prepared in 2002, and left less than \$0.4 M to build and install the observatory. The EarthScope Management Team was informed of budgetary impact on the observatory at the SAFOD Annual Review Meeting in Paso Robles, CA on September 7, 2007. During the review meeting, the SAFOD PI's were strongly questioned by other member of the EMT about the scientific opportunities that would be sacrificed by cutting-back the types and numbers of instruments. NSF informed us at the same meeting that SAFOD would receive no additional funds under the MREFC, and so the die was cast.

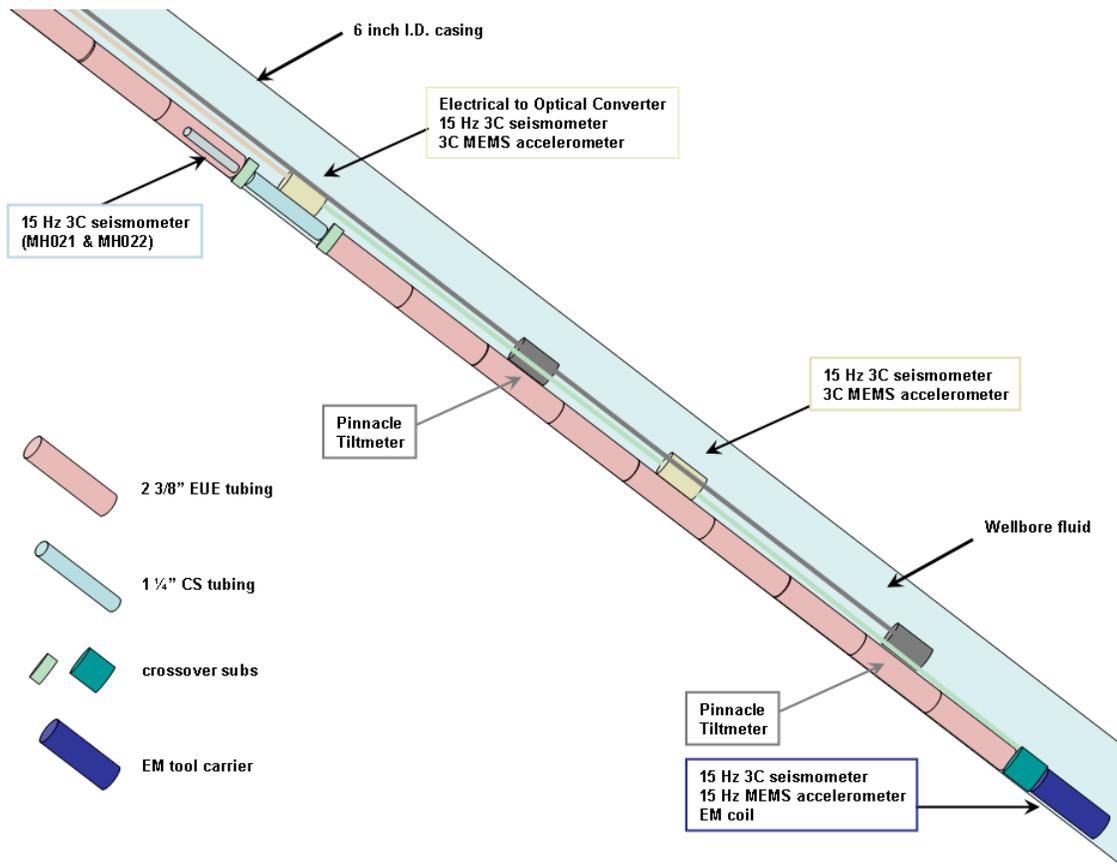


Figure 1. Layout of instrument section of the SAFOD observatory deployed in September 2008. The five instrument pods are rigidly attached to the supporting EUE tubing, and coupled to the inside of the casing by bow springs located on the top side of the pods. Oyo Geospace DS150 digital borehole seismometers are located in the 1st, 3rd and 5th pod. One DS150 contains 15 Hz geophones and the other Colybris MEMS accelerometers. Pod 5 also contains a 3rd DS150 connected to a large EM coil provided by funding from NASA. Pods 2 and 4 contain Pinnacle Technologies tiltmeters. Location of the currently operating analog seismometer (MH022) is shown.

The observatory as deployed in September 2008 consisted of two independent systems, one for the tiltmeters and one for the seismic and electromagnetic sensors attached to the outside of 2-3/8-in-diameter EUE tubing. It took over a week of operations with a small drill rig and large technical crew to install the system to a depth of 10,400 ft. The main risk of failure during installation was judged to be damage to the control lines during the lowering of the system into the well. These parts are particularly vulnerable because they had to be attached to the outside of the EUE tubing, and as such were subject to abrasion as the system slid down the well. We used best industry practice to protect the control lines, including the use of protective clamps at every joint between pieces of EUE tubing (30 ft), and at every mid-joint. We also used centralizers to keep the control lines away

from the casing in the dipping portion of the well. Despite our best efforts, we lost contact with one of the tiltmeters before we reached bottom. The other tiltmeter arrived on bottom in good condition. About 2 weeks ago it began to have problems and ultimately stopped working on October 14. Ralf Krug at Pinnacle Technologies, who was monitoring the instruments very carefully, is of the opinion that the system sprang a leak which caused it to fail.

The seismic array arrived on bottom in fully functional condition. Difficulties with the seismic data, however, began to appear after several days of operation in the form of communication problems between the 7 modules. The problems showed a perplexing pattern of "noise" that had a clearly daily (24 hour) cycle. Problems were most severe in the hours before midnight and improved during the daylight hours. Because of this daily cycle we concluded that it was highly unlikely that the problems were strictly downhole. This initiated several trips to SAFOD to investigate possible uphole problems with power supplies, the GeoRes computer, etc. On October 10 we lost communication with all but the top instrument, and the decision was made to continue recording it in the hope that additional work would allow us to restore the other 6 instruments. Unfortunately, this was not to be the case. After an additional four days of operation, the last surviving instrument went into a spasm of drop-outs, spikes and reboots that ultimately led to no data coming from the tool.

In early December, 2009, the USGS installed an analog seismometer inside of the EUE tubing that provides support for the SAFOD observatory in a manner that did not interfere with the SAFOD observatory or in any way compromise access to the observatory for its extraction, repair and replacement in the future. As of May 25, 2009, the other operational systems at SAFOD include the UCSD optical fiber strainmeter in the main hole; a Guralp VBB seismometer and accelerometer in the pilot hole (to be removed later this week after a year+ of successful cooperative deployment); and the LBL 3C accelerometer in the main hole installed in 2008 that is part of Carnegie's crosshole seismic monitoring experiment. These other instruments are in the vertical parts of the respective wells and at depths of about 1 km, and are located about 1.8 km southwest of the San Andres Fault. The data from the strainmeter and VBB seismometer are flowing as planned into the EarthScope data repositories. Data from the analog seismometer at the bottom of the main hole is archived and available to the community through the Northern California Earthquake Data Center at UC Berkeley. Data from the LBL accelerometer is under the control of the PIs.

A primary science objective of the SAFOD experiment continues to be the observation of the microearthquakes located nearest to the instruments, the "target" earthquakes. The drilling plan was designed from the beginning to come as close as possible to them. These target earthquakes are repeating earthquakes that re-rupture the same area of the fault in nearly identical earthquakes. The rupture areas of these events have been stable since at least 1984 (when digital waveforms from the regional seismic network first became available). Figure 2 shows the location of the target earthquakes relative to the SAFOD well at the completion of Phase II drilling in 2005. The current hole terminates at the "3190 m" fault. The "Hawaii" target earthquake is located approximately 100 m

below the well, and the “S.F.” and “L.A.” target earthquakes are located approximately 300 m above and northeast of the well. The most recent occurrence of the target events were in August 2008 (Hawaii) and December 2008 (S.F. and L.A.). Their recurrence intervals are currently lengthening following the speed-up caused by the 2004 Parkfield earthquake. The next recurrences of all three sequences will likely occur in 2010.

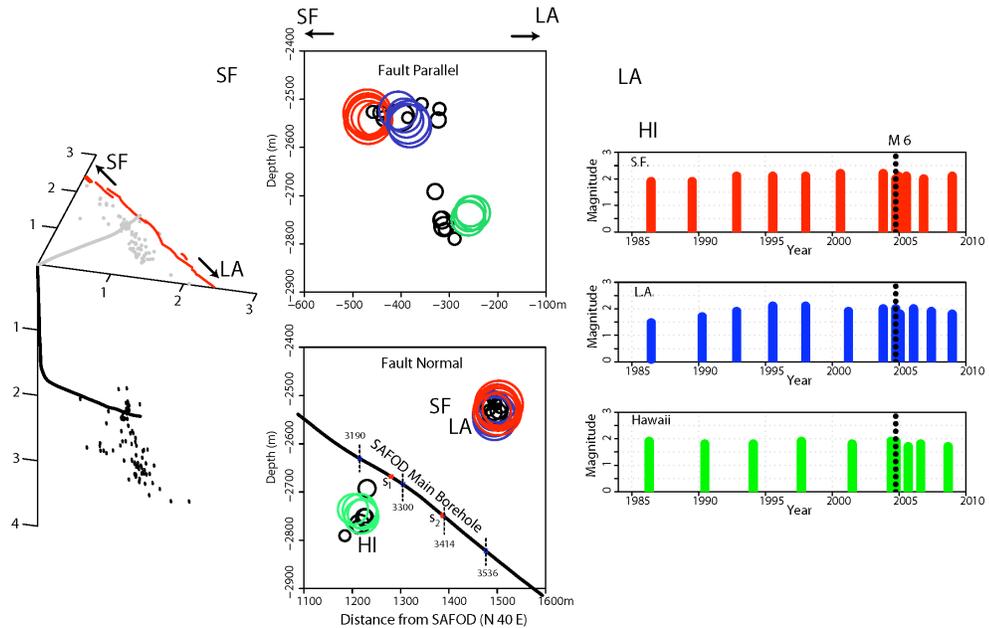


Figure 2

Figure 2. Left) Perspective view of microearthquakes occurring on the San Andreas Fault in the vicinity of the SAFOD drillsite and the trajectory of the SAFOD mainhole. Center Top) View of the plane of the San Andreas Fault at ~2.7 km depth. The red, blue and green circles represent seismogenic patches of the San Andreas Fault that produce the regularly repeating target microearthquakes discussed in the text. Center Bottom) Cross-sectional view of the target earthquakes, the trajectory of the SAFOD borehole and some of the most significant faults encountered during drilling. Right) The time sequence of the repeating earthquakes.

Scientific Drilling Into the San Andreas Fault Zone

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This year, the world has faced energetic and destructive earthquakes almost every month. In January, an $M = 7.0$ event rocked Haiti, killing an estimated 230,000 people. In February, an $M = 8.8$ earthquake and tsunami claimed over 500 lives and caused billions of dollars of damage in Chile. Fatal earthquakes also occurred in Turkey in March and in China and Mexico in April.

These recent disasters reinforce the critical need to better understand earthquakes and active faults. One way to help gain this understanding is by drilling into active faults at seismogenic depth. Through such drilling, it is possible to exhume core for analysis of mineralogy, deformation mechanisms, and constitutive properties of actual fault zone materials. Further, studies can be carried out to measure the state of stress and pore pressure in and near the fault zone, to determine the nature and significance of time-dependent chemical and physical fault zone processes, and to closely monitor the physics of earthquake nucleation and rupture (see review by *Zoback et al.* [2007]).

Several recent scientific drilling projects have addressed these types of fundamental questions. The Nojima fault scientific drilling project exhumed core from the near-surface projection of faults associated with the 1995 Kobe earthquake ($M = 6.8$ [see *Ando*, 2001]). Similarly, a Taiwanese scientific drilling project exhumed core from about 1-kilometer depth in the Chelungpu fault, responsible for the 1999 Chi-Chi earthquake ($M = 7.6$ [see *Tanaka et al.*, 2002]). More recently, EarthScope's San Andreas Fault Observatory at Depth (SAFOD) project drilled into a creeping portion of the San Andreas Fault, immediately north of Parkfield in central California, where frequent and repeating small earthquakes occur.

The SAFOD drilling provides a comprehensive case study of how future scientific drilling into active fault zones may be conducted. Table S1 in the online supplement to this *Eos* issue (<http://www.agu.org/eos>

_elec/) provides links to information about the project, including drilling data, geophysical logs, physical samples, and earthquake recordings on observatory instrumentation. Insights revealed through SAFOD can help scientists to better understand transform plate boundaries around the world.

Investigating the Fundamentals of a Transform Plate Boundary

As summarized by *Hickman et al.* [1994], part of the motivation for fault zone drilling arises from the San Andreas stress/heat flow paradox, originally posed by *Brune et al.* [1969]. A substantial body of heat flow data [*Lachenbruch and Sass*, 1980] and stress orientation data [*Mount and Suppe*, 1987; *Zoback et al.*, 1987] indicates that slip in crustal earthquakes along major plate-bounding faults occurs at much lower levels of shear stress than observed on intraplate faults or predicted by laboratory friction measurements on common rock-forming minerals under hydrostatic pore pressure. In other words, plate-bounding faults appear to be weak faults in an otherwise strong crust [*Rice*, 1992].

There have been three general classes of hypotheses proposed to explain the weakness of plate-bounding faults: extremely high pore pressure within the fault zones with respect to the surrounding crust [e.g., *Rice*, 1992], abnormally low friction minerals within these faults (but generally not found elsewhere), or dynamic weakening during earthquake rupture due to processes such as shear heating [e.g., *Lachenbruch*, 1980]. Numerous theoretical and laboratory studies have been carried out to further develop these concepts, yet a definitive resolution of the stress/heat flow paradox has remained elusive. Only through deep drilling, down-hole measurements, and sampling of fault rocks and fluids can one directly test the many hypotheses related to the physical and chemical processes that are active within plate-bounding faults at depth.

At SAFOD it was possible to build upon the extensive research that has been conducted on the most studied fault in the world. An important criterion in selecting the SAFOD drill site was the ability to drill

through the fault zone close to repeating $M < 2$ microearthquakes [*Thurber et al.*, 2004] with near-identical sources at relatively shallow depths (Figure 1). The closely spaced source zones for these microearthquakes are shown in red and blue in Figures 1b and 1c as the San Francisco (SF) and Los Angeles (LA) events, respectively, for their relative positions with respect to those cities. The Hawaii (HI) cluster of events shown in green occurs on a parallel branch of the San Andreas Fault to the southwest of SF and LA. Aseismic creep (at a rate of ~ 2.5 centimeters per year) occurs on the fault surrounding these seismogenic patches.

In preparation for SAFOD, a pilot hole 2.2 kilometers deep was drilled and instrumented in 2002 as a collaborative effort between the International Continental Scientific Drilling Program (ICDP), the U.S. National Science Foundation, and the U.S. Geological Survey (see special issues of *Geophysical Research Letters*, 31(12) and 31(15), 2004, for scientific findings).

SAFOD drilling was conducted in three phases during the summers of 2004, 2005, and 2007. Phases 1 and 2 involved rotary, directional drilling to intersect the San Andreas fault zone near the SF, LA, and HI target earthquake clusters (see Figure 1b). During rotary drilling, extensive drill cuttings were collected and formation gases dissolved in the drilling mud were continuously analyzed [*Wiersberg and Erzinger*, 2008]. In addition, comprehensive suites of geophysical measurements were made over the length of the borehole. These include a wide variety of physical property measurements, borehole imaging, and stress measurements.

After steel casing was cemented in the borehole following Phase 2, repeated measurements of the shape of the casing revealed that it was being progressively deformed by fault movement. This occurred at measured depths of 3192 and 3302 meters (corresponding to vertical depths below ground surface of 2620 meters and 2675 meters, respectively). Because these likely represent active fault traces, referred to as the southwest deforming zone (SDZ) and central deforming zone (CDZ), respectively, they were the principal targets for coring during Phase 3 in 2007.

Structure and Properties of the San Andreas Fault Zone

Analyses of drill cuttings obtained during Phases 1 and 2 revealed a number of

distinct lithologic units, seen in Figure 1. In the interval that later proved to be the active San Andreas fault zone, trace amounts of unusual minerals such as serpentine [Solum *et al.*, 2006] and talc [Moore and Rymer, 2007] were found. Phase 3 involved coring multilaterals off and adjacent to the Phase 2 hole to obtain cores from units adjacent to the fault zone and across the SDZ and CDZ.

Downhole measurements and geophysical logs acquired during Phases 1 and 2 revealed much about the structure and properties of the San Andreas fault zone at depth. An approximately 200-meter-wide damage zone of anomalously low P and S wave velocities and low resistivity (Figure 2a) is interpreted to be the result of both physical damage and chemical alteration of the rocks due to faulting. There are also a number of localized zones where the physical properties are even more anomalous, particularly within the SDZ and CDZ (Figure 2b). Note the remarkable similarity of the anomalously low compressional (V_p) and shear (V_s) wave velocities and resistivity within these two deformation zones. The HI earthquake cluster occurs on the SDZ about 100 meters below the point where the borehole passed through this fault (Figure 1c). Because of the uncertainty in the location of the SF/LA events with respect to HI, it is possible that the SF/LA cluster correlates with the fault at 3413 meters. This fault defines the northeastern edge of the damage zone and has geophysical characteristics very similar to the SDZ and CDZ (Figure 2a), although no casing deformation was detected on the 3413-meter fault during surveys carried out between 6 October 2005 and 6 June 2007.

Forty meters of 10-centimeter-diameter core were exhumed during Phase 3, including cores from the SDZ and CDZ. High-resolution photographs and descriptions of all Phase 3 cores are in a comprehensive core atlas (see Table S1 in the online supplement). The core is curated at the Integrated Ocean Drilling Program (IODP) Gulf Coast Repository at Texas A&M University, and samples from all three SAFOD phases may be requested as described on the EarthScope Web site (<http://www.earthscope.org>; see also Table S1).

Figures 2c–2f show images of core samples obtained during Phase 3 drilling from the SDZ and CDZ at increasingly finer scales. The cohesionless, foliated gouge from the CDZ (Figures 2c and 2d) is highly altered and pervasively sheared and contains clasts of various types of rock, most notably serpentinite. Phase 3 core from the SDZ also contains a foliated fault gouge with a complex fabric of anatomizing, polished surfaces with striations at a variety of orientations. The foliated fault gouge recovered from both the SDZ and CDZ correlates (to within 0.5 meter) with the casing deformation and explains the extremely low V_p , V_s , and resistivity illustrated in Figure 2b (see important information about depths in the online supplement). In marked contrast

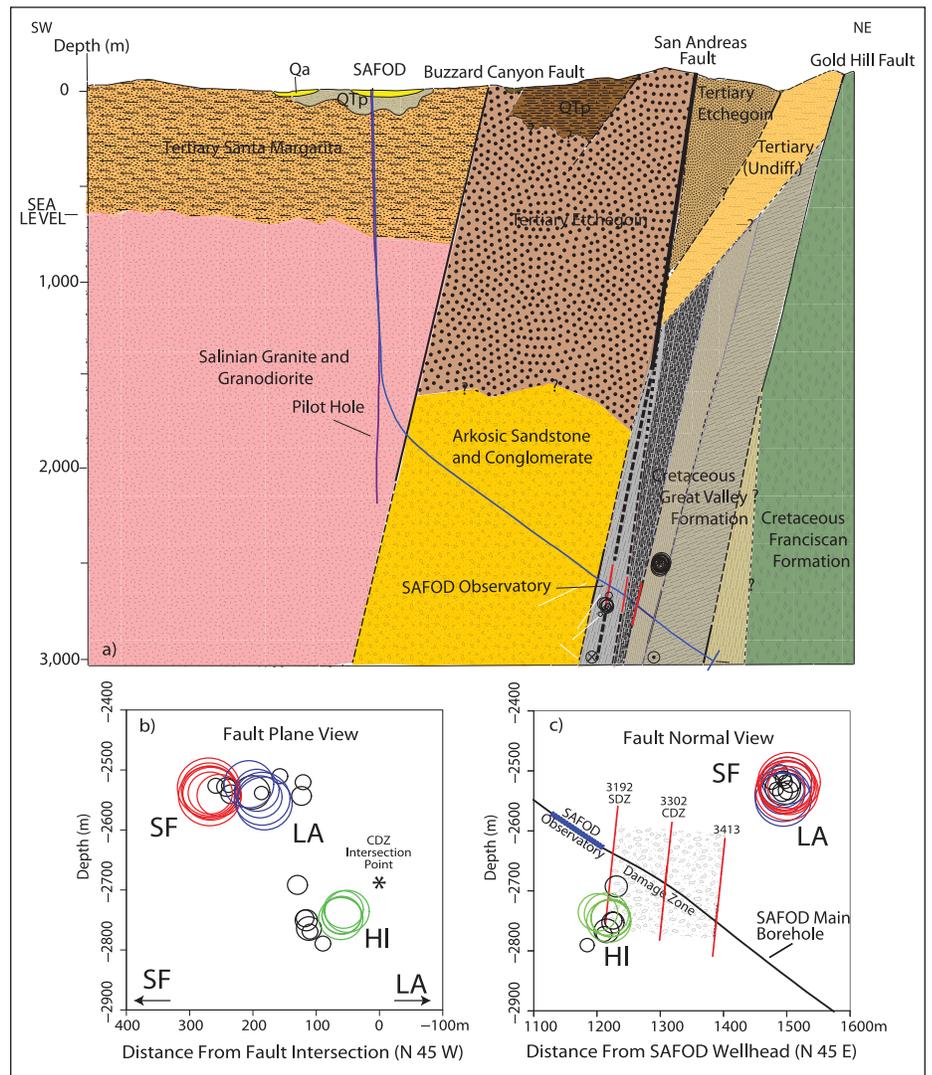


Fig. 1. (a) Simplified geologic cross section along the trajectory of the San Andreas Fault Observatory at Depth (SAFOD) borehole as constrained by surface mapping (courtesy of M. Thayer and R. Arrowsmith) and subsurface information on rock units. The black circles represent repeating microearthquakes. (b) View of the plane of the San Andreas Fault at about 2.7-kilometer depth looking to the northeast. The red, blue, and green circles represent seismogenic patches of the San Andreas Fault that produce nearly identical, regularly repeating microearthquakes, scaled for a 10-megapascal stress drop. These are labeled as the San Francisco (SF), Los Angeles (LA), and Hawaii (HI) clusters. The point at which the SAFOD borehole passes through the central deforming zone (CDZ) is shown by the asterisk. (c) Cross-sectional view of these earthquakes looking to the northwest, including the trajectory of the SAFOD borehole and the principal faults associated with the damage zone shown in Figure 2. Note that the HI events occur about 100 meters below the fault intersection at 3192 meters (measured depth), indicating that the HI microearthquakes occur on the southwest deforming zone (SDZ). Although the accuracy of location of HI is good (being determined by a seismometer deployed in SAFOD directly above the events), the location of SF and LA with respect to HI is relatively uncertain.

to the extremely thin, approximately 1-centimeter-thick shear zones encountered in the Nojima and Chelungpu faults, the foliated fault gouges in the SDZ and CDZ are 1.6 and 2.6 meters thick, respectively, likely a result of the much greater cumulative displacement that has occurred along the San Andreas Fault.

Many detailed analyses of the SAFOD core are just beginning at laboratories around the world (e.g., Figures 2e and 2f), and early results suggest that dissolution-precipitation reactions may play an important role in

deformational behavior of the fault at this location [Schleicher *et al.*, 2009].

Stress, Pore Pressure, and Fault Slip

A number of observations made in SAFOD are directly related to the state of stress and pore pressure within the fault zone. Highly elevated fluid pressures were not observed during drilling in the fault zone; such pressures would have resulted in influxes of formation fluid into the wellbore if the pore pressure was appreciably greater than the

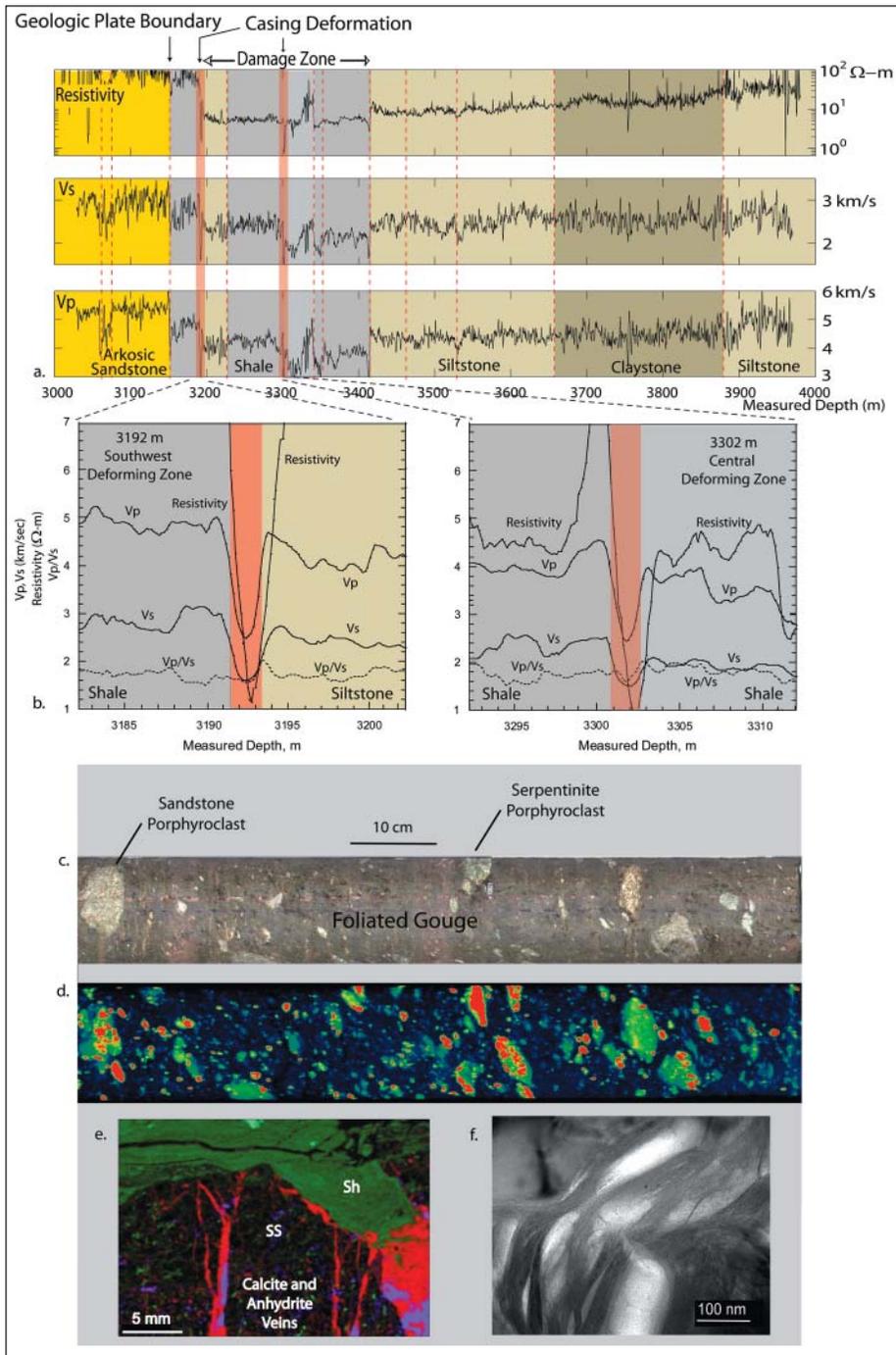


Fig. 2. (a) Selected geophysical logs and generalized geology as a function of measured depth along the Phase 2 SAFOD borehole. The dashed red lines indicate some of the many faults encountered. The thick red lines indicate where fault creep deformed the Phase 2 cased borehole at the SDZ and CDZ. (b) The SDZ and CDZ correlate with localized zones (shown in red) where the geophysical log properties from Phase 2 are even more anomalous than in the surrounding damage zone. (c) A photo of a section of Phase 3 core containing a foliated fault gouge from the CDZ. (d) A colorized three-dimensional maximum intensity projection of X-ray computed tomography from the section of the core in Figure 2c (courtesy of J. Chester). Note that the clasts define a shape-preferred orientation where the long axes are approximately parallel to the San Andreas Fault [Sills et al., 2009]. (e) False-color X-ray fluorescence chemical map of a sample collected from the northeast margin of the SDZ (red, calcium; green, iron; blue, sulfur; courtesy of S. Mittempergher, J. P. Gratier, and J. Richard), showing intrusion of highly sheared and foliated shale (Sh) into a relatively undeformed arkosic sandstone (SS). The sandstone contains cross-cutting anhydrite (magenta) and calcite (red) veins indicative of multiple crack opening and sealing episodes [Mittempergher et al., 2009]. (f) A transmission electron microscope photograph showing nanocoatings of smectite/illite and chlorite/illite clays from the CDZ (courtesy of A. Schleicher and B. van der Pluijm).

drilling mud pressure. While the pressure exerted by the drilling mud was about 40% greater than hydrostatic to stabilize the borehole, in the strike slip/reverse faulting stress state that characterizes the SAFOD area [Hickman and Zoback, 2004], pore pressures within the deforming fault zone would have to exceed the overburden stress (i.e., be twice as high as the drilling mud pressure) in Rice's [1992] model for a weak fault in an otherwise strong crust.

In addition, analysis of the rates of formation gas inflow during periods of no drilling (T. Wiersberg, personal communication, 2009) shows no evidence of elevated pore pressure within the fault zone relative to the country rock, and the ratio of V_p to V_s is relatively uniform (~1.7) across the nearly 200-meter-wide damage zone and the localized shear zones within it (Figure 2b). Altogether, none of these observations indicates the presence of anomalously high pore pressure in the fault zone. Instead, noble gas isotopic analysis of gases coming into the borehole during SAFOD drilling revealed a marked difference in the ratio of helium isotopes ($^3\text{He}/^4\text{He}$) across the San Andreas Fault. This and differences in concentrations of hydrogen, carbon dioxide, and methane on the two sides of the fault [Wiersberg and Erzinger, 2008] indicate that the San Andreas Fault has low permeability relative to the country rock and hydrologically separates the Pacific and North American plates.

Geophysical data show that the direction of maximum horizontal stress not only is at a high angle to the San Andreas Fault in the crust adjacent to fault throughout central California but also remains at a high angle to the San Andreas to within 200 meters of the active fault traces in SAFOD [Boness and Zoback, 2006]. Also, there are no temperature anomalies that might be associated with fault friction in either the vertical pilot hole or in SAFOD itself where it crosses the San Andreas [Williams et al., 2005]. Together with the stress state determined in the pilot hole [Hickman and Zoback, 2004] and in SAFOD [Zoback and Hickman, 2005], these results offer the best demonstration to date that slip on the San Andreas Fault at this location occurs at extremely low levels of shear stress. Because there is no evidence for anomalously high pore pressure within the fault, the most likely explanation for this strong crust/weak fault behavior is that the materials that make up the active San Andreas Fault are intrinsically very weak. As Phase 3 core samples undergo extensive laboratory analysis, these and many other ideas will be tested as scientists determine the composition and frictional strength of the fault gouge and the active physical and chemical processes governing deformation within the San Andreas Fault at depth.

In contrast to the low average shear strength of the creeping fault zone, earthquake source studies indicate an average static stress drop of up to 25 megapascals for the target earthquakes [Imanishi and Ellsworth, 2006] with the possibility of locally much higher stress

drops within the rupture interior [Dreger et al., 2007]. Thus, it is possible that the locked patches responsible for generating these microearthquakes have an intrinsically higher frictional strength than the surrounding, creeping fault. In this way, creep on the surrounding fault brings these patches to failure in accord with typical laboratory friction measurements, apparently with near-complete stress drops. If this interpretation is correct, because only ~1% of the surface area of the San Andreas Fault where crossed by SAFOD moves in earthquakes, these high-stress patches would have a negligible effect on the overall strength of the San Andreas Fault.

Future Fault Zone Drilling

Building on the success of scientific drilling in the San Andreas fault zone and elsewhere, further drilling into the San Andreas Fault is now being discussed for a locked section of the fault where large earthquakes are likely to occur in the future. There are many compelling and still unanswered questions about fault behavior that can only be answered by drilling into a locked section of the fault, to compare and contrast its composition, properties, state of stress, and pore pressure with that of the creeping section.

In addition, scientific drilling is being planned for the Alpine fault, New Zealand [Townend et al., 2009], and in an active low-angle normal fault in central Italy [Cocco et al., 2009]. In concert with drilling into subduction zones at Nankai and elsewhere [see Tobin et al., 2007, and references therein], the Earth sciences are entering an exciting new era of deep, in situ studies into the physics and chemistry of faulting that is engaging both the continental and oceanic scientific drilling communities.

Acknowledgments

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NEWS

Climate Reports Focus on Science, Reducing Impacts, and Adaptation

PAGE 199

In a one-two-three punch, the U.S. National Research Council (NRC) released three related reports on climate change at a 19 May briefing. The reports—focusing on advancing climate change science, limiting the magnitude of change, and adapting to change, respectively—are part of a congressionally requested five-study project known as America's Climate Choices. Together they present evidence of climate change and a series of recommendations for limiting and adapting to any changes.

Ralph Cicerone, president of the National Academy of Sciences and chair of its operating arm, NRC, said the reports indicate the state of climate change science is strong but that more information is needed, including about potential impacts. “We need a national goal, we need a national framework, and a sustained effort to do the research, to limit the impacts, and then to manage the impacts that do occur,” Cicerone, a former AGU president, told *Eos*.

The “Advancing the Science of Climate Change” report reviews scientific evidence of climate change, examines research efforts, and recommends three broad research themes for organizing federal research priorities: improve understanding of human-environment systems, support effective responses to climate change, and examine tools and approaches to improve understanding and responses. The report recommends that the United States Global Change Research Program coordinate and implement an integrated federal research effort if some modifications are made to improve the program's scope, balance, and decision support.

Pamela Matson, who chaired the panel that put together this report, said, “Our panel concluded that the science community needs to enter a new era of climate

change research.” Matson, dean of Stanford University's School of Earth Sciences, Stanford, Calif., said research needs to contribute not just to understanding climate change but also to informing the nation's choices in responding to changes.

She also noted that some uncertainty about climate change is due to scenarios of human activity and the need to better understand Earth system processes. “Confounding all projections of future climate change is [that] abrupt change possibly can happen,” Matson said. “There is good evidence that not all climate change will be smooth and gradual and therefore easy to adapt to.”

The second report, “Limiting the Magnitude of Future Climate Change,” examines strategies to reduce concentrations of greenhouse gases in the atmosphere. It recommends prompt and sustained strategies to reduce emissions, an inclusive national framework for instituting response strategies and policies, and adaptable means for managing policy responses. The report suggests a domestic emissions budget of between 170 and 200 gigatons of carbon dioxide equivalent for 2012–2050, which would be a reduction of U.S. emissions from 1990 levels by 50–80%.

“Meeting that emission budget is a very challenging task,” said Robert Fri, chair of the second report's panel. Fri, senior fellow and former president of Resources for the Future, in Washington, D. C., added that reaching the goal would require new emerging technologies and “a strong dose of American ingenuity.”

The third report, “Adapting to the Impacts of Climate Change,” notes that adaptation calls for “a new paradigm that takes into account a range of possible future climate conditions and associated changes in human and natural systems, instead of managing our

resources based on previous experience and the historical range and variability of climate. This does not mean waiting until uncertainties have been reduced to consider adaptation actions.” The report indicates that actions taken now “can reduce the risk of major disruptions to human and natural systems; inaction could serve to increase these risks, especially if the rate or magnitude of climate change is particularly large.”

“Adaptation is still in its infancy,” said Thomas Wilbanks, chair of the third report's panel. Wilbanks, who is corporate research fellow at the Oak Ridge National Laboratory where he leads its Global Change and Developing Country Programs, added, “Support for adaptation research has only emerged in a significant way in recent years.”

Dan Lashof, director of the Natural Resources Defense Fund's Climate Center, told *Eos* the three reports are valuable and “quite forceful” in their conclusions and recommendations. “It is now up to politicians to respond appropriately to what scientists are saying. I think [the reports] have gone as far as the science community can go in terms of making clear conclusions about what's happening and what response options are.” Lashof noted that the reports' recommendations are consistent with a comprehensive energy and climate bill passed by the U.S. House of Representatives last year and with the American Power Act proposed by Sens. John Kerry (D-Mass.) and Joseph Lieberman (I-Conn.).

Rick Piltz, director of Climate Science Watch, told *Eos* that the reports are “the intellectual basis that could be a template for a much more constructive national approach. But it needs to be taken up by the leadership.”

Matson told *Eos*, “There are some things that are in our control, and climate change is one of them. Humans are causing these changes, humans can fix the problem. We're working on it, and I have great optimism that we will get there.”

America's Climate Choices also includes two additional reports that will be released later this year. For more information, visit <http://www.americasclimatechoices.org>.

—RANDY SHOWSTACK, Staff Writer

Phase 2 Monitoring, Location of Target Earthquakes and Plans for the Permanent Observatory

Bill Ellsworth¹, Steve Hickman¹,
Mark Zoback², Lynn Dietz¹,
Gray Jensen¹, Will Kohler¹,
Jim Luetgert¹, Charley Weiland²,
Eric Davis³, Ralf Krug³,
Etienne Samson³, Mario Aranha⁴,
Doug Neuhauser⁴,
Bob Uhrhammer⁴, Volker Oye⁵,
Mark Zumberge⁶

¹U.S. Geological Survey,

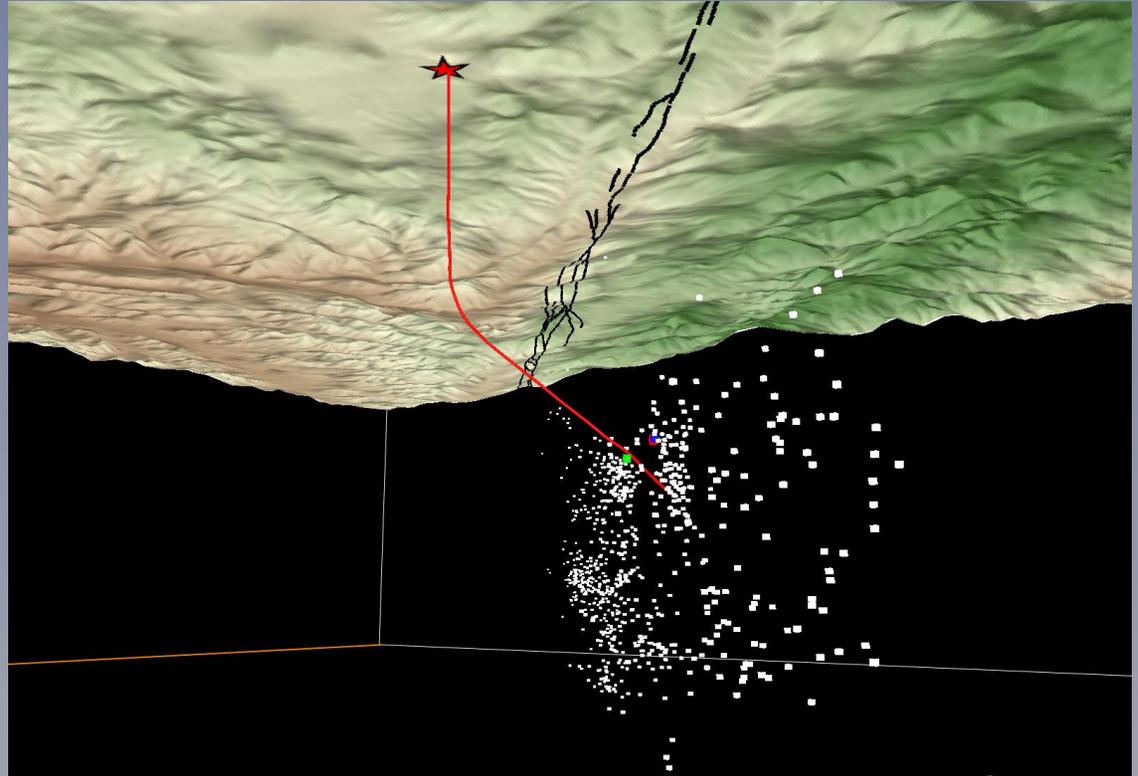
²Stanford University

³Pinnacle Technology

⁴University of California Berkeley

⁵NORSAR

⁶University of California San Diego

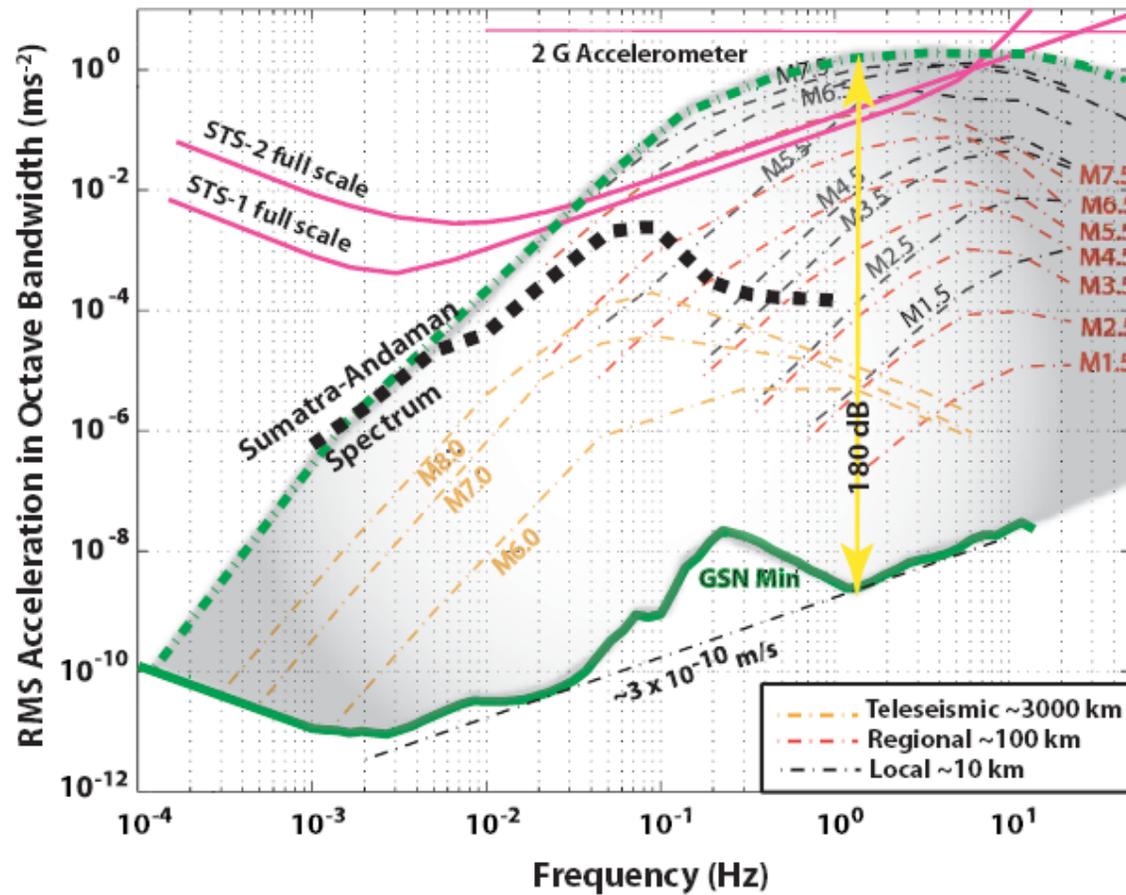


A central goal of seismology is to understand the physics of the earthquake source:

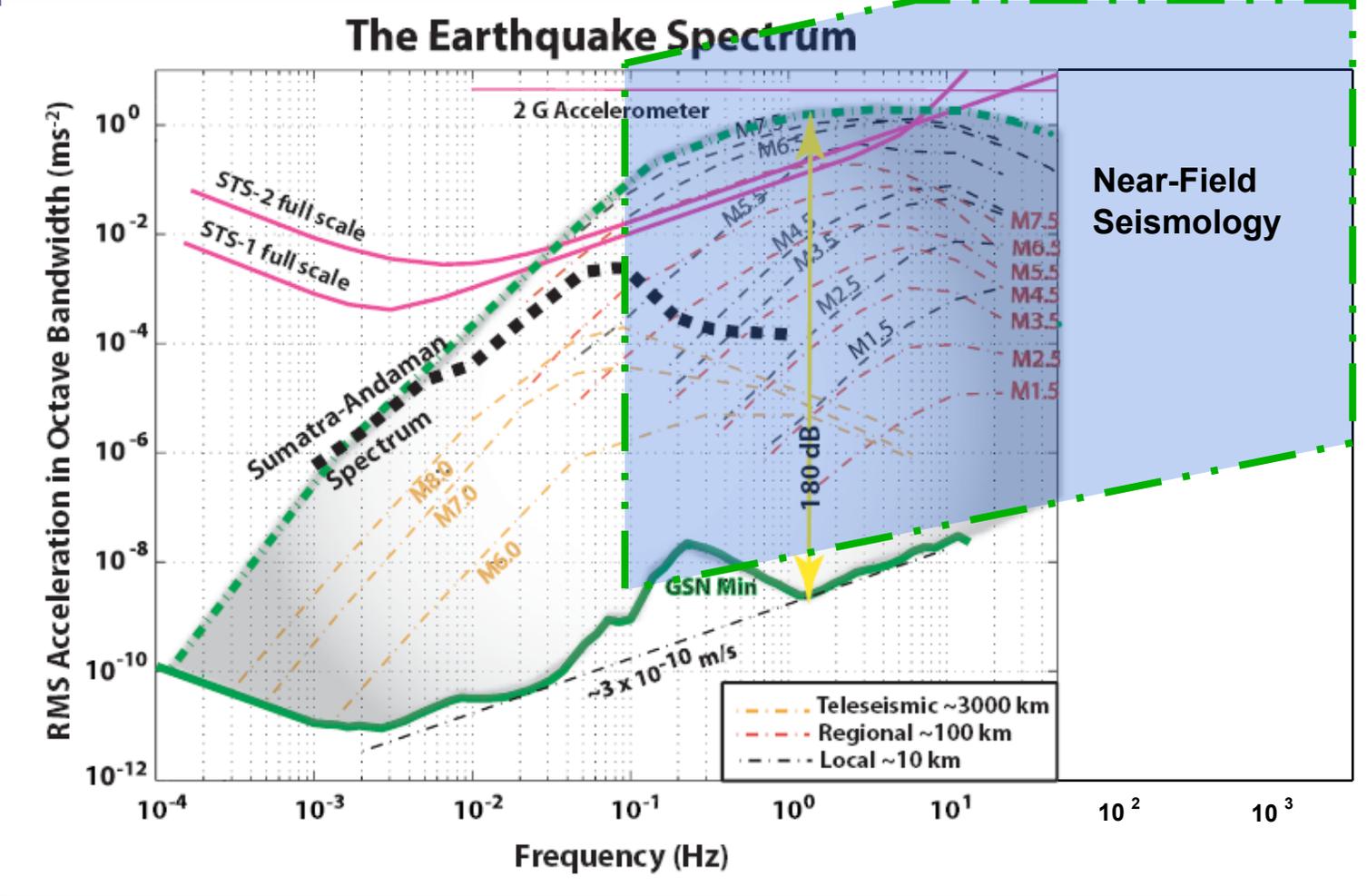
- **How do earthquakes nucleate?**
- **How do they propagate?**
- **Why do they stop?**
- **What controls the spatio-temporal evolution of slip?**
- **Is stress “high” or “low”?**
- **What is friction and how does it evolve with increasing slip?**
- **How is energy partitioned between radiation and dissipation?**
- **What, if anything is predictable?**

To answer these questions, we need observations that are truly broadband with respect to source process time scales.

The Earthquake Spectrum



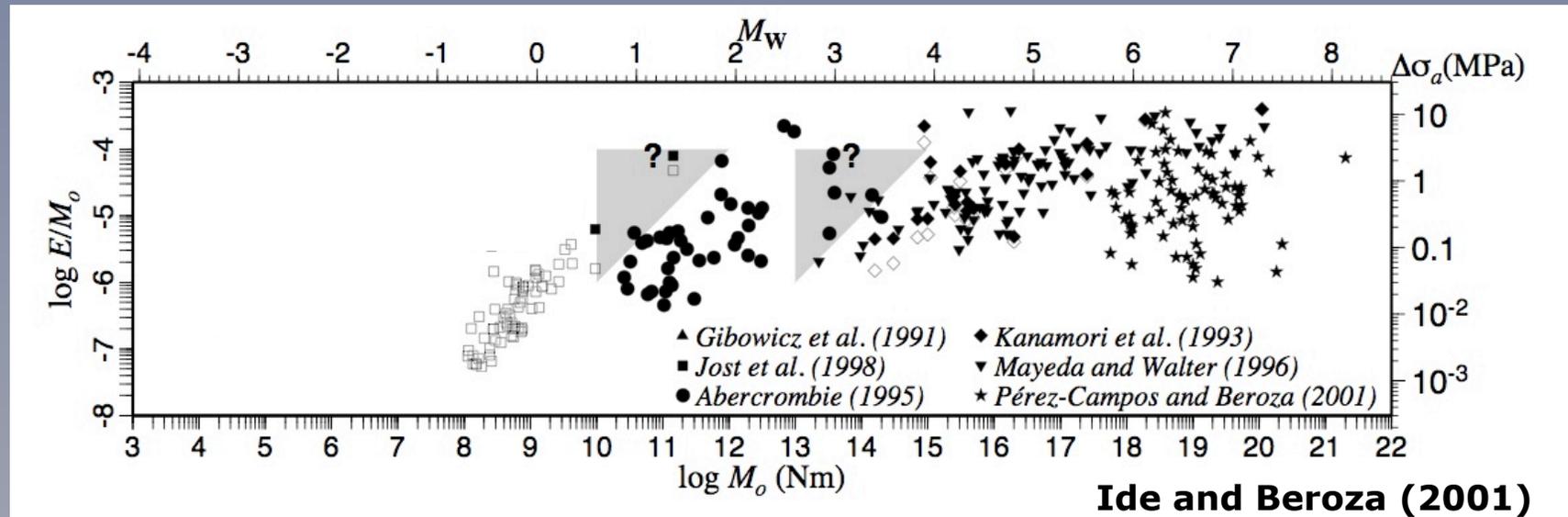
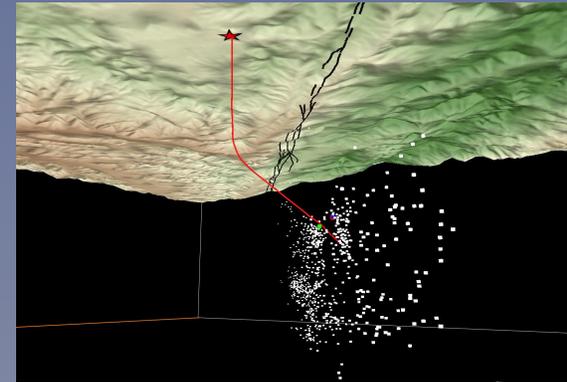
Jon Berger after
Clinton & Heaton (2002)



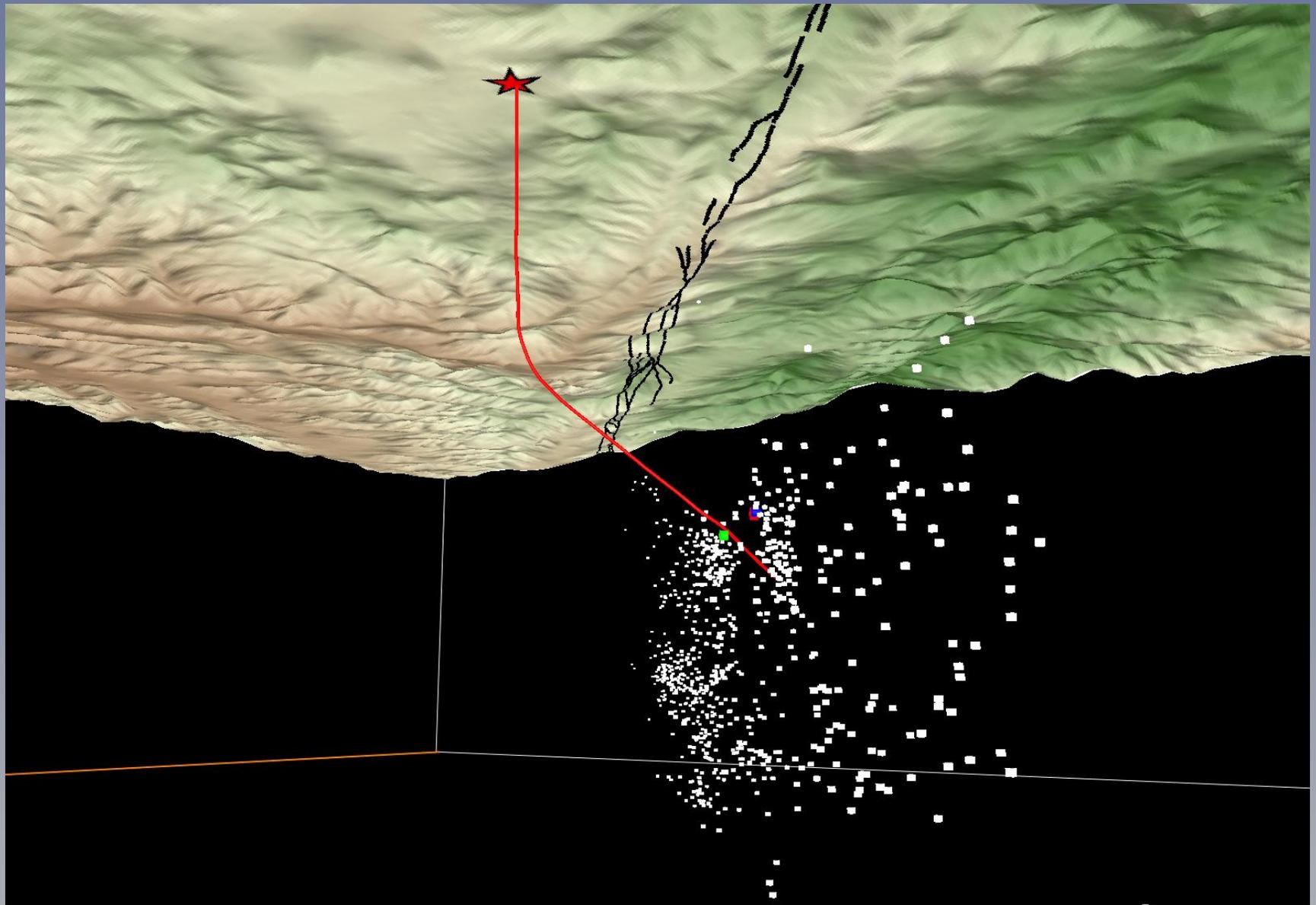
Jon Berger after
Clinton & Heaton (2002)

Instrumentation Very Near the Earthquake Source is Required to Study High Frequency Waves

Range of SAFOD Observations

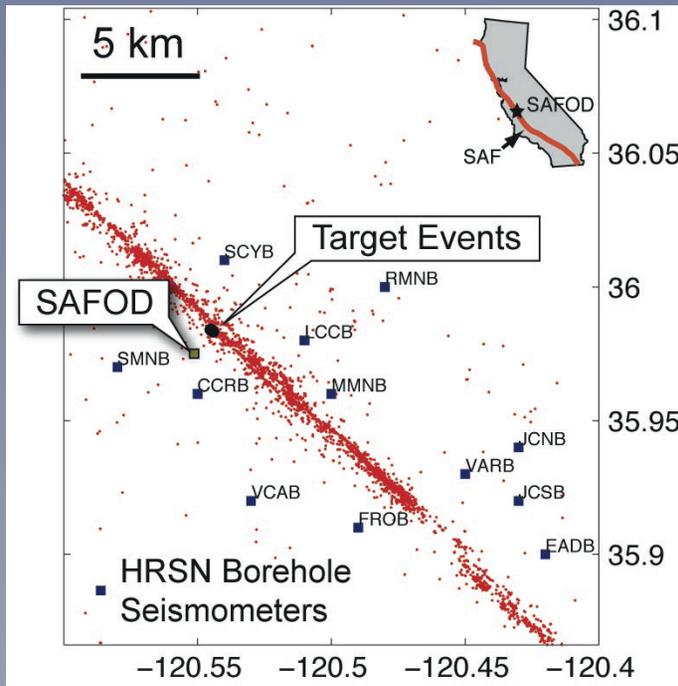


Open question if apparent stress scales with M_0



TomoDD hypocenters by Haijiang Zhang and Cliff Thurber

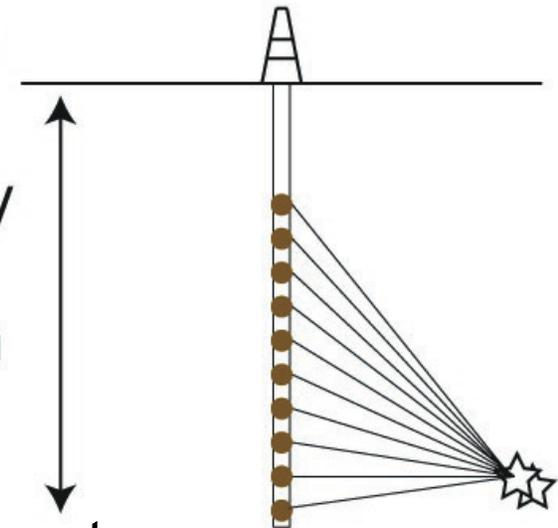
Extensive seismological data sets are available from several networks



SAFOD Pilot Hole

32 level array
from
850 - 2000 m
depth

1 kHz sample rate



HRSN borehole network

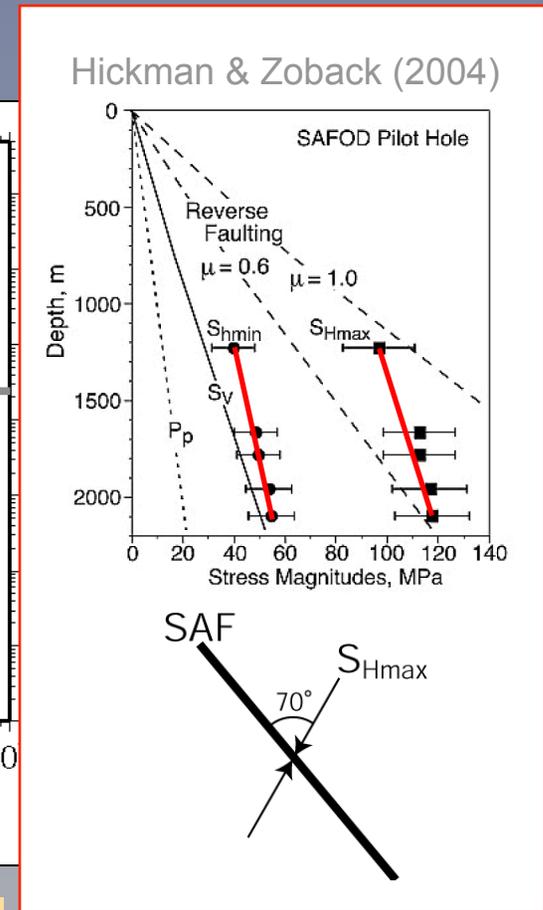
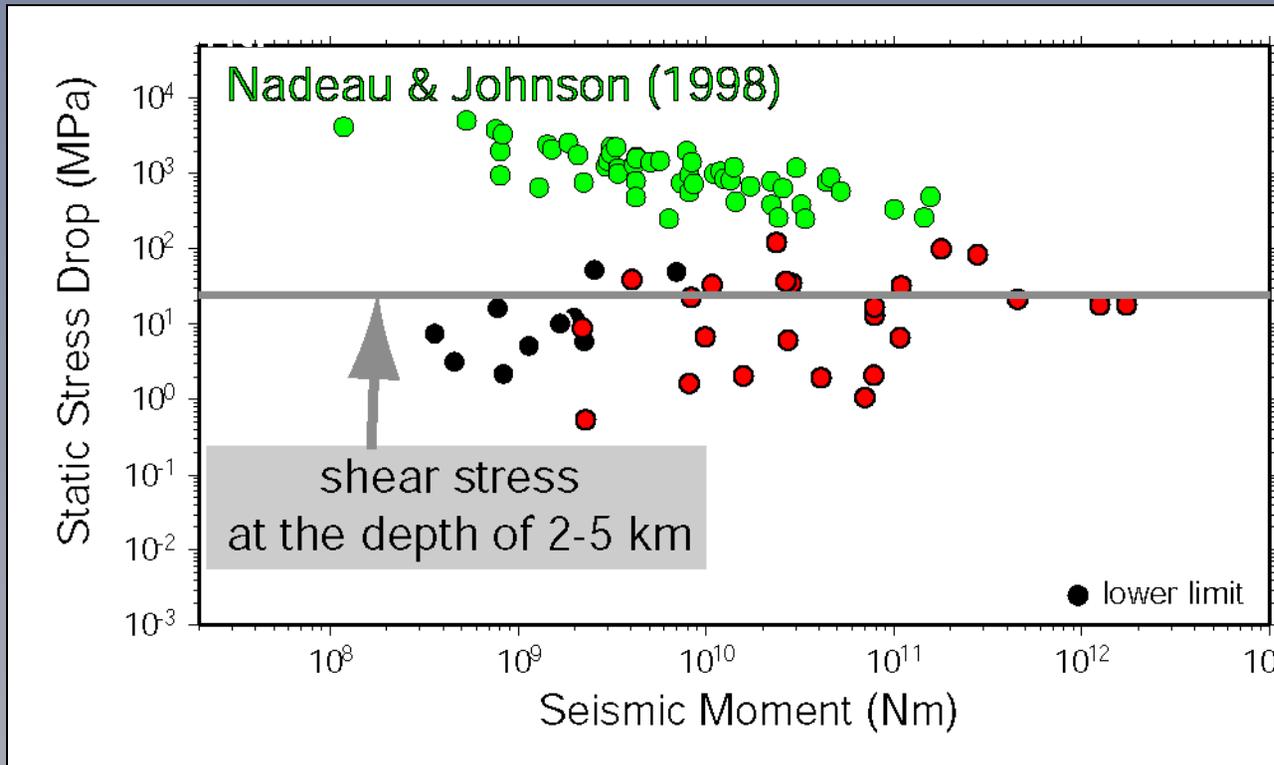
13 stations, 65 - 550 m deep
(typically 250 m)
250 Hz sample rate

Paulsson Geophysical Services, Inc
Array deployment in May 2005

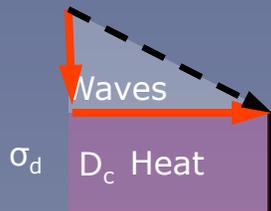
80 3-component levels
4 KHz sample rate; 4 TB data

Static Stress Drop

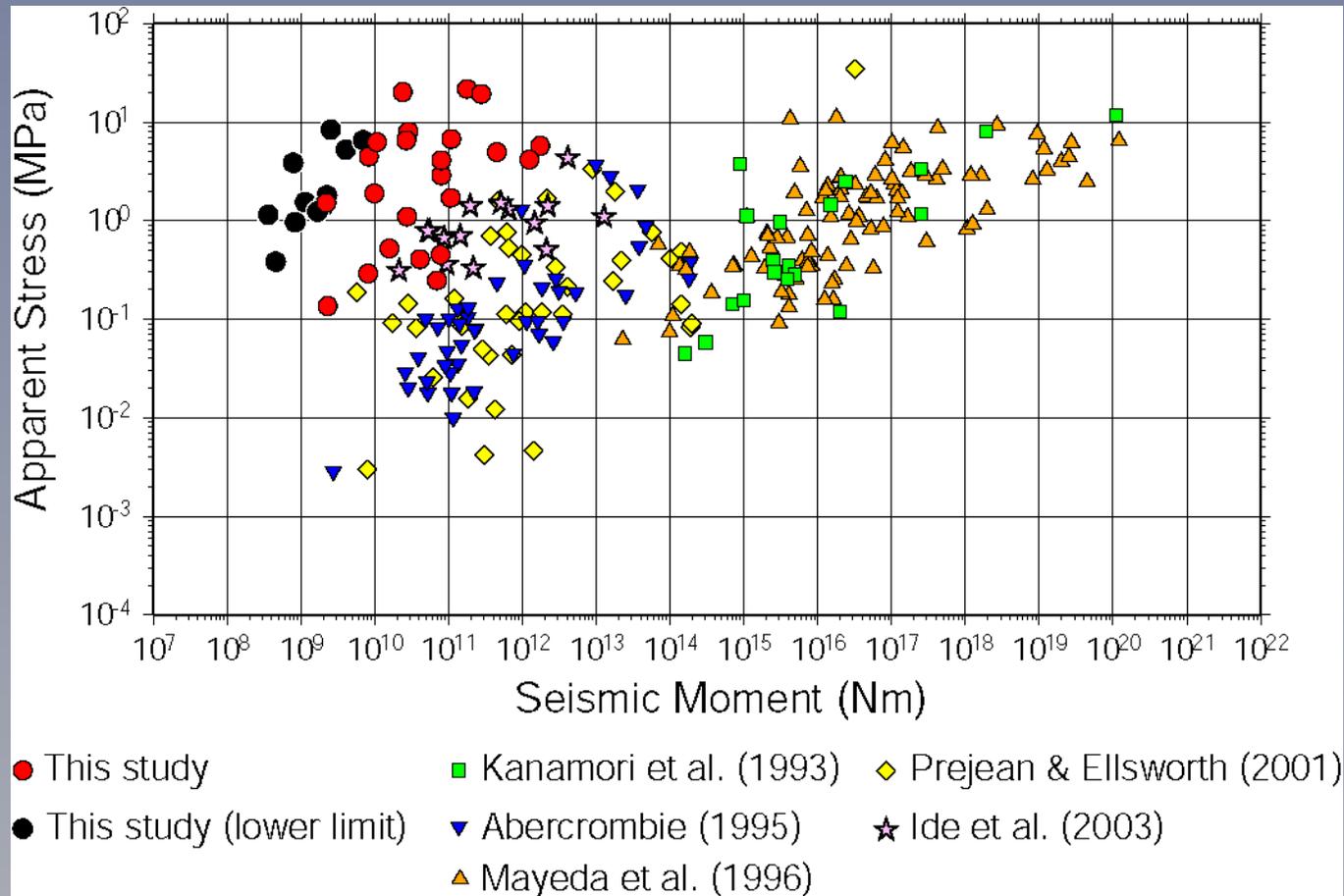
Stress drops do not vary with seismic



Average value is near the strength of the rock.

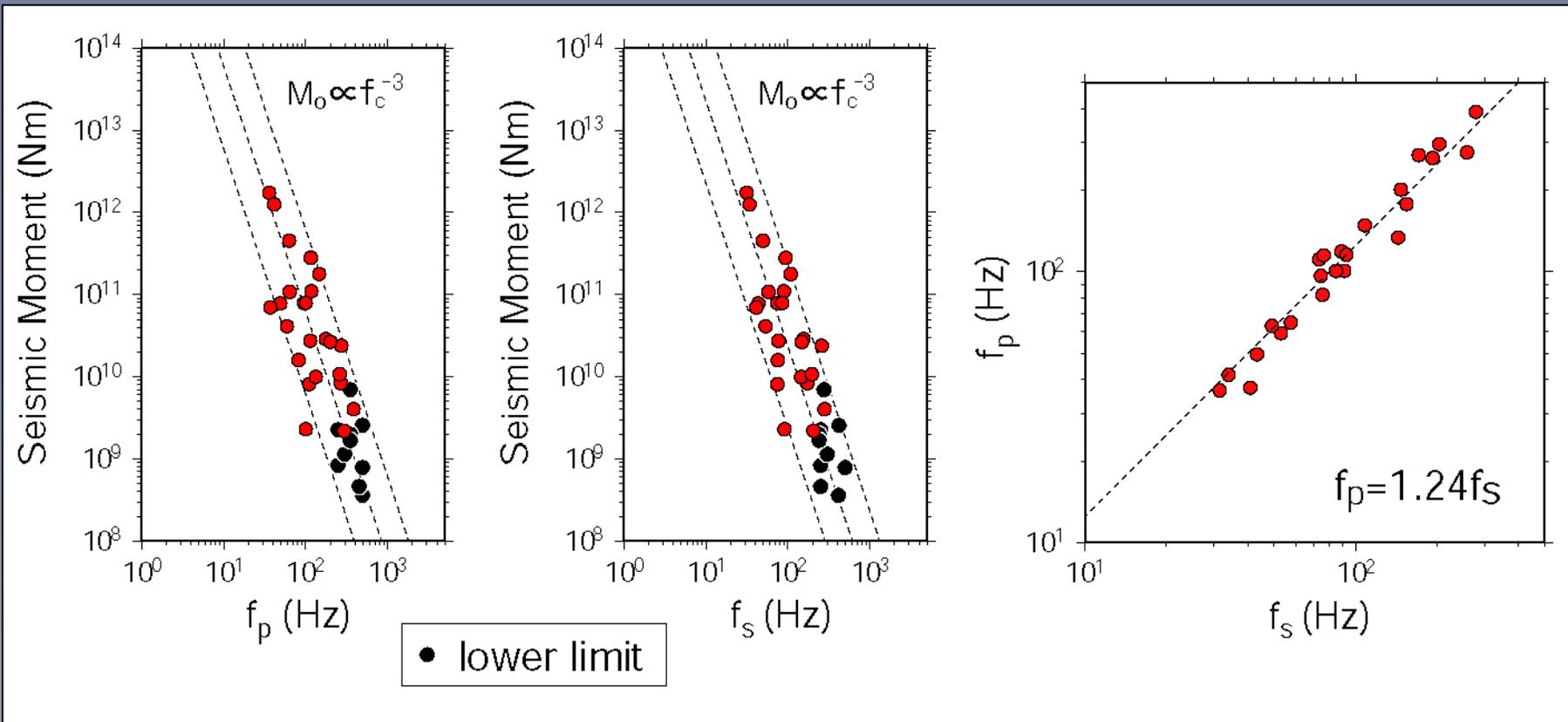


Apparent Stress Scaling

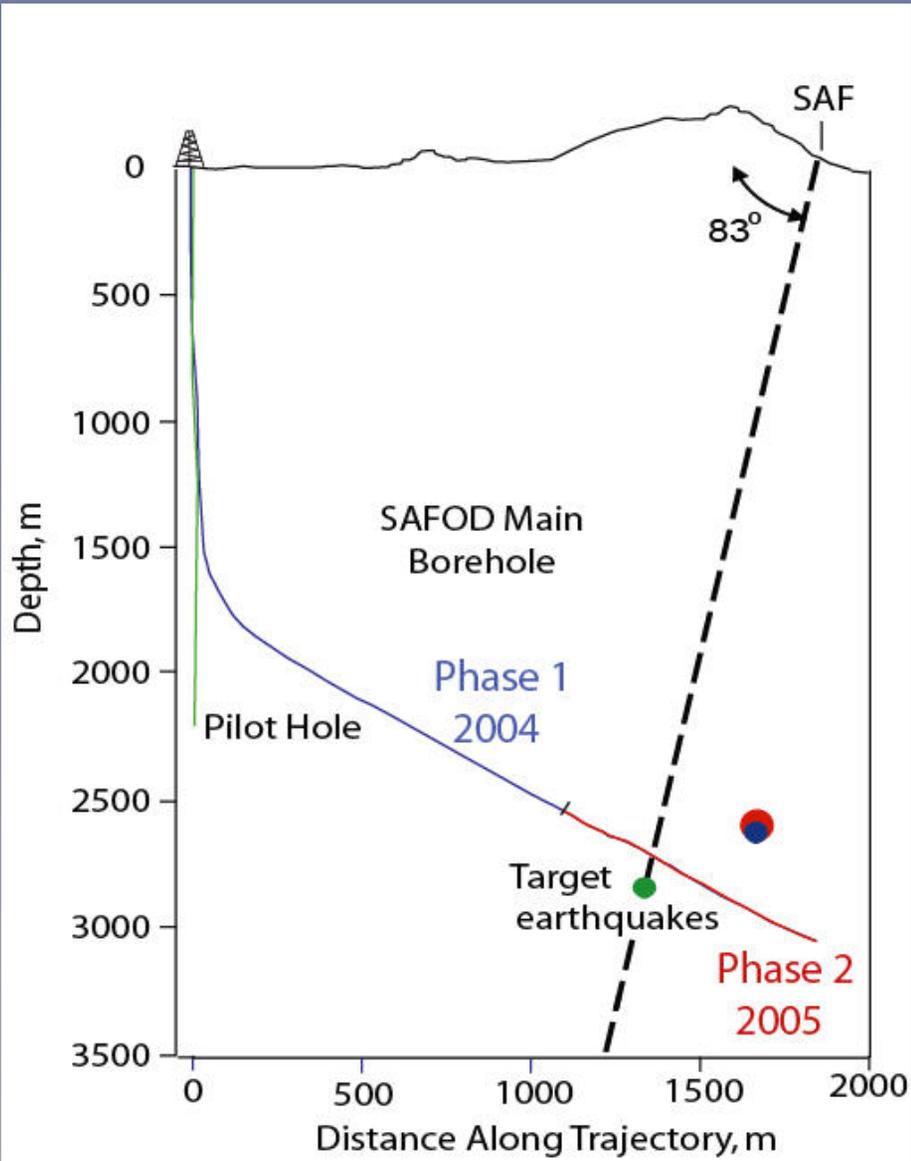


Imanishi and Ellsworth (2006)

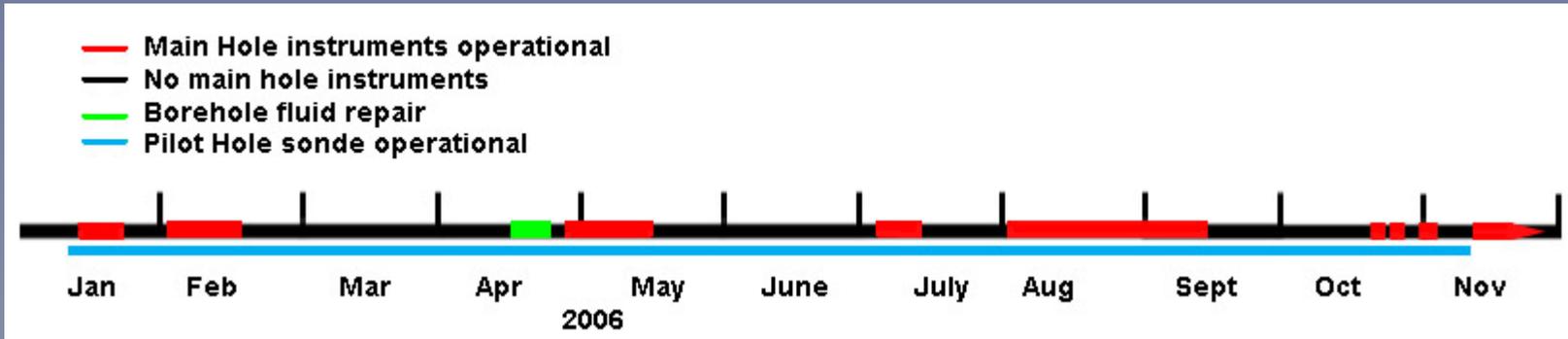
Corner Frequency



Substantial data sets have been gathered over the past 2 years in the SAFOD Main Hole



Operations Summary for 2006



- Pilot hole seismometer and tiltmeter in continuous operation from mid-January until November.
- Operation of main hole instruments proved to have a steep learning curve due to gas in well.
- No instruments are currently in operation.

January



February



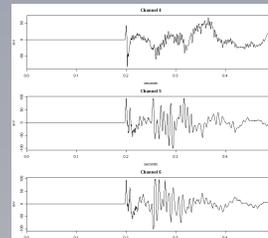
April



July



August - September



SAFOD Surface Facility

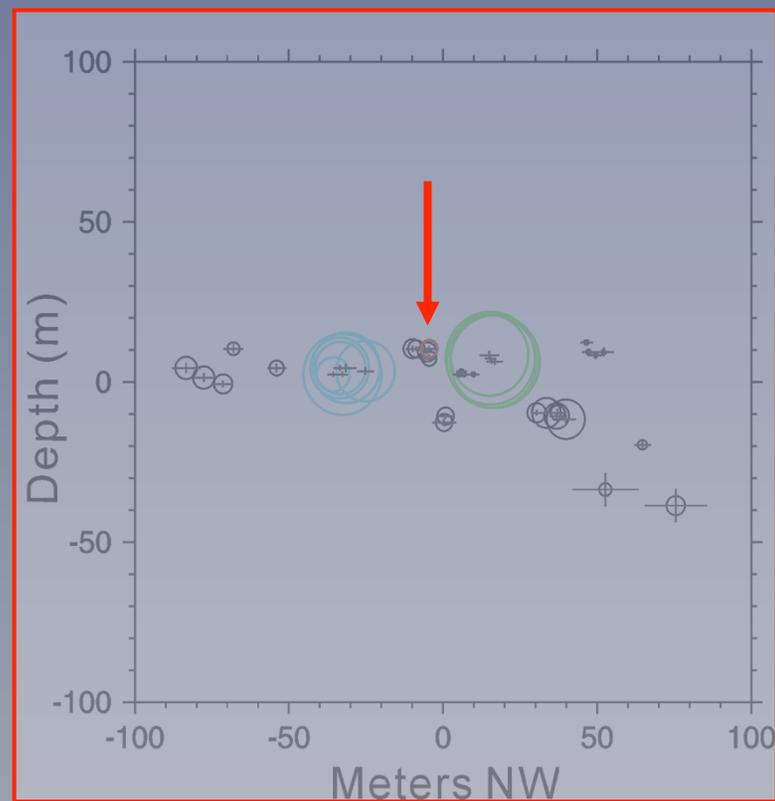
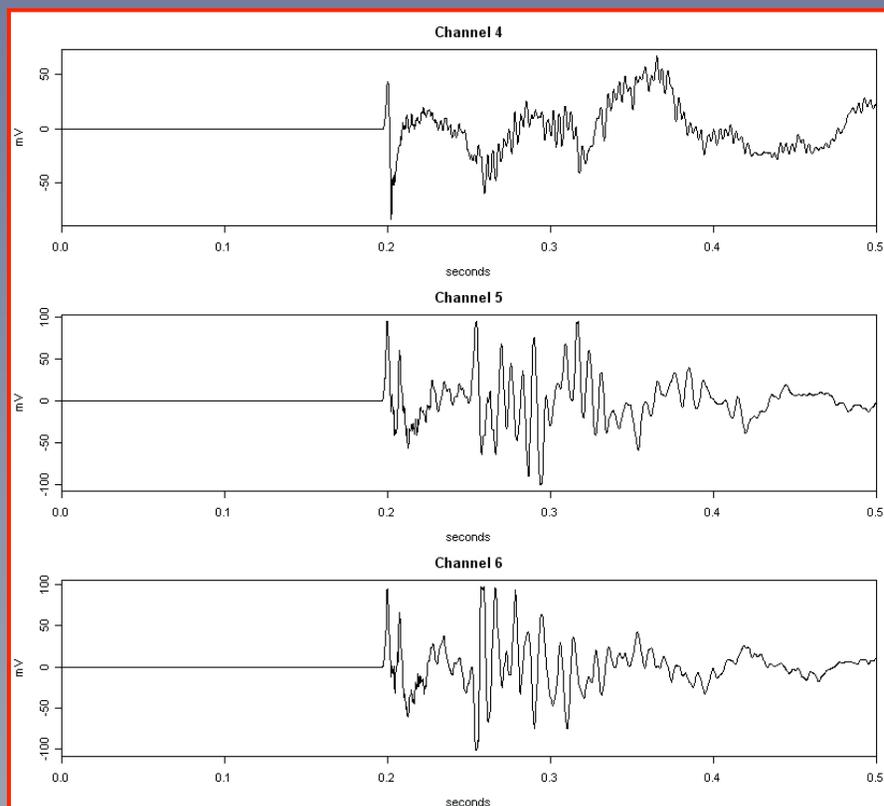
- Access to bore holes
- Computer room
- UPS power
- Telecommunications
- Earthworm hub
- Facilities for sponsored experiments
- Larger capacity A-frame for Main Hole recently completed



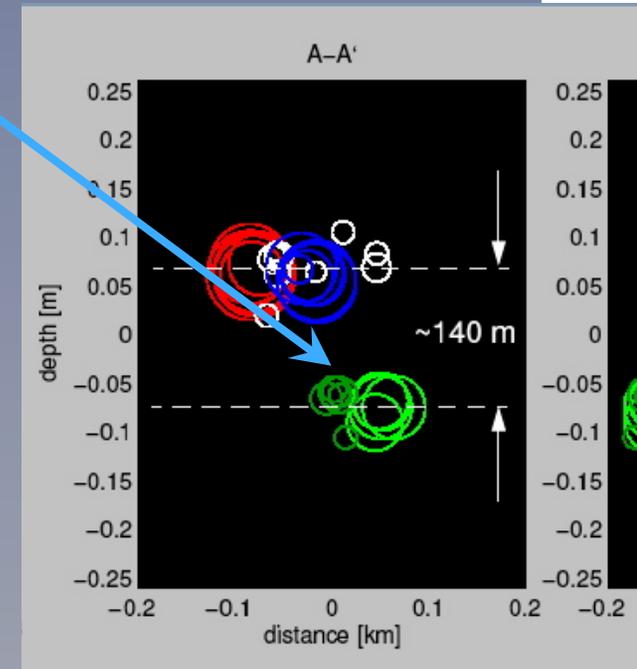
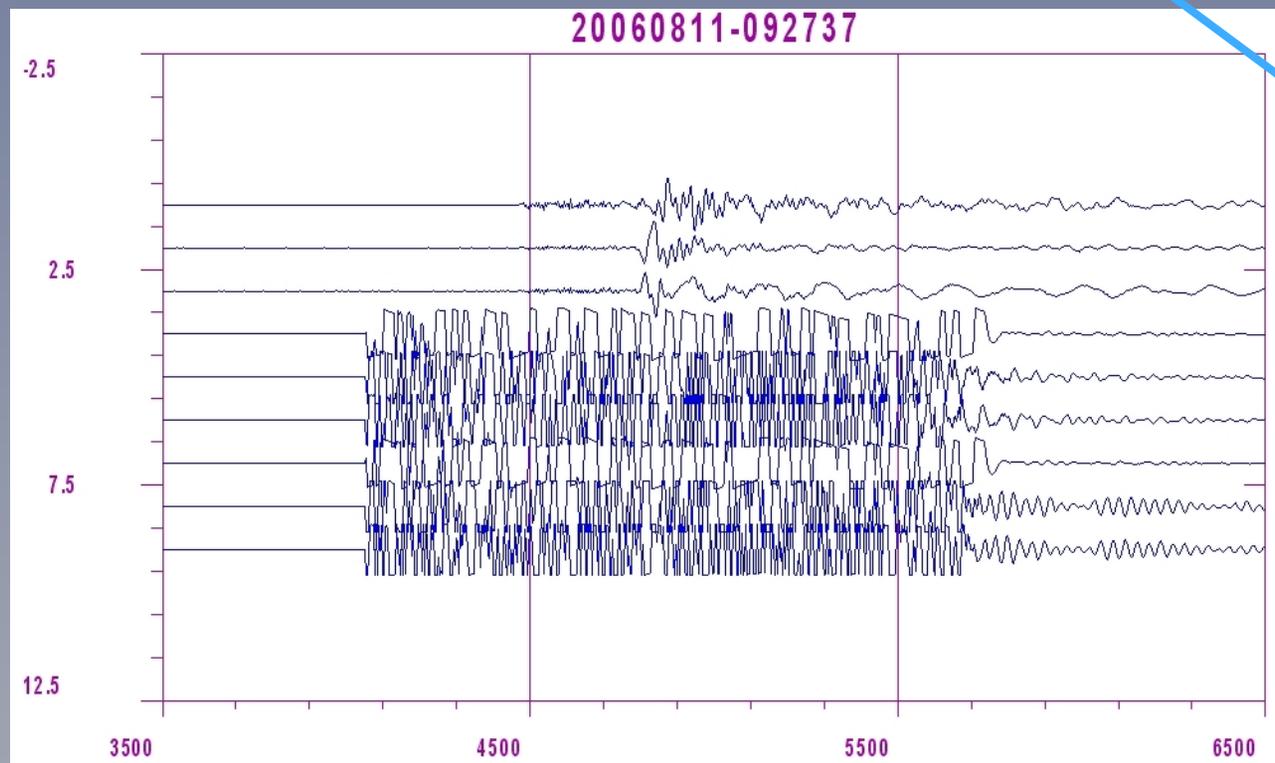
Recent Activity

- Hundreds of earthquakes with PASO “footprint” recorded during 2006 when seismometers were running in the Main Hole
- Many observations of Fault Zone Guided Waves from within fault zone (10,700' m.d)
- M 1.0 in SF-LA target on August 6
- Repeat of M 1.8 HI target on August 11
- Repeat of M 2.1 S.F. target on November 2

August 6 M 1.0 in SF-LA Target Zone

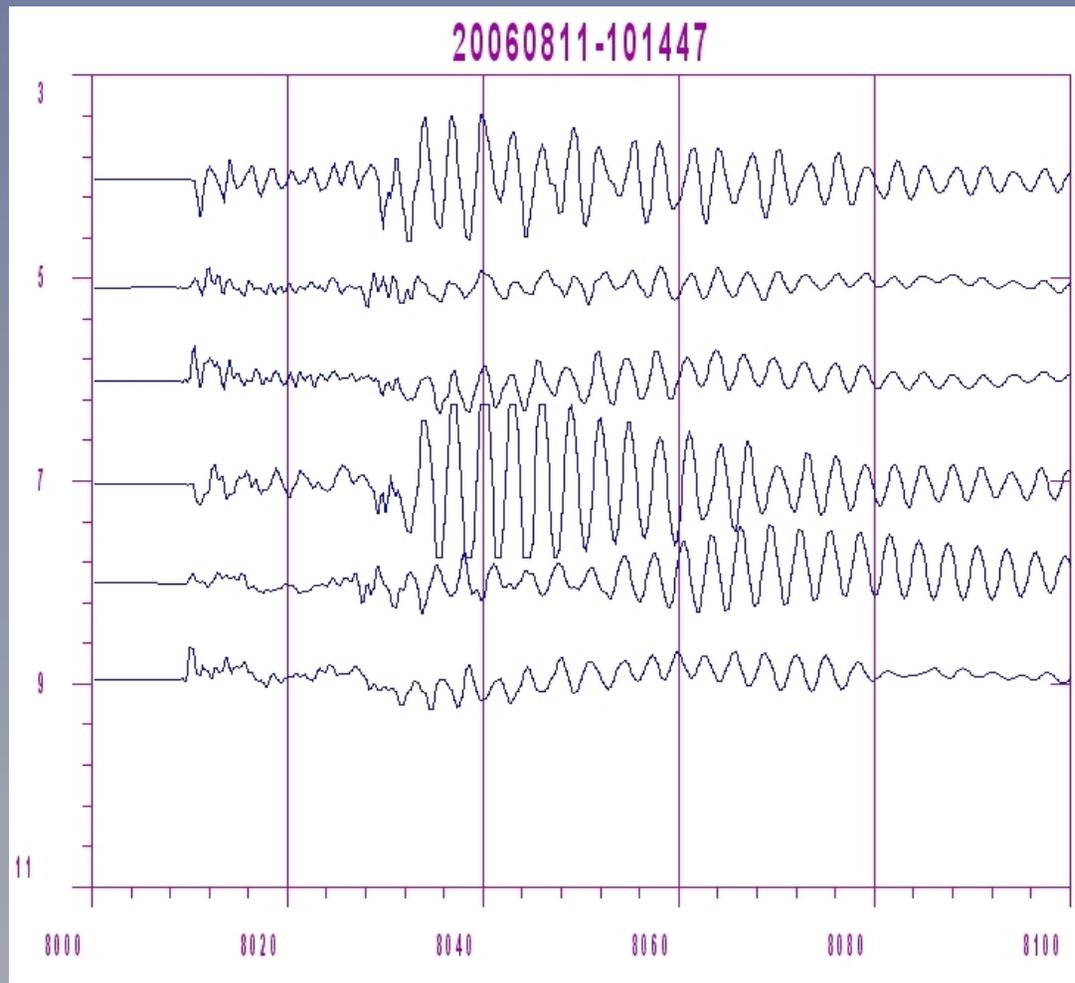


August 11, 2006 M 1.8 Hawaii Repeat



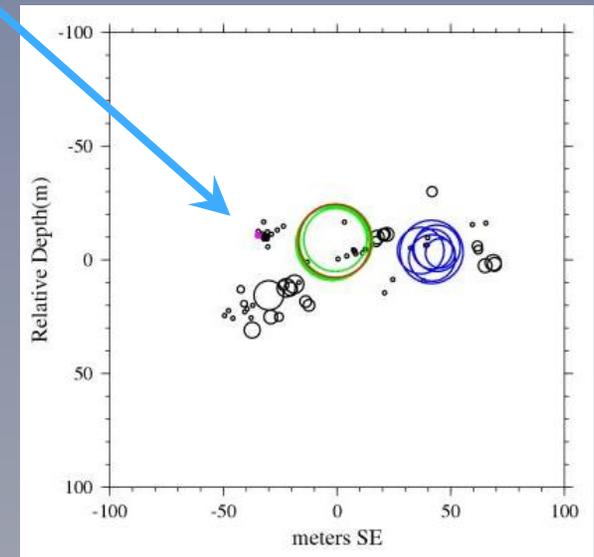
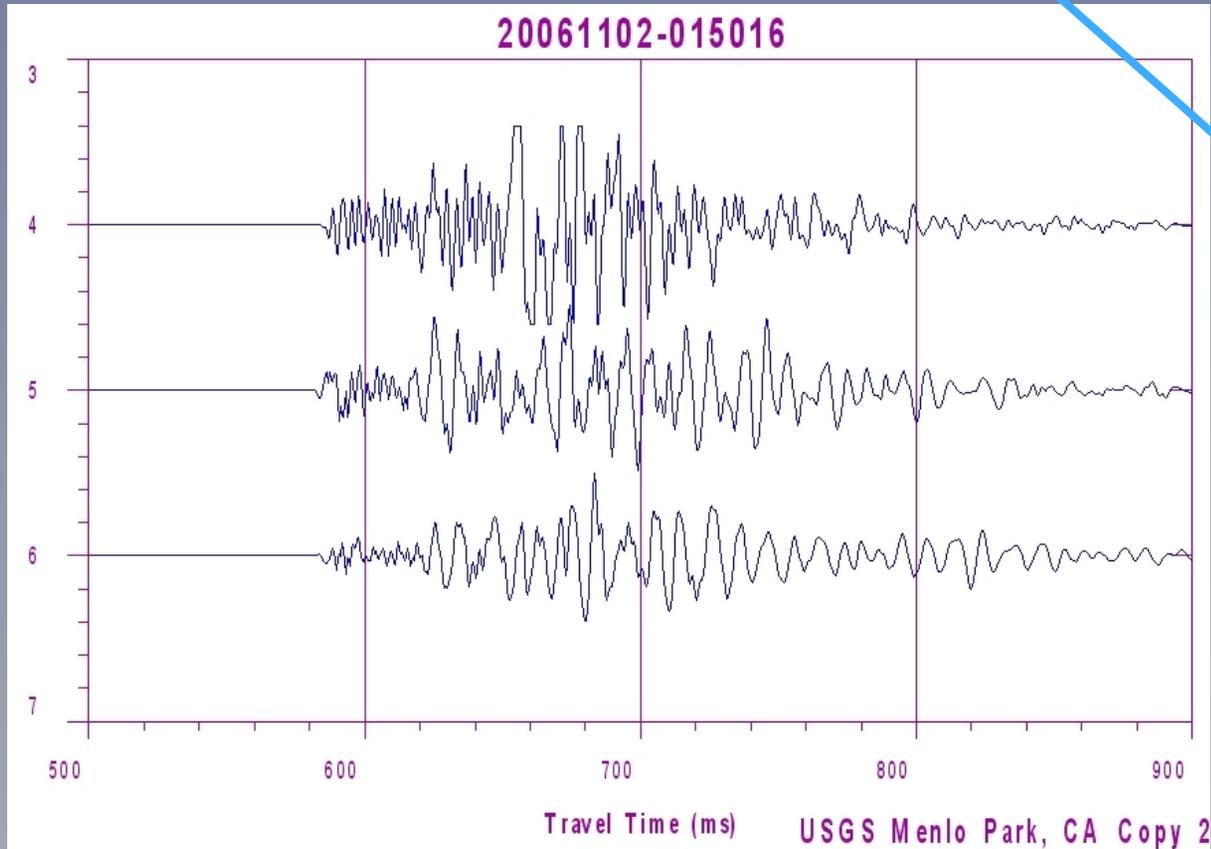
**Seismometer at 2.65 km (3290 m m.d.)
M -2 aftershocks have S-P of 15-22 msec.**

Ultra microaftershock of M 1.8 August 11, 2006 Hawaii Target Earthquake



M -1.5 to -3.0
S-P interval 17 – 25 milliseconds

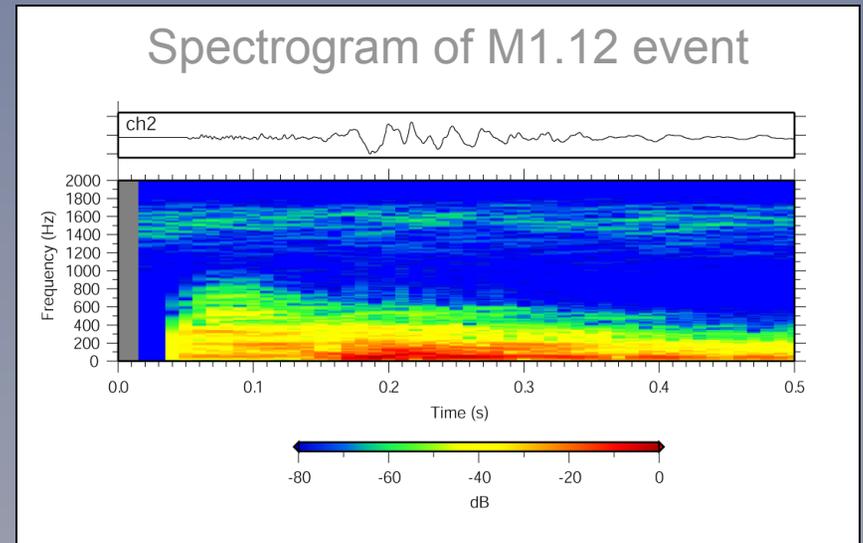
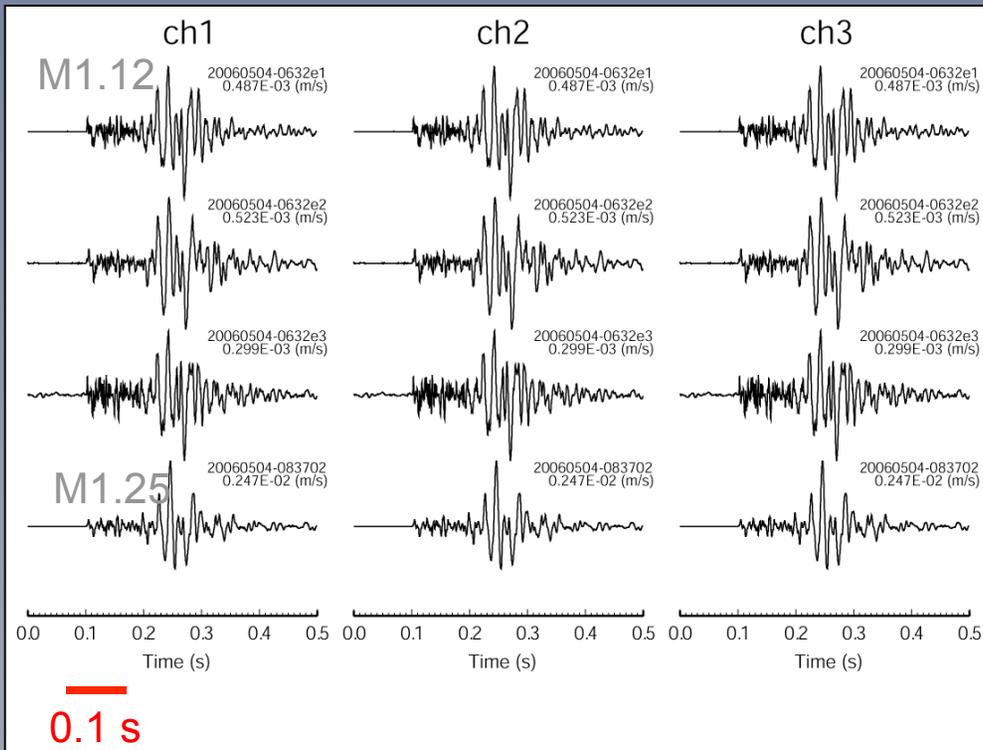
November 2, 2006 S.F. aftershock



Seismometer at 2.74 km depth (3420 m m.d.)

May 2006 Multiplet

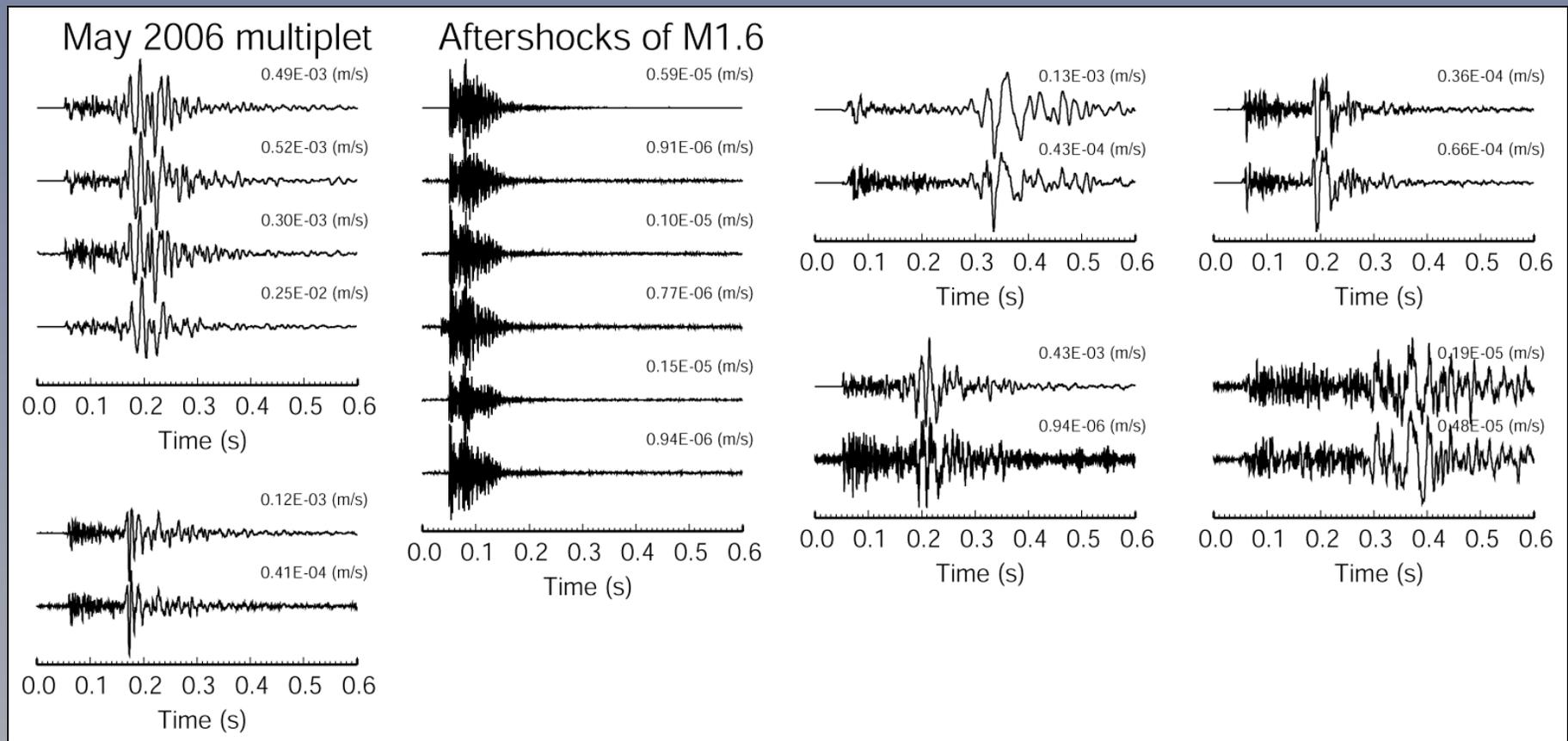
This multiplet occurred at distance of about 600 m (S-P time is 0.1 s).



- High signal-to-noise ratio
- High frequency energy is observed.

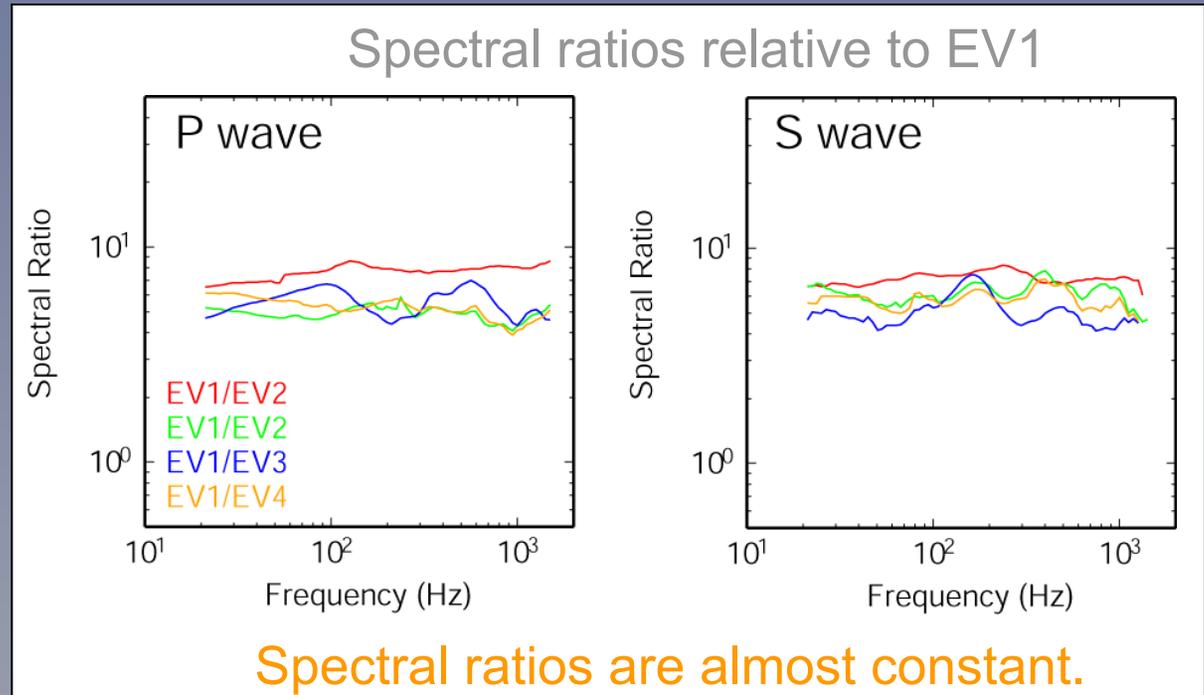
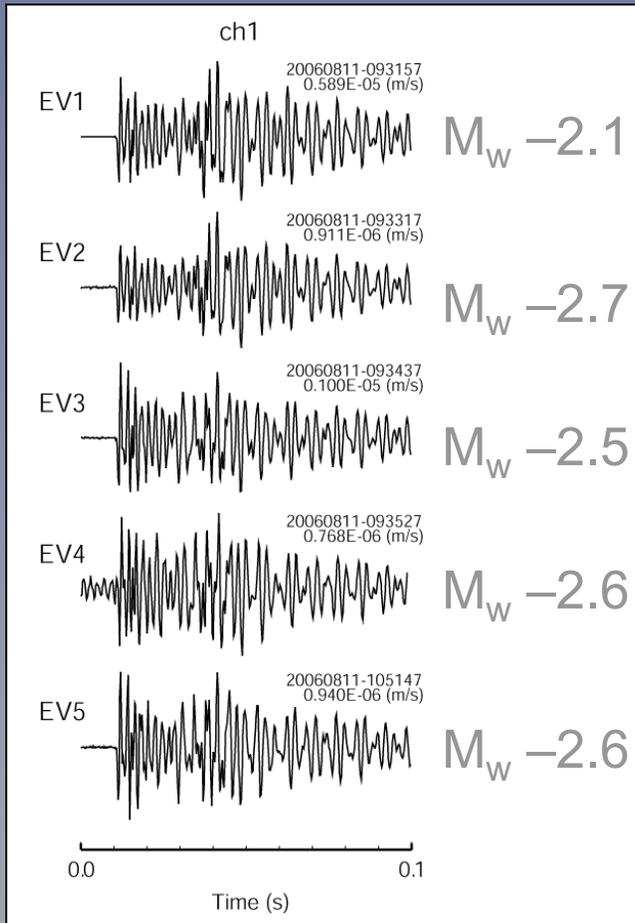
MWSR Analysis

We choose earthquakes with S-P time differences less than 0.2 s.

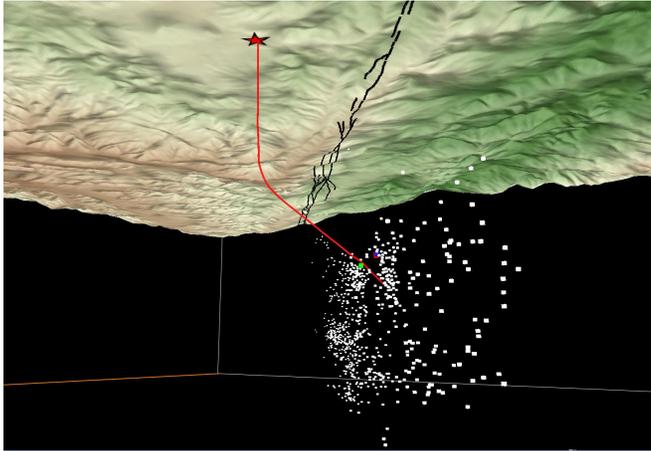


M_w ranges from -2.7 to 1.3 .

Aftershocks of M1.8 "Hawaii" Target (August 11, 2006)



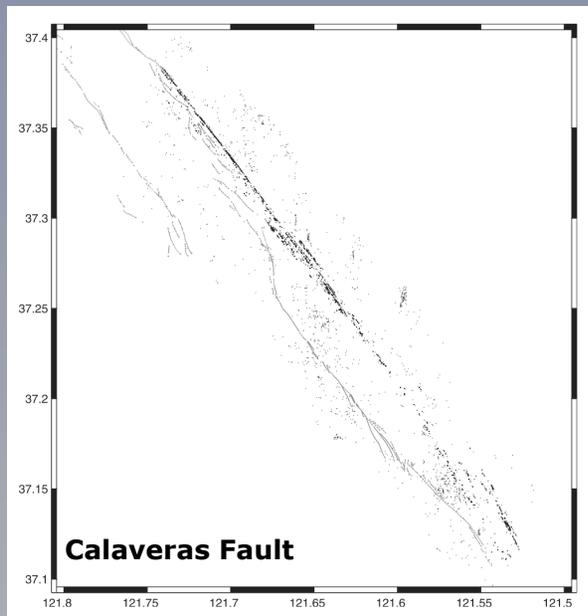
- Corner frequencies of these events are beyond the frequency band
- Or all the events have the same corner frequency



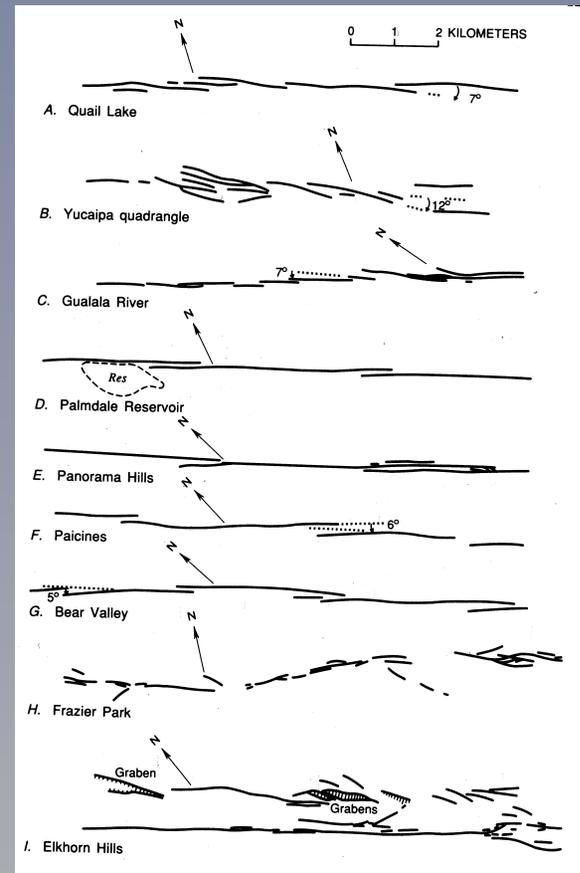
A key goal of SAFOD is to use observations made at depth to define the internal structure of the San Andreas Fault.

Does the highly segmented nature of the San Andreas Fault surface trace extend to depth?

Or does surface complexity give way to much simpler and continuous fault structures at depth?

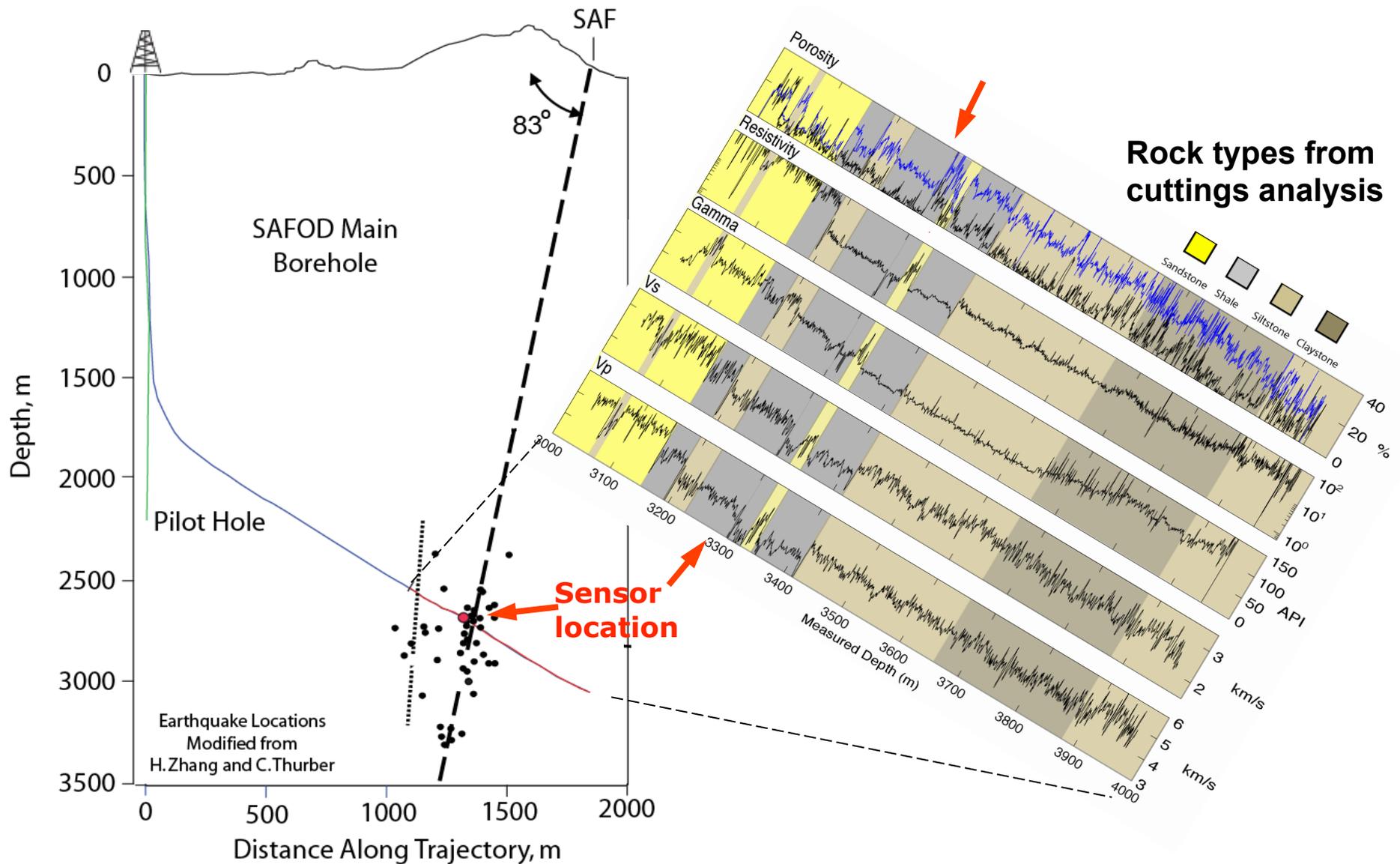


Schaff, et al. (2002)

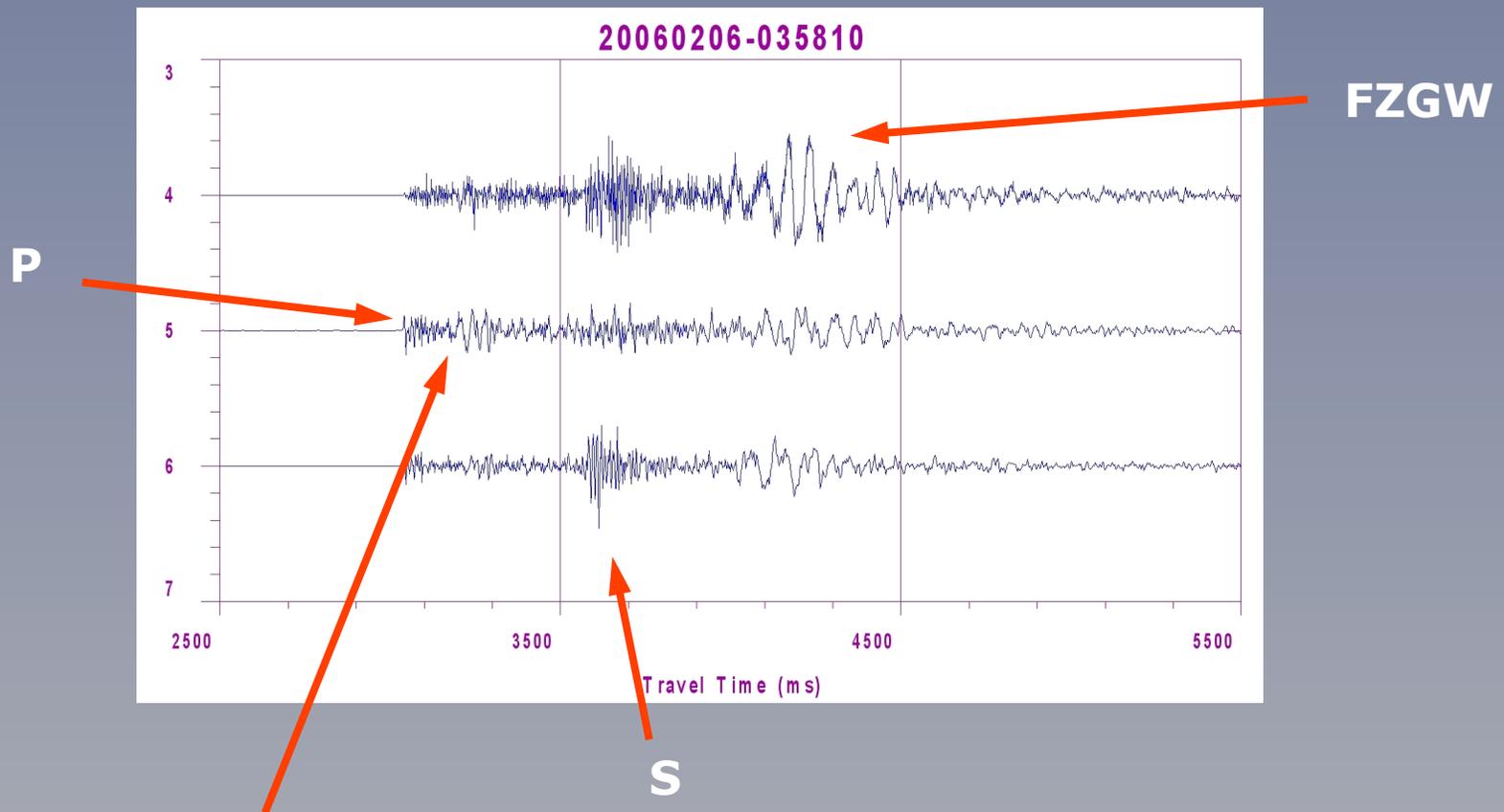


R. E. Wallace (1990)

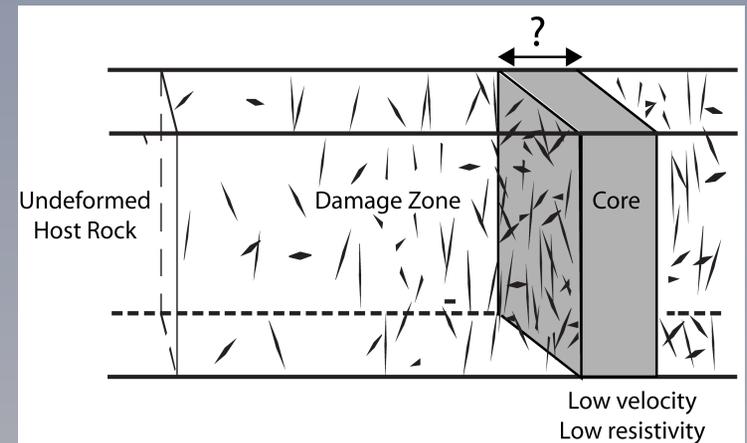
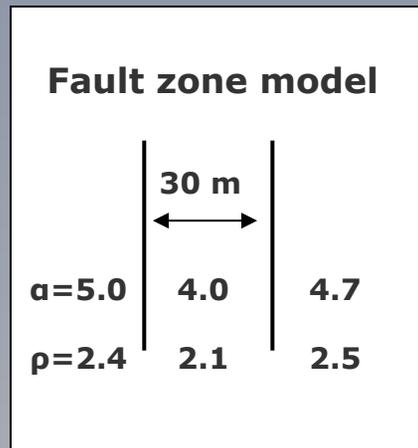
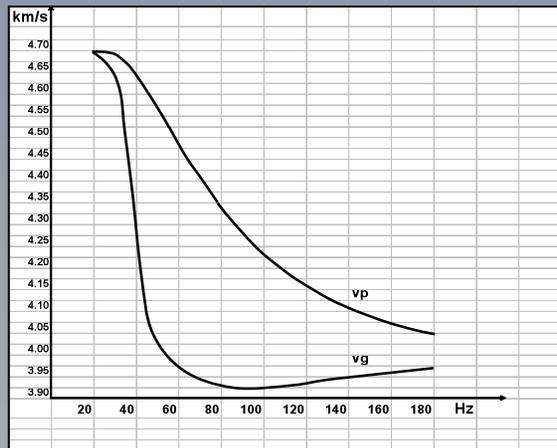
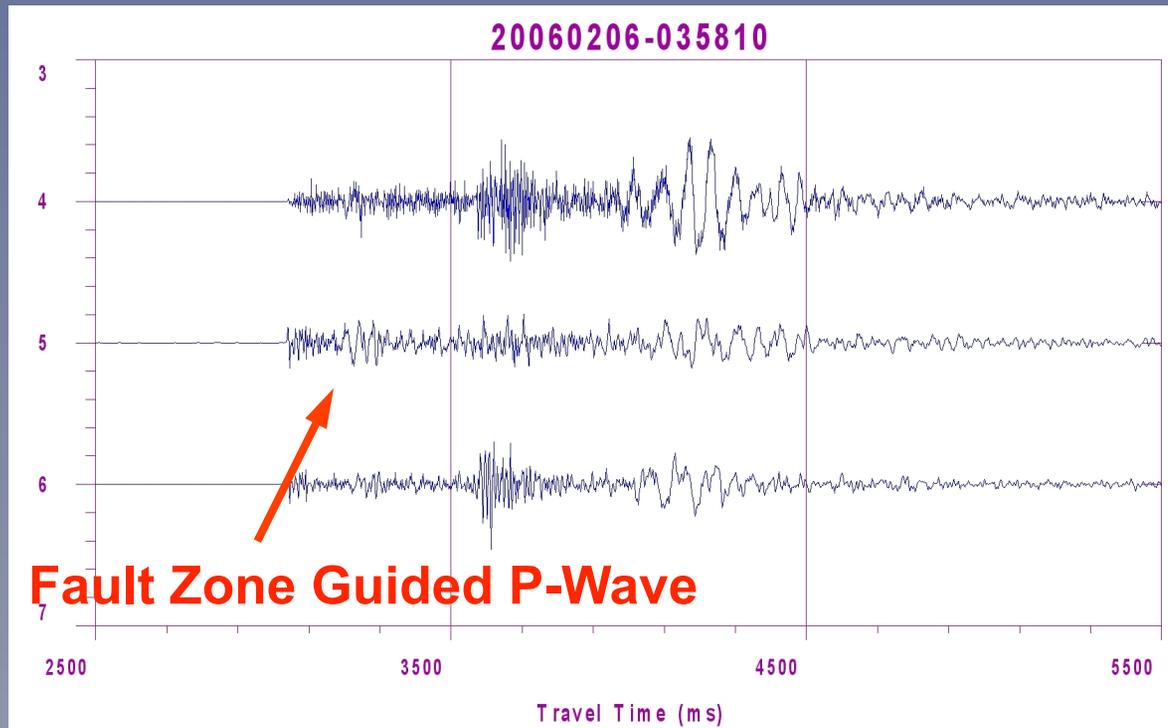
SAFOD Geophysical Logs Reveal Both Broad and Narrow Low Velocity Zones



M 1.1 recorded in SAFOD at 2.7 km depth
Range: 4.3 km
Hypocentral depth: 6.3 km

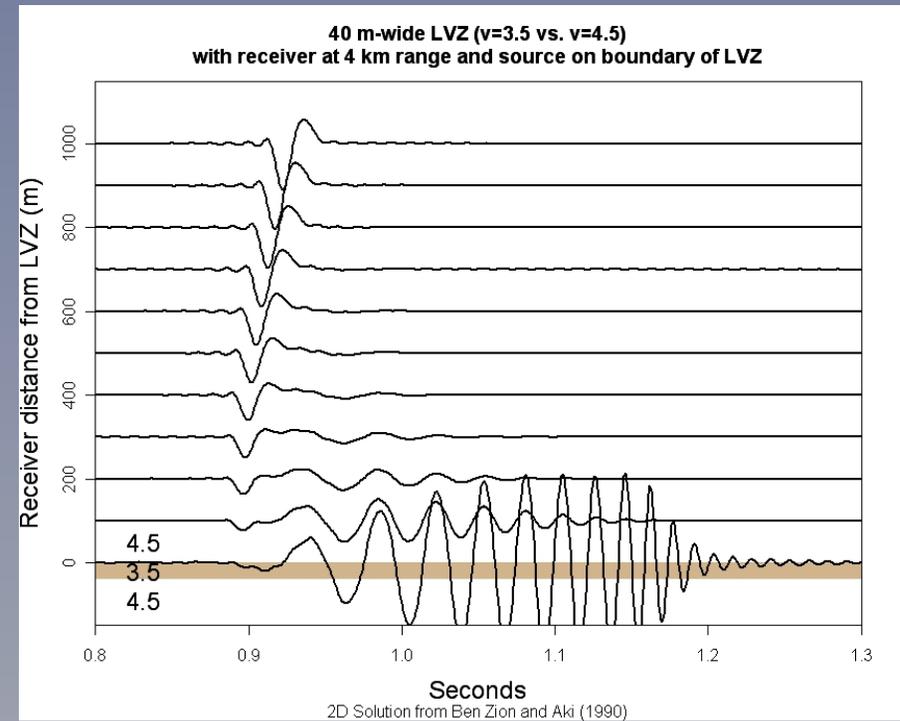
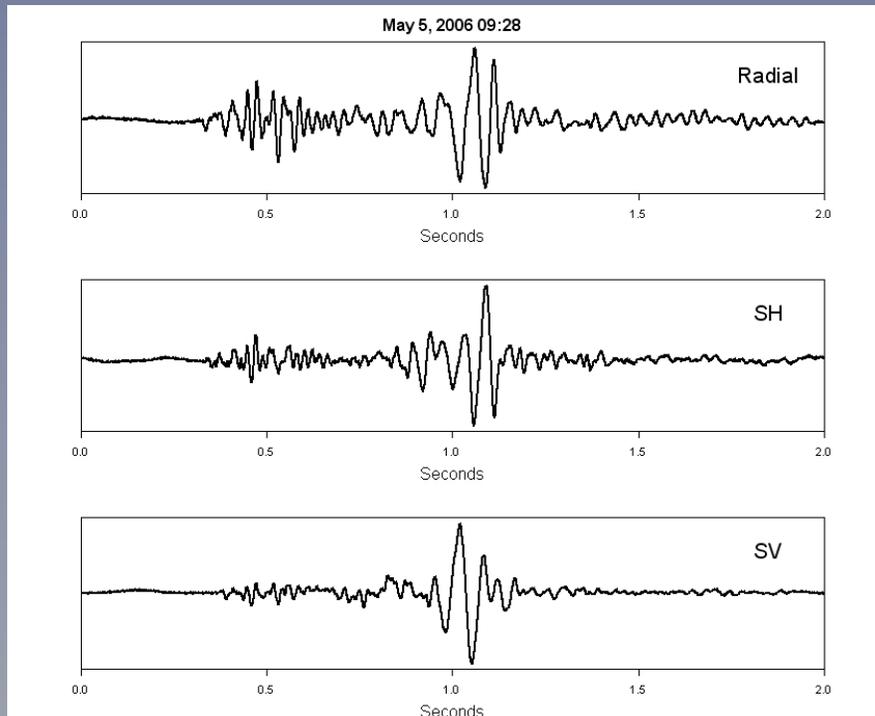


Fault Zone Guided P Wave



Fundamental locked P mode dispersion curve for 30 m low velocity channel.

When body waves are absent, both source and receiver must be located in or very near a continuous waveguide



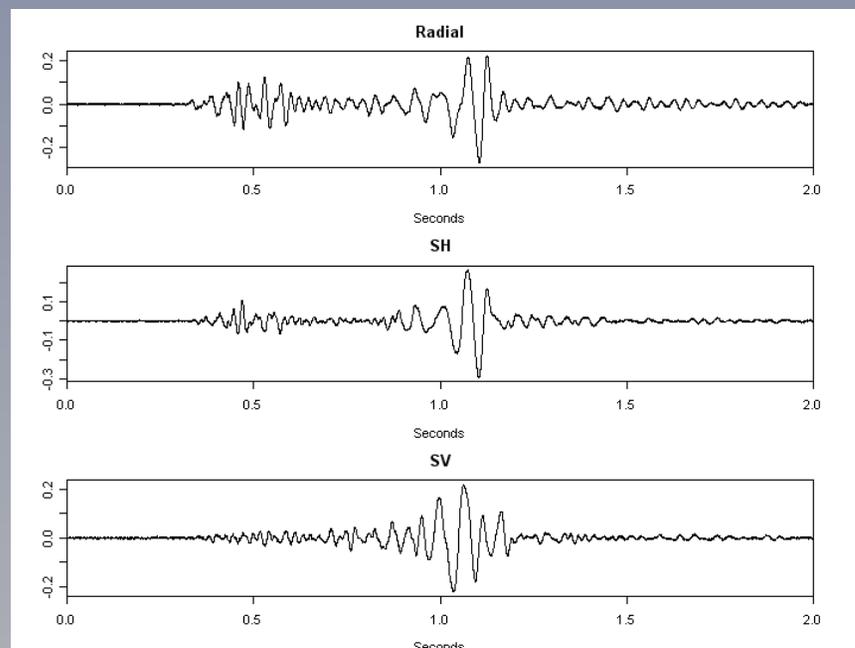
Source in waveguide

High frequency PSV- and S-type guided waves are present at 2.7 km depth in the core of the San Andreas Fault.

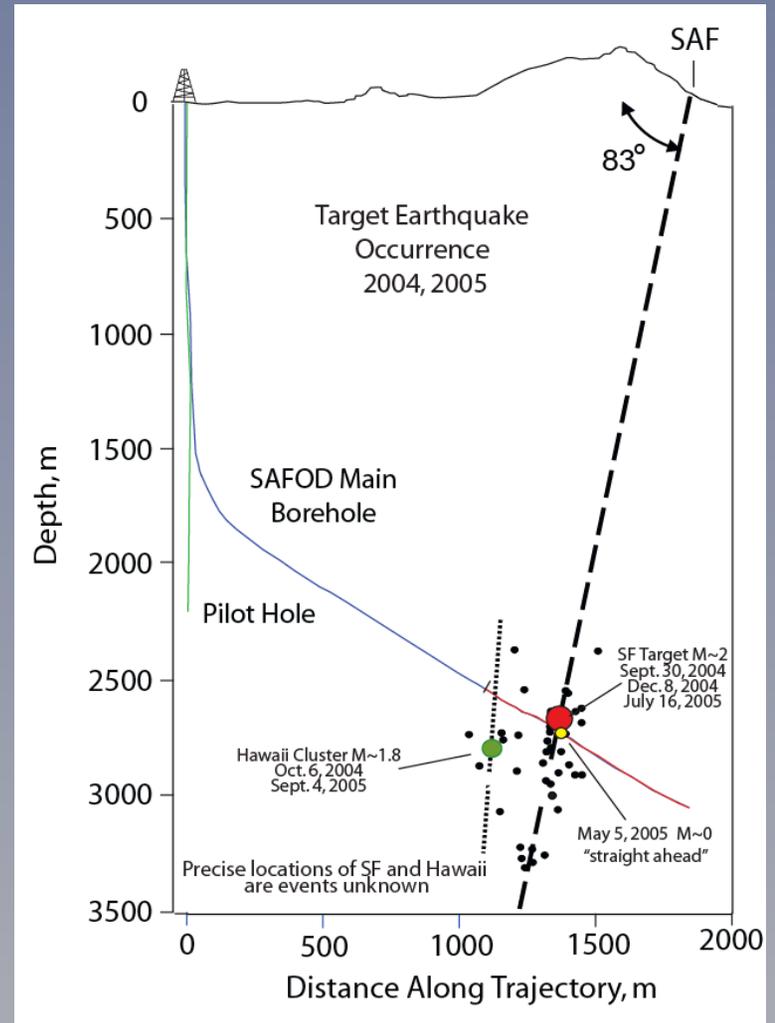
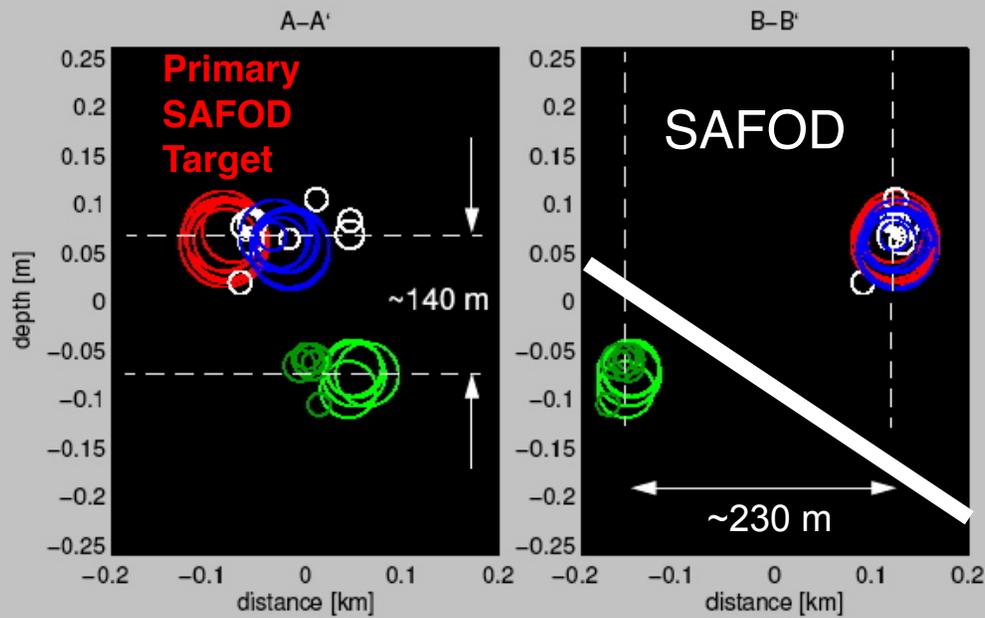
The frequency and dispersion characteristics of both PSV- and S-type guided waves require a narrow (~ 30 m) waveguide with a velocity reduction of 20-25%.

The waveguide must continue for a substantial fraction of the distance between the earthquake source and receiver.

Narrow, low velocity fault zones extend deep into the seismogenic crust beneath SAFOD.

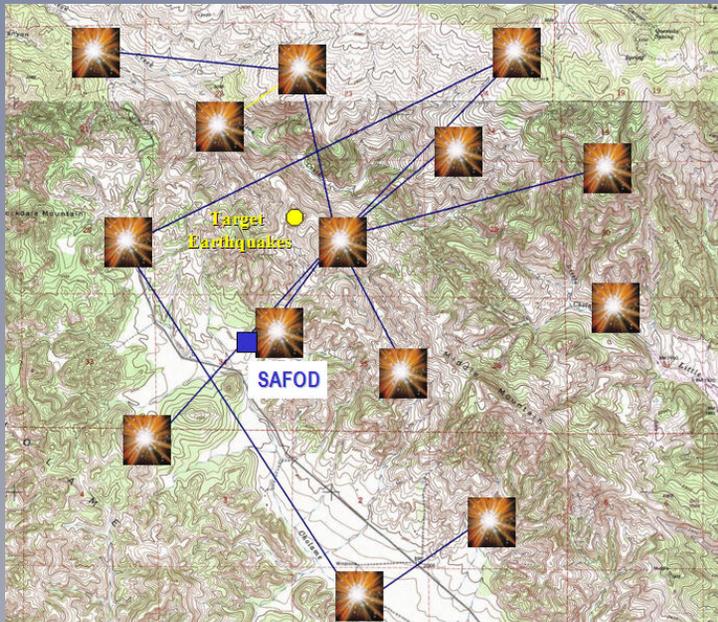


Target Earthquakes

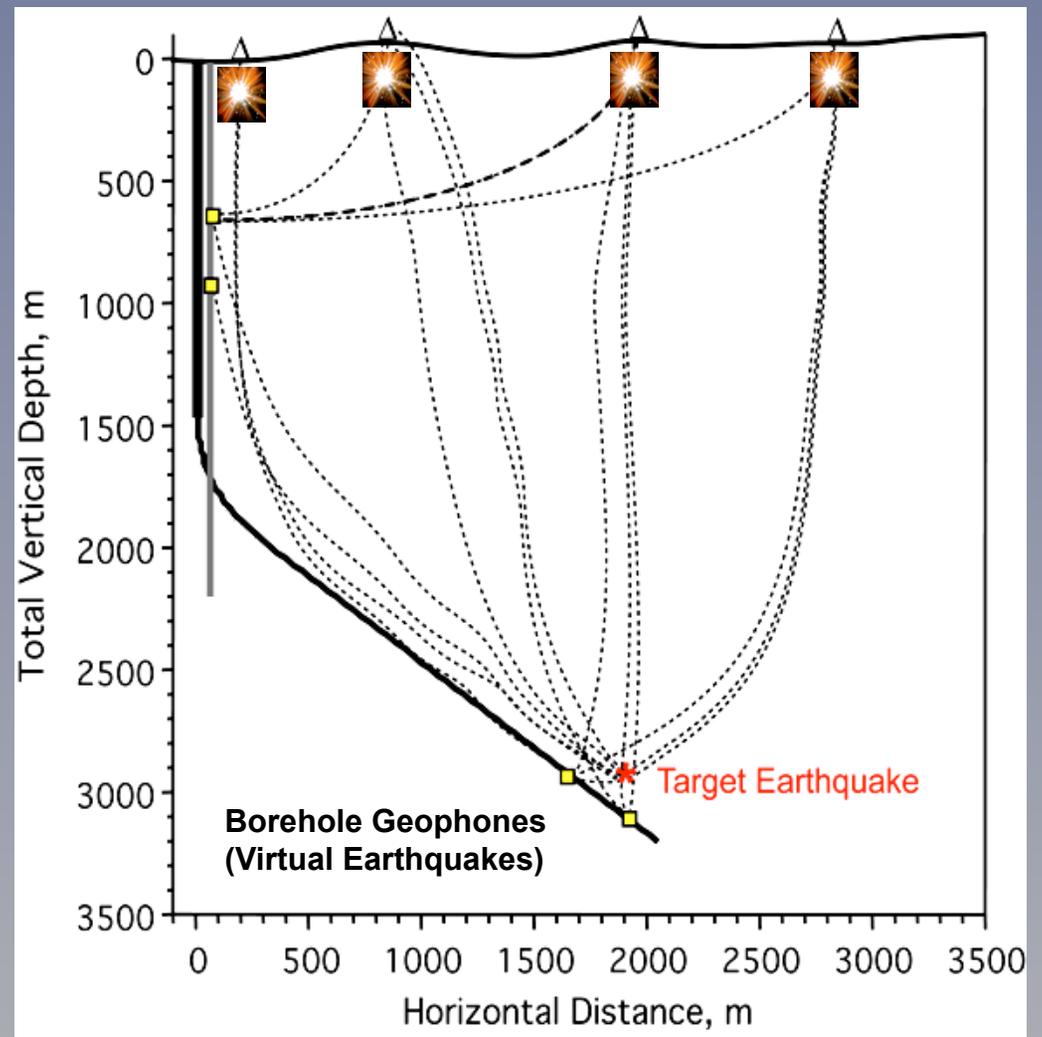


Locating the Target Earthquakes Using Virtual Earthquakes

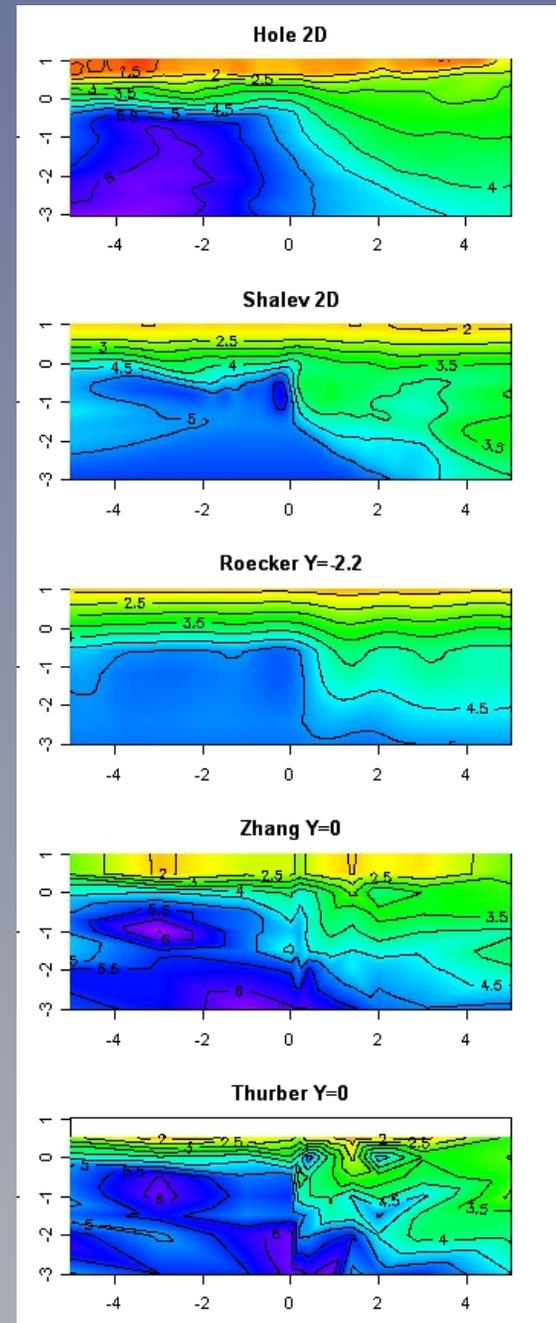
Oct. 26 & Nov. 1, 2006; March 24, 2007: Calibration shots fired at 14 PASO surface seismic stations (Steve Roecker, RPI, and Cliff Thurber, Univ. Wisconsin).



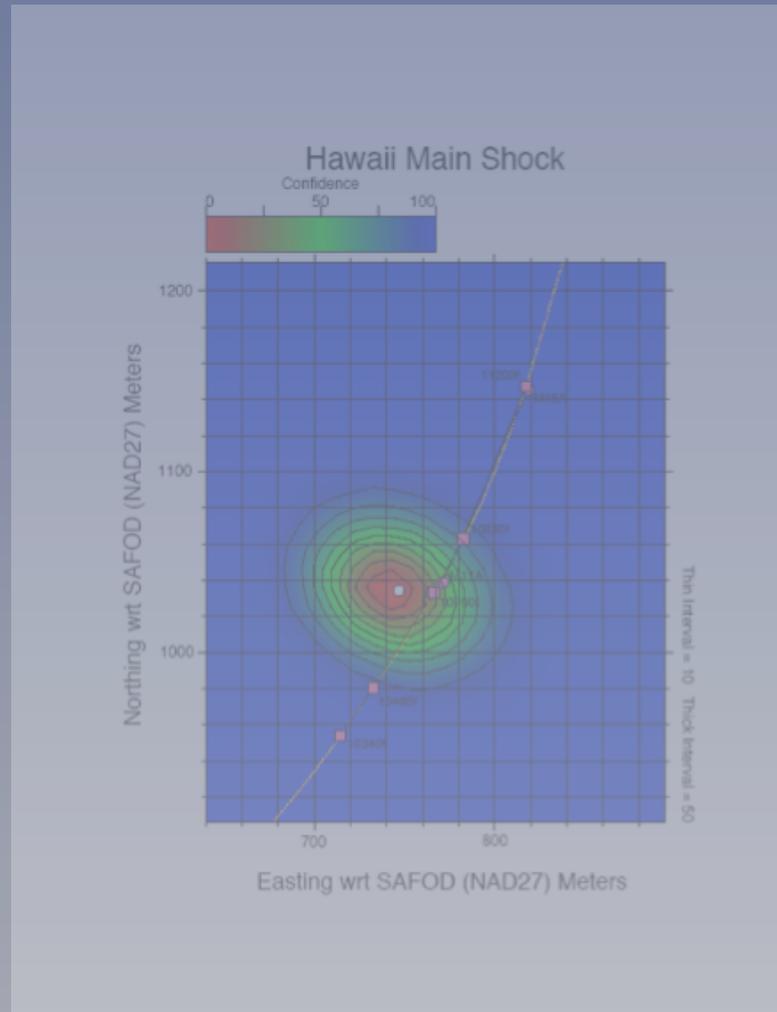
Borehole and surface recordings of shots and target earthquakes used to refine target earthquake locations for Phase 3 coring.



- Multiple velocity models developed from controlled source and earthquake travel times.
- Multiple approaches to location of the target earthquakes in 3D models.
- Particle motions from Main Hole instruments provide independent check on results.

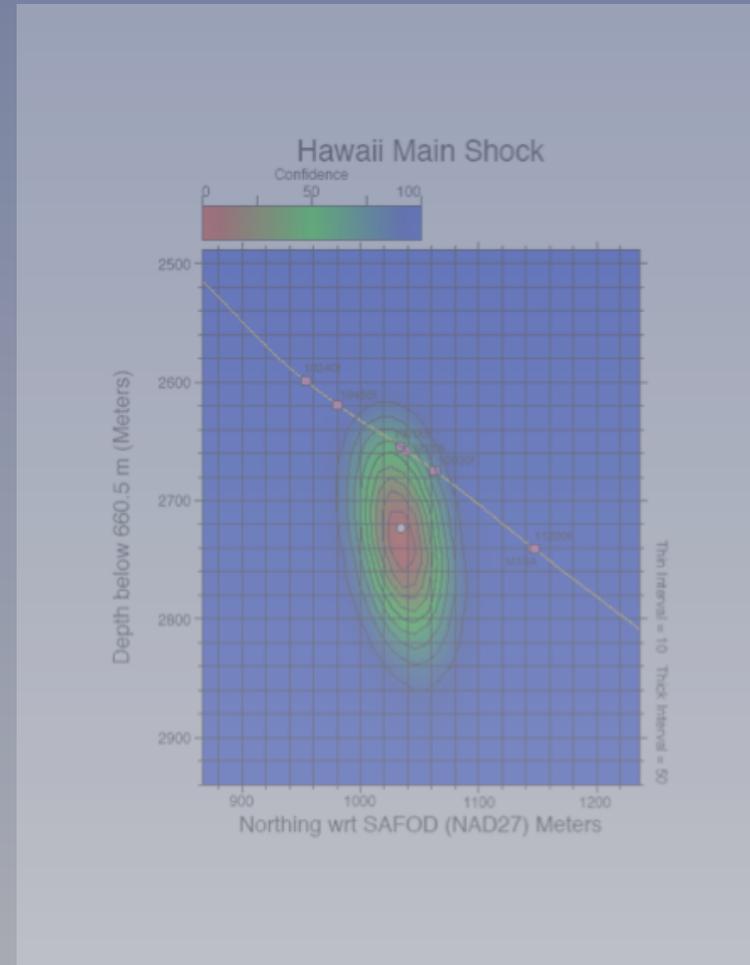
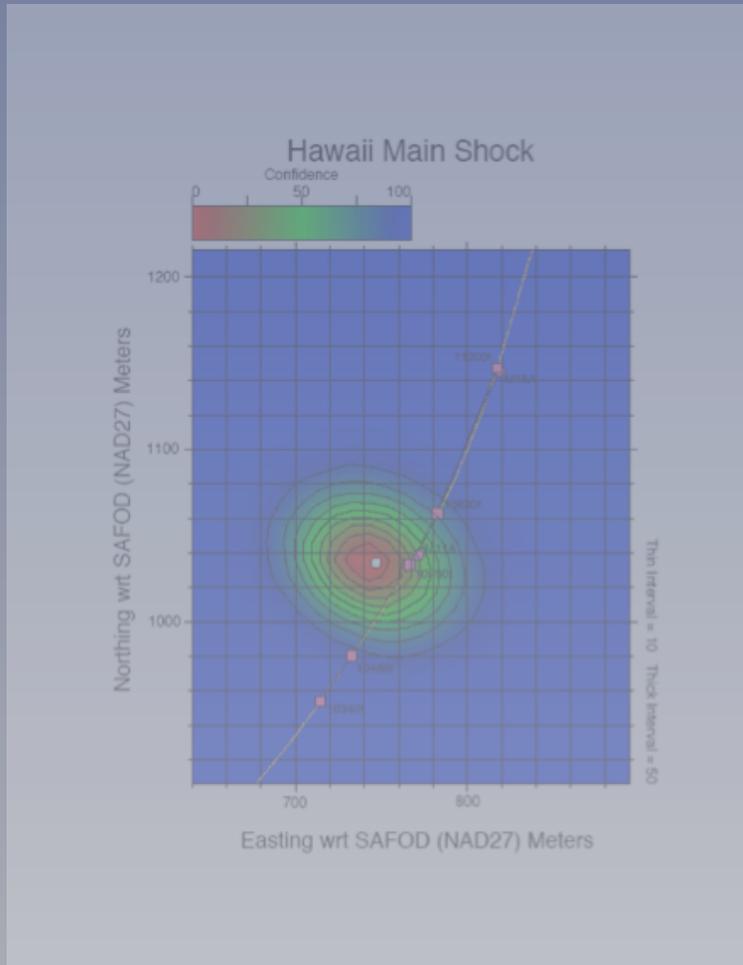


Current Status of Hawaii Target Location

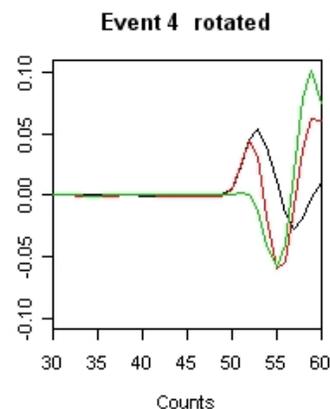
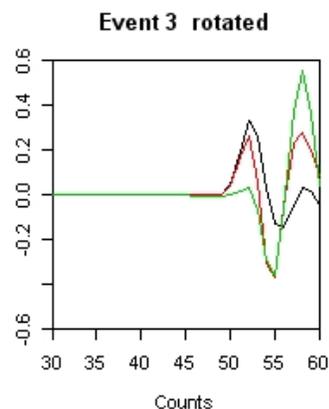
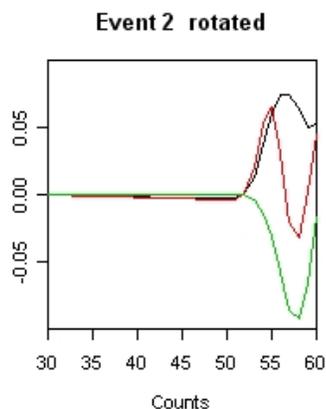


Probability Density Function for Hawaii epicenter by Steve Roecker

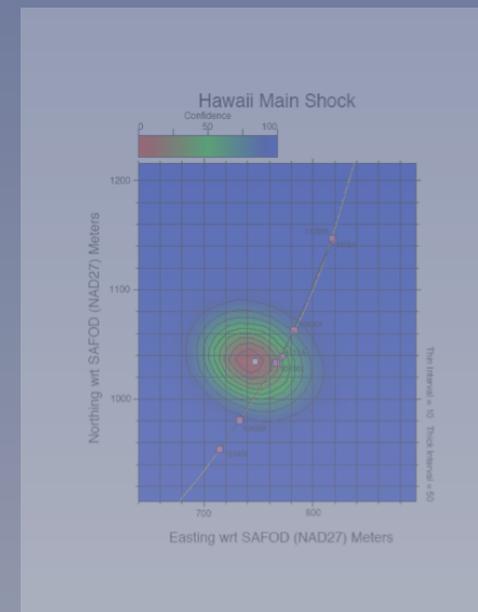
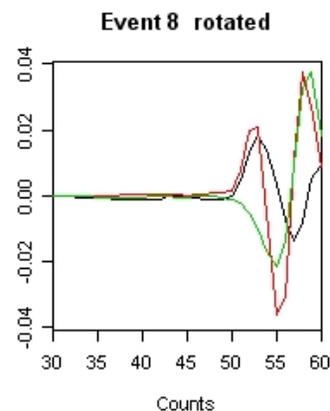
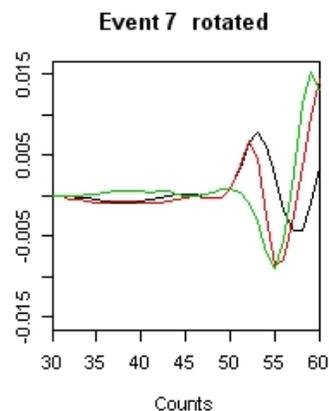
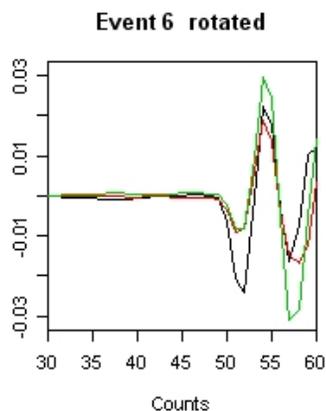
Current Status of Hawaii Target Location



Particle Motion for HI Ultramicroaftershocks

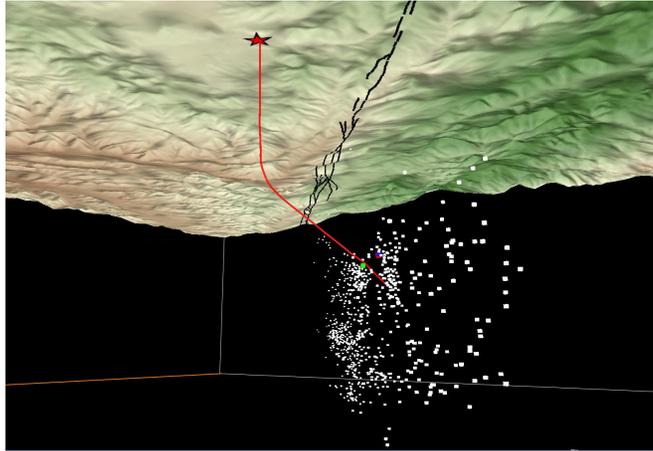


Up: Black
East: Red
North: Green



The initial P-wave arrival typically has roughly equal amplitude on the Up and East components and smaller amplitude on the North component.

Particle motion consistent with a location to the west and below the sensor.

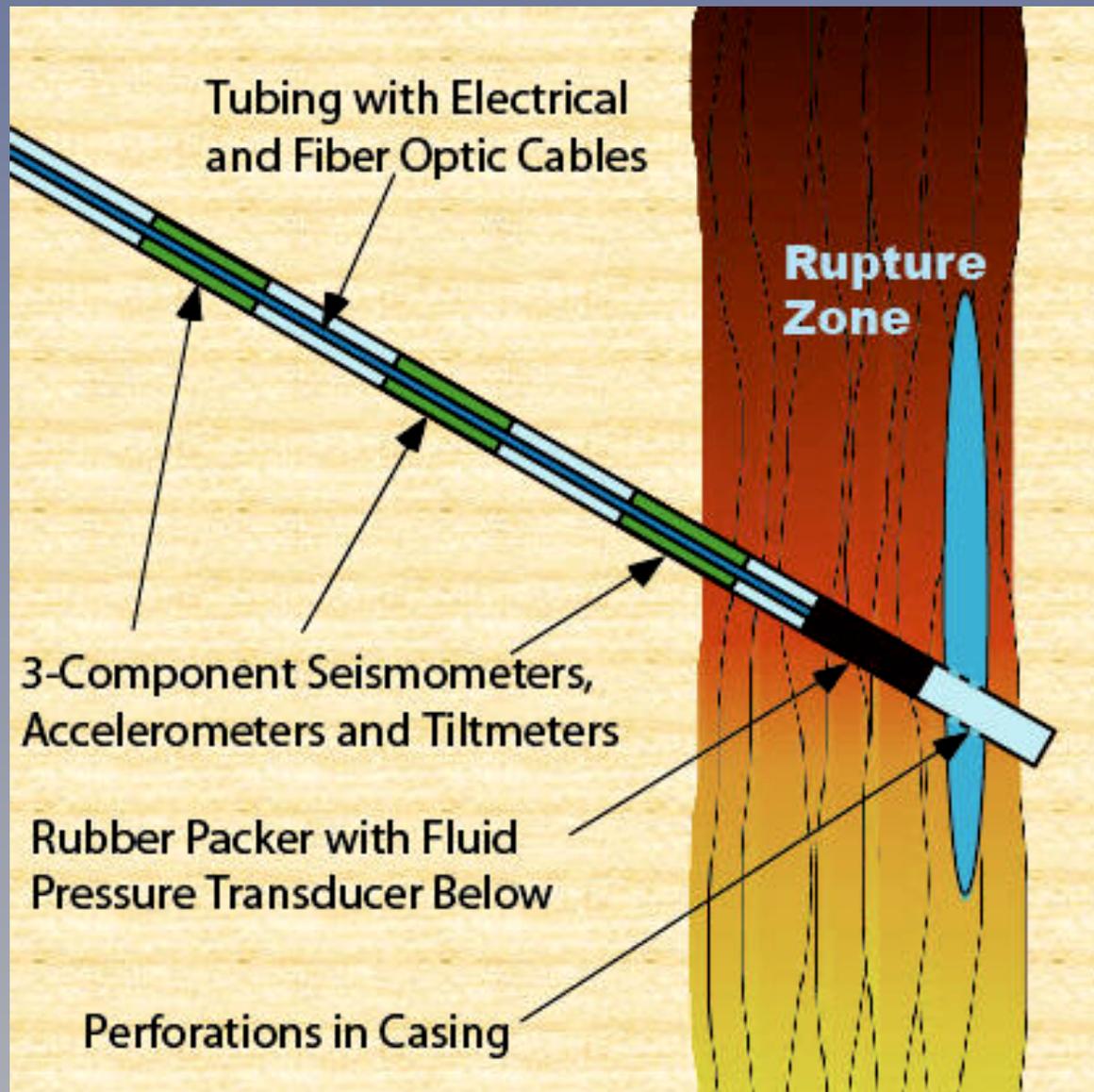


Permanent Monitoring Array Instrumentation

Design goals

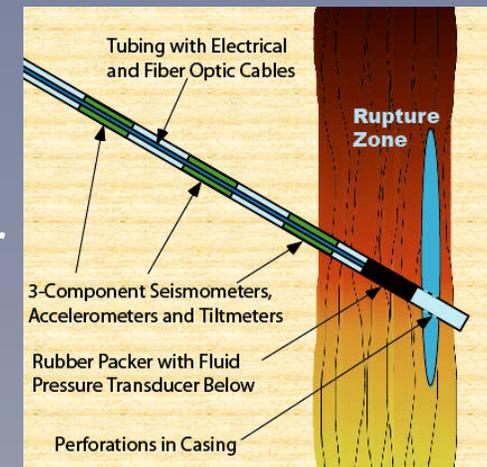
- Record weak motion at the maximum gain consistent with high signal-to-noise in the 10 – 2000 Hz band.
- Record on scale motion of M 2 earthquakes in their near field over a broad band (0.5 – 1500 Hz).
- Maintain linearity of ground motion recording in the sensor, electronics and mechanical coupling to the Earth.
- Record aseismic transient deformation at periods from 1 hour (or longer) to 1 s.
- Record pore pressure fluctuations in the fault zone at periods of days to 1 s.

Permanent Observatory Monitoring Array



Permanent Observatory Monitoring Array

- Pipe deployed system
- Electrical conductors and optical fibers in stainless steel microtubes.
- No O-rings (laser welded sondes)
- Stiff bow spring decentralizers on instrument pods
- 3 levels of multi-component sondes
 - GERI DS150 3C 15 Hz seismometer
 - Modified GERI DS150 with 3C Colibrys MEMS accelerometer
 - Pinnacle borehole tiltmeter
- Hydraulic packer to isolate perforated casing in the fault zone
- Pressure sensor to measure pore pressure below packer
- Optical fiber telemetry (4K sps)
- GERI Geores control computer
- Earthworm data distribution and archiving system
- On-site event detection and integration of SAFOD, HRSN and NCSN waveforms using Norsar MIMO system
- Limited real-time telemetry
- Full data stream recorded on LT03 tapes



Recent failures have all occurred by shorts on the wet side of the cable head or in the wireline



Gas under high pressure diffusing through O-rings

Blistering of Kalrez O-rings



Deformation of Viton O-rings



Replacement of Viton O-rings by Kalrez O-rings (at considerable cost) helped reduce, but not eliminate the gas problem inside the pressure vessels.

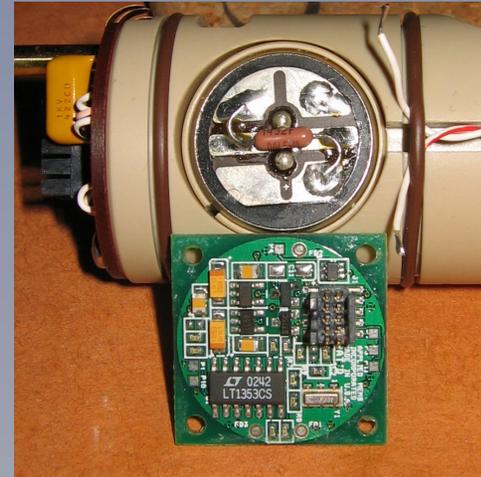
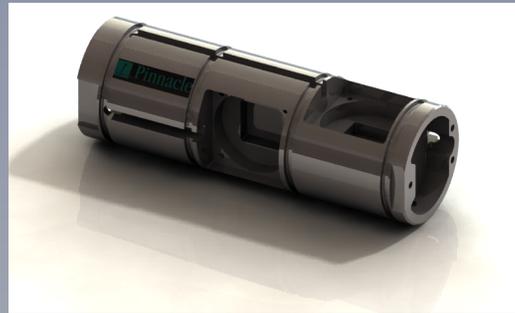
90 durometer Viton O-rings proved to provide better gas protection than Kalrez

Modification and Testing of GERI DS150 Instruments



Replace 15 Hz geophone
with MEMS accelerometer

House MEMS in specially-
designed chassis



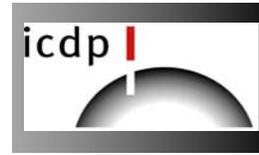
Field testing of DS150 MEMS unit by Pinnacle

Long-term high temperature test of DS150 MEMS unit by USGS

Questions?







EarthScope SAFOD Facility Closeout Report

September 30, 2008

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Introduction and Scientific Goals

The central scientific objective of the San Andreas Fault Observatory at Depth (SAFOD)



Figure 1: SAFOD drilling rig on location in the summer of 2004.

is to study the physical and chemical processes that control deformation and earthquake generation within an active plate-bounding fault zone. Through an integrated program of downhole sampling, measurements and long-term monitoring, SAFOD was designed to (1) determine the structure and properties of the fault zone at depth (2) utilize exhumed fault zone core to determine the frictional behavior, physical properties, and chemical processes controlling faulting through laboratory analyses of fault rocks and fluids, (3) measure stress, permeability, and pore pressure conditions *in situ*, (4) characterize the three-dimensional volume of crust containing the fault, (5) directly monitor strain, pore pressure, and near-field seismic radiation during the cycle of repeating microearthquakes, and (6) observe earthquake nucleation and rupture processes in the near field.

Completed Facility

Site and Lease

SAFOD is located in central California at the transition between the creeping segment of the San Andreas Fault and the Parkfield segment, a section of the fault where seven moderate (~M6) earthquakes have occurred since 1857, most recently on Sept 28, 2004 (Figure 2). The Parkfield segment of the San Andreas Fault is the most densely instrumented fault segment in the world. Seismic and deformation data from SAFOD are an integral part of the Parkfield Earthquake Experiment, which is described at

<http://earthquake.usgs.gov/research/parkfield/index.php>.

The SAFOD site is situated on 5 acres of leased land on private property located northwest of the town of Parkfield and approximately 1.8 km SW of the San Andreas Fault. The lease is held by the USGS through September 30, 2019.

A photo of the SAFOD site during Main Hole drilling operations is shown in Figure 3, and a map of the current site layout is shown in Figure 4.



Figure 2: Location of SAFOD relative to the San Andreas Fault, including segments that fail periodically in moderate to large earthquakes (red) and the segment that moves through a combination of fault creep and ongoing microseismicity (blue).

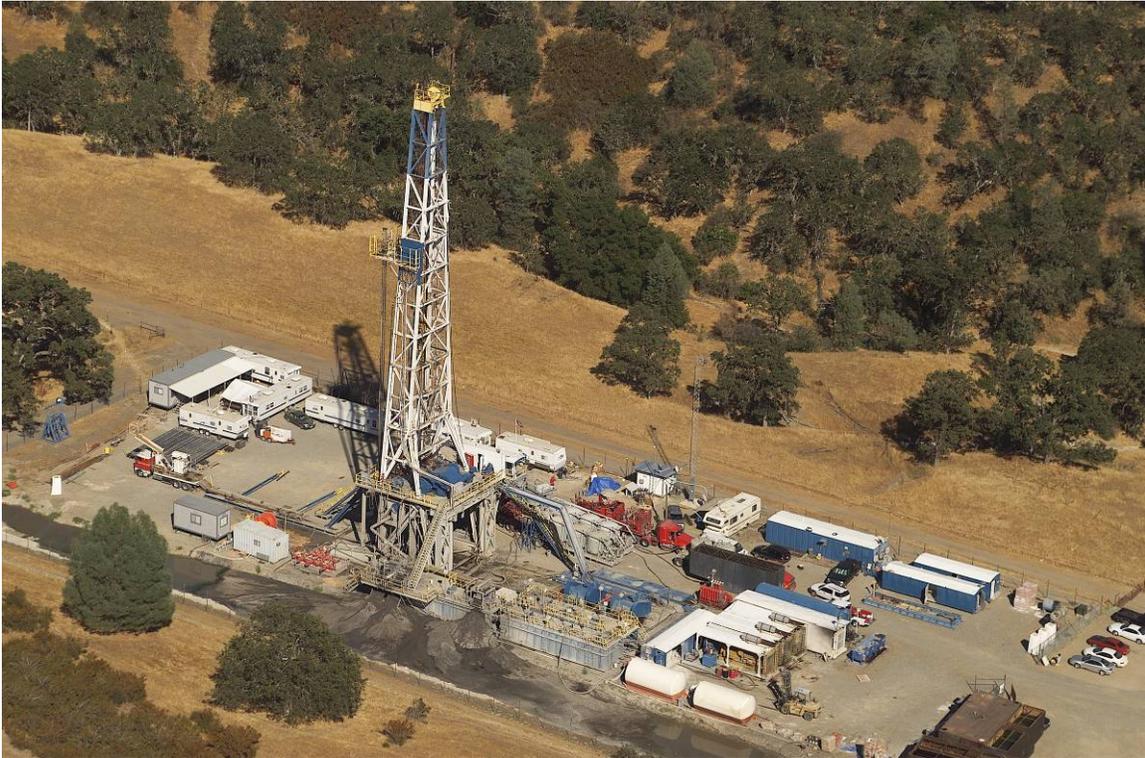


Figure 3: Aerial view of SAFOD during drilling operations in the summer of 2005.

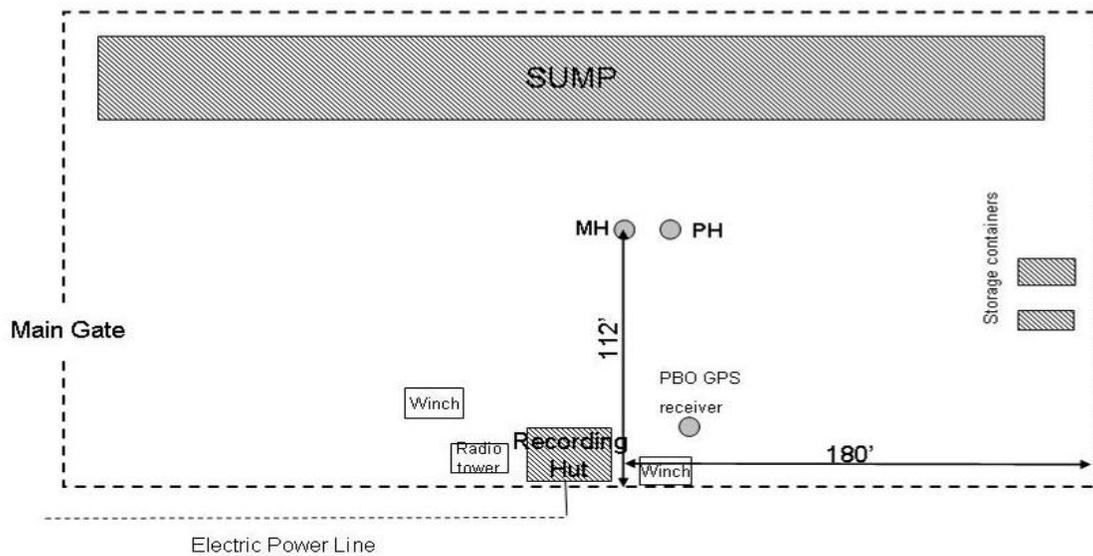


Figure 4: Schematic map of SAFOD site as of September 30, 2008. MH and PH denote the SAFOD Main Hole and Pilot Hole, respectively.

The site is the location of both the SAFOD Pilot Hole, drilled in 2002 through funding from the International Continental Scientific Drilling Program (ICDP), and the SAFOD Main Hole, drilled as part of the EarthScope Program in 2004, 2005 and 2007 (Figure 4).

Also located on the site are several other temporary structures used for storage of equipment, on-site tool assembly and data recording. There are also two A-frames (see below) and wireline logging winch units on site that are used during borehole logging operations and temporary deployments of monitoring tools. The recording hut houses all of the computers, surface control electronics, data logging and telemetry equipment needed to support downhole instrumentation and telecommunications links to the internet. Electrical power to the site is provided by PG&E through a residential-style hookup. As described below, all surface infrastructure at SAFOD is managed by the USGS, including site power, leases, permits, and telemetry. Next to the data hut are several radio towers for data transmission. There is also a PBO GPS station located on the site.

USGS Maintained Equipment

The USGS is responsible for the management of the data hut, its contents, power and telemetry. The USGS also maintains the radio towers, which are used for data transmission. Consequently, all the Internet access at the site is through the USGS, and all equipment that needs Internet access must get prior approval from the USGS. This will include certain internet security settings. Remote access to the onsite computers can only be achieved via the USGS Virtual Private Network (VPN).

PBO Equipment

PBO is responsible for the operations and maintenance of the GPS receiver on location.

University of Auckland/Duke Equipment

Peter Malin, formerly of Duke University and now at the University of Auckland, is responsible for the winch used for downhole deployments in the Pilot Hole (although the cable belongs to SAFOD). Peter Malin also has some equipment on site, including small tools and two large pulleys.

Pilot Hole

In preparation for SAFOD, a 2.2-km-deep vertical Pilot Hole was drilled and instrumented at the SAFOD site in the summer of 2002. The Pilot Hole was a collaborative effort between the ICDP, NSF and the USGS. The Pilot Hole was rotary drilled with an 8 ¾ inch bit, and cased with 7” O.D. steel casing (Figure 5). The Pilot Hole is now available for instrument testing, cross borehole experiments, or related scientific activity; however, due to the intersection of the Pilot Hole by the Main Hole in the summer of 2004, the Pilot Hole is currently only open to a depth of 1.11 km. The Pilot Hole wellhead is located at latitude 35.9742579 longitude -120.5521071 (WGS 1984 reference). The ground level at the site is 660.5 m above mean sea level.

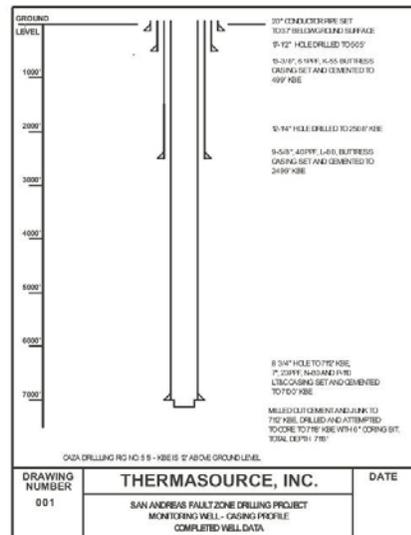


Figure 5: Pilot Hole completion diagram.

Main Hole

The SAFOD Main Hole was rotary drilled during the summers of 2004 (Phase 1) and 2005 (Phase 2). The wellhead of the Main Hole is located at latitude 35.9742039 and longitude -120.5521414, at a distance of 6.75 meters from the Pilot Hole wellhead (see Figure 4). As can be seen in Figure 6, the Main Hole starts vertically, but at approximately 1.5 km depth, directional drilling techniques were employed to deviate the borehole at an angle ~60 degrees from vertical to intersect the San Andreas Fault in the vicinity of the repeating “target” earthquakes at a vertical depth of ~2.7 km.

The various SAFOD Main Hole casing sizes are shown in the well completion diagram at http://www.icdponline.org/contenido/icdp/upload/pdf/safod/SAFOD_CASING_102005.pdf

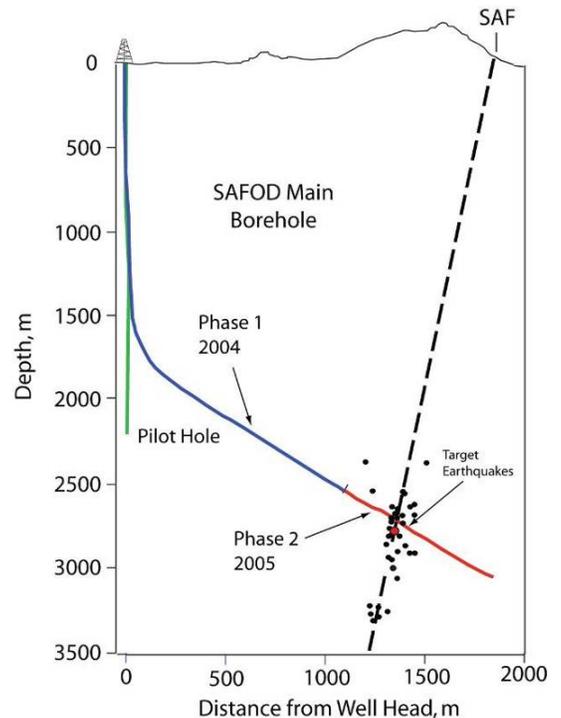


Figure 6: SAFOD Main Hole and Pilot Hole in cross-section

As shown in Figure 7, during Phase 3 several sidetracks were drilled laterally off the Main Hole primarily for the purpose of obtaining core from the two actively deforming traces of the San Andreas Fault as identified by repeated casing deformation logs. The two active fault traces are referred to as the 10,480 and 10,830 faults, corresponding to the approximate measured depths along the hole where casing deformation was detected in the Phase 2 hole. An additional core was obtained from just outside the contact between coarse sandstones and conglomerates of the Salinian Terrane and shales, siltstones and fine sandstones thought to be associated with the Great Valley Formation.

Sidetracking the hole for coring required the abandonment of the Phase 2 Main Hole below the kickoff point of the sidetracks (Figure 7). The first sidetrack, Hole E was abandoned and cemented off after one successful coring run. Two cores were obtained from the second coring sidetrack, Hole G, which was then reamed out after coring to allow for installation of the 7” diameter casing. The casing was set to a measured depth of 10,546 ft.

SAFOD Phase 3 Cored Intervals:

- 1- Near Salinian/Great Valley(?) Contact (sandstone/shale contact)
- 2 - Across 10,480 Fault (Phase 2 casing deformation zone)
- 3 - Across 10,830 Fault (Phase 2 casing deformation zone)

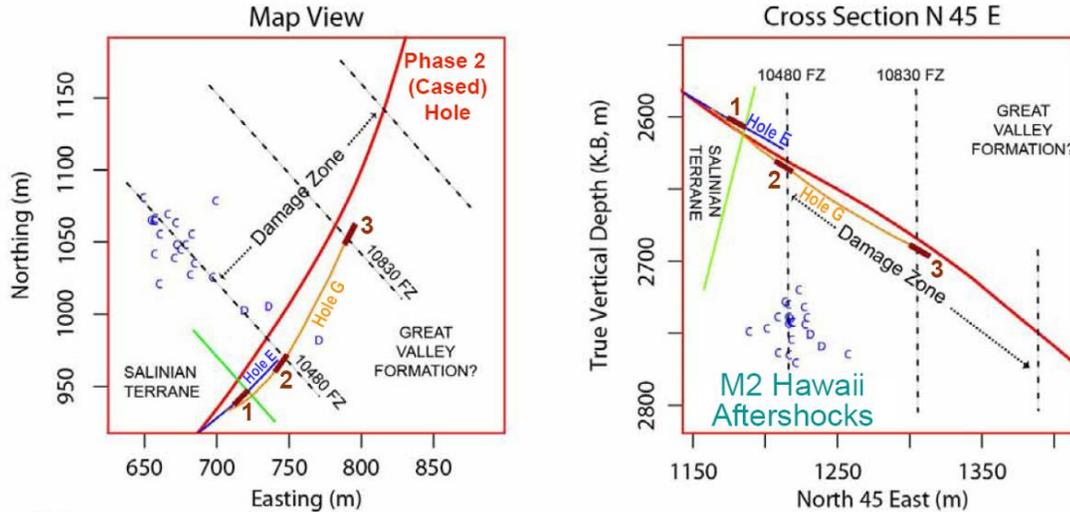


Figure 7: Detailed trajectories of the SAFOD Phase 3 coring runs relative to the contact between the Salinian terrane and the presumed Great Valley Formation (in green) and the actively deforming traces of the San Andreas Fault identified at 10,480 ft MD and 10,830 ft MD in the Phase 2 hole.

Schedule

As seen in Table 1, nearly all the SAFOD milestones were completed on schedule. The only significant activity that was late was deployment of the permanent observatory (Stage 3 deployment). A Gantt chart is shown at the end of this report (Figure 12).

Table 1: SAFOD Milestones

Year 1 Milestones	Completed?	When?
Quarter 1 (9/1/03 – 12/31/03)		
1.2 Stage 1 SAFOD monitoring subcontract awarded.	Yes	Y1Q2
1.2 Phase 1 Drilling subcontract signed	Yes	Y1Q1
1.2 SAFOD Advisory Board and Technical Panels named	Yes	Y1Q1
1.2 SAFOD Data Manager hired	Yes	Y1Q1
Quarter 2 (1/1/04 – 3/31/04)		
1.2 Construction of SAFOD Stage 1 monitoring instrumentation initiated	Yes	Y1Q2
1.2 Subcontract for SAFOD Stage 2 monitoring instrumentation issued	Yes	Y1Q3
Quarter 3 (4/1/04 – 6/30/04)		
1.2 Phase 1 drilling of SAFOD Main Hole initiated	Yes	Y1Q3
1.2 Construction of Stage 2 monitoring instrumentation initiated	Yes	Y1Q3
Quarter 4 (7/1/04 – 9/31/04)		
1.2 Phase 1 drilling and related downhole activities completed	Yes	Y2Q1
1.2 Stage 2 monitoring instrumentation deployed	Yes	Y2Q1
1.2 Stage 1 monitoring system in SAFOD Pilot Hole deployed	Yes	Y2Q3

Year 2 Milestones		Completed?	When?
Quarter 2 (1/1/05 – 3/31/05)			
1.2	Contract for Stage 3 monitoring system signed	Yes	Y3Q4
1.2	Samples and data distributed	Yes	Y2Q2
1.2	Subcontract for Phase 2 drilling and related services signed	Yes	Y2Q1
Quarter 3 (4/1/05 – 6/30/05)			
1.2	Construction of Stage 3 prototype monitoring system initiated	Yes	Y4Q1
1.2	Phase 2 drilling of SAFOD Main Hole initiated.	Yes	Y2Q3
Quarter 4 (7/1/05 – 9/31/05)			
1.2	Phase 2 drilling of SAFOD Main Hole and related downhole measurements completed	Yes	Y2Q4
Year 3 Milestones		Completed?	When?
Quarter 1 (10/1/05 – 12/31/05)			
1.2	Prototype Stage 3 monitoring system deployed	changed during baseline review	
1.2	Preliminary analysis of cuttings and core complete and archive established	Yes	Y3Q1
1.2	Gyroscopic well survey and azimuthal casing bond log carried out	Yes	Y3Q1
1.2	Phase 2 samples distributed	Yes	Y3Q1
Quarter 2 (1/1/06 – 3/31/06)			
Quarter 3 (4/1/06 – 6/30/06)			
Quarter 4 (7/1/06 – 9/31/06)			
1.2	Prototype Stage 3 monitoring system deployed	Yes	Y4Q4
Year 4 Milestones		Completed?	When?
Quarter 1 (10/1/06 – 12/31/06)			
Quarter 2 (1/1/07 – 3/31/07)			
1.2	Subcontract for Phase 3 drilling and related activities established	Yes	Y4Q2
Quarter 3 (4/1/07 – 6/30/07)			
1.2	Prototype Stage 3 monitoring instrumentation retrieved	Yes	Y4Q4
1.2	Gyroscopic well survey and azimuthal casing bond log carried out	Yes	Y4Q2
1.2	Intervals for Phase 3 continuous coring selected	Yes	Y4Q2
Quarter 4 (7/1/07 – 9/31/07)			
1.2	Engineering design for Phase 3 hole completion finalized	Yes	Y4Q3
1.2	Phase 3 drilling and coring initiated	Yes	Y4Q3
1.2	Real-time analysis of core completed and sample archive established	Yes	Y5Q2
1.2	Performance of Stage 3 prototype monitoring system evaluated and redesign and modifications initiated as necessary	Yes	Y5Q2
Year 5 Milestones		Completed?	When?
Quarter 1 (10/1/07 – 12/31/07)			
1.2	Phase 3 drilling and related activities completed	Yes	Y4Q4
Quarter 2 (1/1/08 – 3/31/08)			
1.2	Phase 3 samples distributed	Yes	Y5Q4
Quarter 3 (4/1/08 – 6/30/08)			
1.2	Stage 3 monitoring instrumentation deployed	Yes	Y5Q4
Quarter 4 (7/1/08 – 9/31/08)			
1.2	Data archiving and sample distribution completed	yes	Y5Q4
1.2	Permanent installation of well site instrumentation completed	Yes	Y5Q4

Information for Researchers, Visitors, Training and Education

Procedures for researchers wishing to obtain access to samples are described in the EarthScope Data Policy, available at the EarthScope website. Because the drill site is on private property and unstaffed, visitors are not allowed without permission. Individuals interested in potentially visiting the SAFOD site should contact Bill Ellsworth ellsworth@usgs.gov 650-329-4784 or Andy Snyder asnyder@usgs.gov 805-463-2382.

Permanent Array

The installation of the long-term observatory was completed on Sept 28, 2008. The observatory instruments were deployed in Hole G, with the bottom of the array located approximately 100 m above aftershocks from a recent occurrence of the M2 Hawaii target earthquake (see Figure 7). The configuration of the downhole instrumentation is shown schematically in Figure 8.

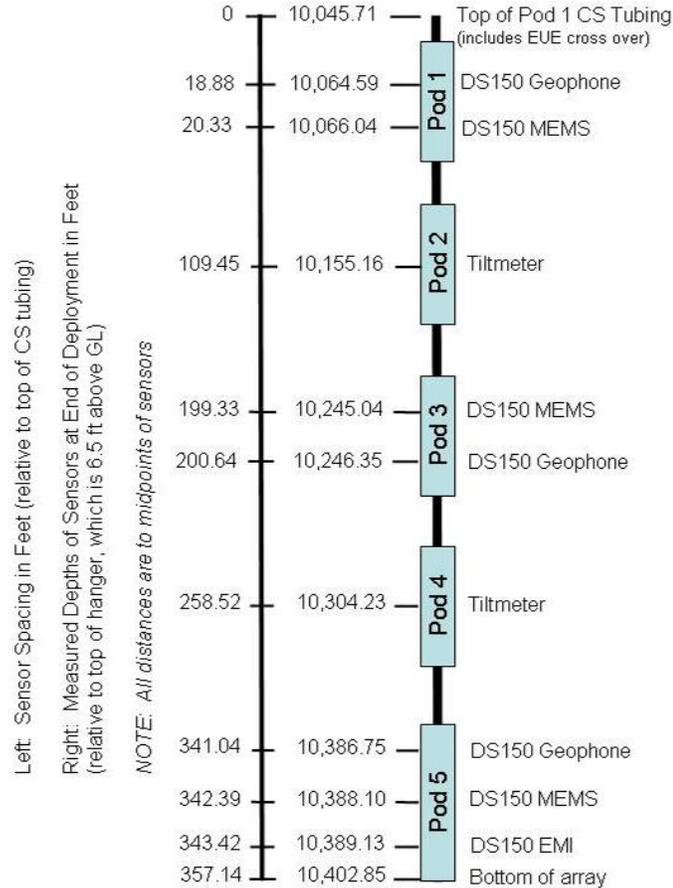


Figure 8: Schematic of final SAFOD monitoring array with measured depths

The array is located between 10,045.7 and 10,402.9 ft measured depth. The instrument package consists of 5 pods containing the following sensors (see Figure 8):

Pod 1: Oyo Geospace DS250 cablehead and crossover; OyoGeospace DS150 digital 3-component borehole seismometer (geophone); modified DS150 with 3-component Colybris MEMS accelerometers.

Pod 2: Pinnacle Hybrid Tiltmeter.

Pod 3: Modified DS150 with 3-component Colybris MEMS accelerometers; OyoGeospace DS150 digital 3-component borehole seismometer.

Pod 4: Pinnacle Hybrid Tiltmeter.

Pod 5: OyoGeospace DS150 digital 3-component borehole seismometer; modified DS150 with Colybris 3-component MEMS accelerometers; DS150 digitizer and Electromagnetic coil (EMI).

All of the instruments are housed in sealed steel pods that isolate them from contact with the wellbore fluids. The pods are welded to steel pipe (2-3/8 in EUE tubing) and coupled to the casing by decentralizing bowsprings. The seismic and tilt systems are completely independent systems. Each has its independent power and data telemetry lines encapsulated in 1/4 in stainless steel tubing with pressure-tight connections in and out of the pods. Power and communications with the surface are accomplished through 1/4 inch plastic encapsulated stainless-steel control lines, affixed to the EUE tubing at every joint connection and in the middle of joints with Canon, Inc. clamps and terminated at the surface through a pressure-tight wellhead hanger and packoff assembly.

The seismic system includes a DS150 borehole sonde containing 3-component, 15 Hz Omni-2400 geophones manufactured by Oyo Geospace. Three additional DS150's were modified by removing the geophones and replacing them with Colybris SF1500 MEMS accelerometers. The EM coil in pod 5 is connected to the A/D inputs in a DS150. Fiber optic telemetry is used to transmit the 4000 sample/second data to the surface, where they are received by an Oyo Geospace GeoRes computer. Data packets are then transferred to a USGS Earthworm computer system. The Earthworm system archives the data locally on LT3 tapes, downsamples selected channels to 250 samples/second and transmits them to the Northern California Seismic Network where they are integrated into the real-time data system and archived at the Northern California Earthquake Data Center. The continuous tapes are collected every several weeks and sent to the Northern California Earthquake Data Center for archiving there and at the IRIS DMC.

The two tiltmeters are manufactured by Pinnacle Technologies. Each tiltmeter produces two channels of tilt data, recorded at 1 sample/3 seconds. Data are received at the surface by a dedicated PC computer and transmitted to the Northern California Earthquake Data Center for processing and archiving.

Fiber Optic Strainmeter

At the conclusion of Phase 1 drilling, SAFOD, in collaboration with Mark Zumberge of UC San Diego, installed an experimental fiber optic strain sensor behind the casing. These sensors were installed between the annulus formed by the 12.25" ID initial casing and the 9.625" OD casing. The fiber sensors were attached to the outside of the inner

casing as it was installed and then cemented in place. Two fiber optic loops were deployed, one between the surface and 864 m, and the other between 864 m and 782 m. The first loop is no longer operational. In addition, there is a loop at the surface that serves as a simple time-of-flight reference.

A key component of the strainmeter is the custom laser which must have a suitable wavelength stability for strain measurements precise to 0.01 to 0.1 nε (10^{-11} to 10^{-10}) over short periods (seconds to minutes) and 1 to 2 nε (1 to 2×10^{-9}) for longer periods (hours to weeks). Annual stability is limited by the fiber index of refraction drift of 1 με (10^{-6}) per year.

The data system samples the fringe pattern at 100,000 samples per second, solves for optical phase, and filters and decimates the results, which are recorded at a sample rate of 400 samples per second. The system has the capability to resolve displacement rate (velocity) up to 30 mm/s.

Differences from Planned Configuration

There are two substantive changes with respect to the plan in PEP v3. The most significant change is the omission of the pore pressure system that was to have consisted of a pressure transducer and a packer assembly at the bottom of the array. Based upon the failure of the Schlumberger cased-hole logs to reach the casing shoe (at 10,546 ft MD) when the Main Hole was logged in November, 2007, we determined that the hole was blocked below a depth of 10,451 ft. Thus, it was doubtful that we could have established hydraulic communication with the bottom of the well without a very expensive clean-out operation. We hope that funds might be found in the future to clean out the well to total depth, so that pore pressure can be monitored in the fault zone with future deployments.

The second significant change is that some levels now have only seismic/accelerometers, while others have only tiltmeters. This change was cost-driven because of unexpected costs associated with preparation of the hole for monitoring array deployment even after additional funds were made available by USGS and NASA for construction and deployment of the monitoring system described above.

Detailed Refurbishment/Replacement Schedule

The refurbishment/replacement schedule involves making two deployments during the next 5 years, approximately 2.5 years apart, tentatively in Spring 2011 and Fall 2013. However, with changes in the O&M budget resulting in transfer of management of SAFOD to PBO starting in October 2008, the refurbishment/replacement schedule is likely going to be difficult to achieve, perhaps resulting in replacement every four years instead. The first replacement cycle will involve all new equipment, cables, sensors and tool carriers. Only the EUE tubing from the surface to the top of the array at 10,046 ft will be re-used. The second deployment will attempt to re-use parts from the 2008 deployment, including DS150 housings and tool carriers.

Prototype Deployment History

Table 2 lists the dates of the various preliminary deployments in both the Pilot and Main Hole. The list is also available from <http://www.iris.washington.edu/mda/SF>. The web site also links to the data and metadata from each deployment.

Table 2: Seismic Deployments at SAFOD

Station	Site	Hole	Start	End
MH001	SAFOD	Main Hole	11/13/2004	11/14/2004
MH002	SAFOD	Main Hole	11/14/2004	11/14/2004
MH003	SAFOD	Main Hole	12/16/2004	2/9/2005
MH007	SAFOD	Main Hole	1/17/2006	1/19/2006
MH008	SAFOD	Main Hole	2/4/2004	2/16/2006
MH009	SAFOD	Main Hole	4/28/2006	5/14/2006
MH010	SAFOD	Main Hole	7/12/2006	7/16/2006
MH011	SAFOD	Main Hole	8/2/2006	9/14/2006
MH012	SAFOD	Main Hole	10/24/2006	10/26/2006
MH013	SAFOD	Main Hole	10/26/2006	10/27/2006
MH014	SAFOD	Main Hole	10/31/2006	11/1/2006
MH015	SAFOD	Main Hole	11/1/2006	11/2/2006
MH016	SAFOD	Main Hole	11/9/2006	11/16/2006
MH017	SAFOD	Main Hole	1/11/2007/	1/18/2007
MH018	SAFOD	Main Hole	3/24/2007	3/27/2007
PH001	SAFOD	Pilot Hole	9/13/2002	11/14/2004
PH002	SAFOD	Pilot Hole	5/4/2005	5/6/2005
PH003	SAFOD	Pilot Hole	5/21/2005	9/12/2005
PH004	SAFOD	Pilot Hole	1/17/2006	11/8/2006
PH005	SAFOD	Pilot Hole	3/24/2007	6/7/2007
PH006	SAFOD	Pilot Hole	6/6/2007	2/8/2008
PH007	SAFOD	Pilot Hole	2/8/2008	2/14/2008
PH008	SAFOD	Pilot Hole	3/6/2008	present



Photos of instrument deployment

Physical Samples

One of the major successes of SAFOD was the exhumation of 39.9 meters of 4-inch-diameter core from the actively deforming San Andreas Fault Zone. As described above, the core was obtained from two different sidetracks off the Main Hole. A photograph of one piece of core from the actively deforming portion of the 10,480 ft fault zone is shown in Figure 9. The phase 3 core atlas (see http://www.icdponline.org/content/icdp/upload/projects/safod/phase3/Core_Photo_Atlas_v3.pdf) presents photos and details related to all Phase 3 cores, as well as supplemental information including thin section and preliminary XRD analyses performed by Diane Moore of the USGS.



Figure 9 : Core from one of the two active traces of the San Andreas Fault Zone (“the 10,480 fault”) cored during SAFOD Phase 3 (core is from Hole G Run 2 Section 7). Core contains a massive serpentinite block (black) containing intersecting calcite veins (white) and bounded by a highly sheared serpentinite layer (green), all embedded within a pervasively sheared, foliated and relatively cohesionless fault gouge..

Many other physical samples were obtained during all 3 phases of SAFOD drilling, as summarized in Table 3. More complete descriptions and photos are available at http://www.icdp-online.org/contenido/icdp/front_content.php?idart=1037. All physical samples are stored at the Gulf Coast Repository of the Integrated Ocean Drilling Program at Texas A&M, as are petrographic thin sections prepared from selected cuttings and core samples. Procedures for requesting samples or gaining access to the SAFOD thin section collection are described at http://www.earthscope.org/es_doc/data/esdatapolicy.pdf.

Table 3: Summary of Physical Samples obtained from SAFOD.

	Phase 1	Phase 2	Phase 3
washed cuttings, small sample bag	3 sets, every 10 ft	3 sets, every 10 ft	intermittent depths
washed cuttings, large (6x10") sample bag	every 100 ft	every 100 ft	na
washed cuttings, large (10'x17") sample bag	every 300 ft	every 300 ft	na
unwashed cuttings	every 10ft	every 10 ft	na
drilling mud	every 100 ft	every 100 ft	na
core	28 ft at 1.5 km MD, 4 inch diameter	12 ft of 2.6 inch diameter core at 4 km MD	Hole E 11.08 m, 4 inch diameter
	36 ft at 3.0 km MD, 4 inch diameter		Hole G runs 1-3, 12.03 m, 4 inch diameter Hole G runs 4-5, 16.15m, 4 inch diameter
sidewall cores		52 small (0.75" dia. x 1") side-wall cores at 3.1 - 4.0 km MD	
misc rock samples	3 samples	40 samples	

Data Management Systems

The SAFOD data management systems cover 3 classes of data:

- 1) Time series observatory data collected by borehole seismometers, accelerometers, tilt and strain meters.
- 2) Drilling and downhole measurements data.
- 3) Physical samples.

Time Series Data

The time-series observatory data are divided into 2 sub-classes,

- A) Seismic (including accelerometers and electromagnetic data)
- B) Tilt and strain.

Seismic Data Description

The goals for near-field observation of the earthquake source require sampling data at high rates (4000 samples/second). The high sampling rate drives up data volumes, which impacts telemetry and data archiving. The operational goal for SAFOD seismic data handling is to get as much data to the community as rapidly as possible. A limiting factor for data handling is bandwidth; SAFOD is in a remote environment and shares the only T1 line with the USGS and UC-Berkeley seismographic networks. Consequently the data will follow two paths from the site to the community as illustrated in the following figure.

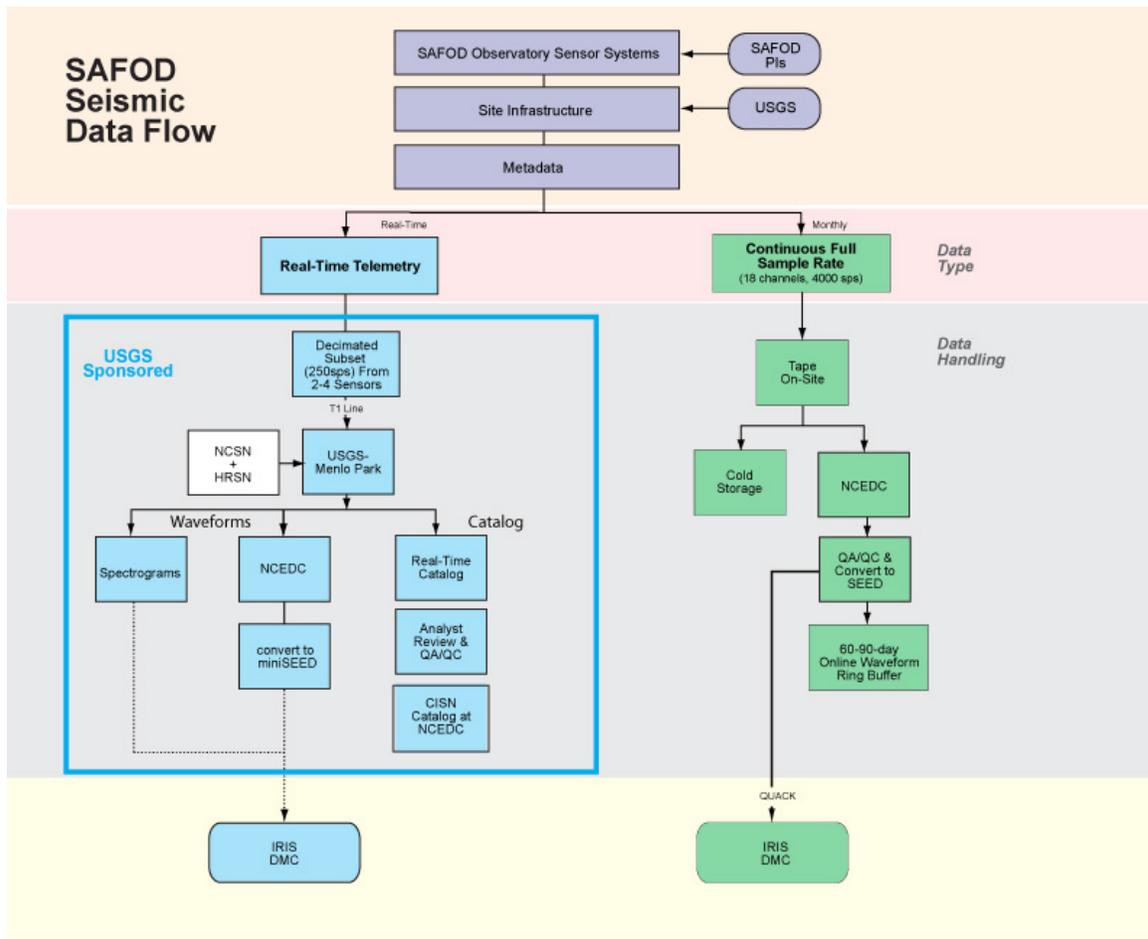
The complete suite of seismic instruments at SAFOD will produce over 1 TB/month of data. Due to limited internet bandwidth available at SAFOD, the only reliable way to store these data is to write them to tape at the drillsite. These tapes will be picked up on a monthly basis and delivered to the NCEDC for processing. Each raw SEG-2 data file will contain all waveforms for a 10 second period, resulting in 8640 SEG-2 files per day. These files will be combined into single channel miniSEED files (one file per hour). Because of the large volume of this data set, the long-term archive will be at the IRIS DMC, but conversion to SEED format at NCEDC will ensure that the metadata is consistent for all derivative data streams, and the NCEDC will archive the field tapes.

From the full-resolution 4000 sample/second data, selected channels are downsampled to 250 samples/second and then transmitted in real-time to the Northern California Seismic Network of the USGS, where they are added to the data stream from the California Integrated Seismic Network (CISN). These data are used by the USGS, in combination with data from the NCSN and HRSN to detect and catalog earthquakes with magnitude greater than 1. The CISN data then flows to the NCEDC where it is converted into the SEED format for discovery and access. The SEED data are then relayed to the IRIS DMC thus the data will be available through standard IRIS and NCEDC data request methods. These include NetDC, BREQ_FAST, FISSURES/DHI, STP, and the SeismiQuery web interface for data availability and instrument responses. In addition, helicorder and

spectrogram plots of these data are generated and posted to the internet at <http://quake.wr.usgs.gov/waveforms> and stored at the IRIS DMC at <http://www.iris.washington.edu/dms/spade.htm>. The real-time data stream (including data handling and archiving) will be supported by the USGS.

Seismic Data Processing and Access

Figure 10 shows the data flow path and processing for the SAFOD seismic data. The NCEDC will generate the miniSEED data and SEED metadata for both full resolution and real-time data streams. NCEDC will maintain the most recent 2-3 Terabytes (60-90 days of data) in an online data buffer. IRIS DMC will obtain the miniSEED data from the NCEDC data buffer, and run their QA/QC (QUACK) before moving the data into the mass storage system at IRIS. This will provide long-term online data access to this unique seismic data set. By converting the data to miniSEED prior to transfer, we ensure that the metadata are captured and the best tools for the discovery of the data are available to the community.



NOTES:
 1. Events with Magnitude 1 and greater only
 2. Data Volume Estimate = 100 GB/year

NOTES:
 1. Tapes shipped from SAFOD to Data Center on monthly basis
 2. Data Volume = 0.5 TB/month

Figure 10: SAFOD Seismic Data Flow

Tilt Data

Data from the Pinnacle borehole tiltmeters are recorded at low sample rate (1 sample/3 seconds). The tilt data are transmitted on a daily basis to the NCEDC. The raw data are converted to SEED, for long term archiving and broad distribution.

The tilt data collected during deployments between 2004 and 2007 will not be converted to SEED format. The native files have been packaged and sent to IRIS as an assembled data set.

Strain Data

As mentioned above, the SAFOD laser strainmeter is cemented behind the casing of the Main Hole between the surface and approximately 800 meters depth. SAFOD will acquire 20 (out of a total of 26) channels of data from the laser strain meter. The highest rate channels are at 400 samples/second in double precision.

The data are transmitted in real-time to UCSD for QA and QC. At the UCSD data center the data stream is converted into daily CSS files. The daily CSS files are then transmitted to NCEDC, where the data are converted to SEED format for long term archiving. The strain data will then be transmitted to the PBO strain data analysis center for analysis and generation of higher level data products along with all PBO strain data. Eventually all the PBO strain data becomes archived at the IRIS DMC.

Performance Metrics for SAFOD Observatory Data

The following performance goals were set for SAFOD observatory data in the 2007 O&M Proposal. Because the permanent array was installed during the final month of the project there are no actual network performance data for the final SAFOD monitoring array.

- 1) 99% of the data from the real-time telemetered channels will be accessible through the NCEDC within seconds of transmission.
- 2) 95% of triggered-event data files will be accessible through the NCEDC within one work day of occurrence and all files will be available within one month (to accommodate seismic crises such as the Parkfield or San Simeon earthquakes, which would overwhelm the telemetry bandwidth).
- 3) 95% of continuous full-sample rate data will be available on a ring buffer at the NCEDC within one month of collection.
- 4) 100% of archived data will be available with zero loss due to catastrophic infrastructure failure.

Drilling Parameters and Downhole Measurements Data

Drilling Parameters and Borehole Engineering

Drilling engineering information includes (but is not limited to) daily drilling reports, drilling mud analyses, preliminary lithologic reports, the casing plan, and borehole location and trajectory. These data can be accessed through the ICDP website <http://safod.icdp-online.org>

Downhole Measurements

A variety of geophysical logs have been carried out throughout each phase of SAFOD drilling, as illustrated in Figure 11 and shown in Table 4.

The raw data files for all these logs are available for download via the ICDP website, and the EarthScope Data Portal. In addition to the raw data files, there are also graphical files that plot the data versus depth.



Figure 11: Geophysical logging tools used at SAFOD.

Table 4: SAFOD Geophysical Logging Data

Run Number	Depth Range	Logging Technique	Parameters measured
Run 1	1977-4736 ft	Open Hole, Wireline	Density, porosity, gamma, caliper, resistivity, sonic velocity, FMI
Run 2a	4488-6659 ft	Open Hole, Wireline	Density, porosity, gamma, caliper, resistivity, sonic velocity, FMI, UBI, ECS
Run 2b	6200-9983 ft	Open Hole, Pipe Conveyed	Density, porosity, gamma, caliper, resistivity, sonic velocity, FMI
Run 3	4450-9950 ft	Cased Hole, Wireline	Sonic Velocity, Elemental Chemistry, Cement Bond
Run 4	9989-12179 ft	Open Hole, Logging While Drilling	Density, porosity, gamma, caliper, resistivity, FMI
Run 5	9989-13010 ft	Open Hole, Pipe Conveyed	Density, porosity, gamma, caliper, resistivity, sonic velocity, FMI
Runs 6-11*	9690 - 12515 ft	Cased Hole, Wireline	caliper, direction, temperature

* Runs 6-11 include caliper logs run 6 different times between Sept 2005 and June 2007

Physical Samples

The SAFOD physical samples are summarized in Table 3, above. All samples are stored at the Gulf Coast Repository at Texas A&M. In addition, thin sections were prepared from representative spot core, cuttings and side-wall core samples collected during all three phases of SAFOD and are available for loan to interested investigators (photographs and descriptions of available thin sections are at the ICDP web site). The process by which access to the samples and thin sections can be obtained is described at http://www.earthscope.org/es_doc/data/esdatapolicy.pdf

The GCR staff is responsible for preserving the materials in refrigerated and fluid-saturated state. They are also responsible for maintaining records of core, cuttings, and fluid sample requests filled; to whom these samples were provided; and final disposition of samples (date samples returned and condition of samples). This information is available via a graphical user interface at the EarthScope web site.

Web Sites

Several websites are used to support SAFOD, as shown in Table 5. The ICDP website is the primary location of information related to the drilling activities at SAFOD. This includes daily news and site photos from the drilling operations. ICDP, as previously described, is also the primary repository for drilling related data such as data from borehole measurements and photographs and descriptions of the physical samples.

The Earthscope website also has a wealth of information related to SAFOD. In general, both websites provide the same information, but the EarthScope website provides links to important and unique data access tools. One is the EarthScope Data Portal, which provides easy access to all SAFOD data products and links both the SAFOD time series observatory data and the borehole measurements and physical samples data. The other data tool linked to the EarthScope website is the SAFOD Core Viewer, which shows the full, high-resolution core scans from Phase 3. During the O&M phase this core viewer will also provide links to results of physical samples research, as well as sample tracking information and updated images as the samples are extracted from the core.

Table 5: Important URLs for SAFOD

ID	URL	Description
1	http://safod.icdp-online.org	ICDP Website
2	http://www.earthscope.org	EarthScope Website
3	http://portal.earthscope.org/gridsphere/gridsphere	EarthScope Data Portal
4	http://www.earthscope.org/data/safod_core_viewer	SAFOD Core Viewer

SubAwards

1) ThermaSource: Drilling and coring Phases 1, 2 and 3, CEO Lou Capuano Jr, Amt \$20.75M

ThermaSource is the prime contractor for the construction of the SAFOD observatory and has been responsible for executing all aspects of well construction and drilling-related activities at the site. These include engineering design, project management and supervision of service providers. During Phases 1 and 2, ThermaSource rotary drilled the Main Hole across the entire San Andreas Fault Zone through the region of repeating microearthquakes.

During Phase 3, ThermaSource directed the coring operations. There were three successful coring runs which recovered a total of approximately 39.93 m of 4 inch diameter core.

Concurrent with the drilling activities during all three phases of SAFOD, ThermaSource has also played a key role in the construction of the SAFOD observatory infrastructure and contributed significantly to the SAFOD monitoring program. In particular, ThermaSource played a critical role in getting electrical power to the site, helped deploy the Paulsson array in the Pilot Hole, and tried to seal off the lower part of the Main Hole to prevent gases and other contaminants from destroying the monitoring equipment. The budget details for this subaward are presented under WBS 1.2.2 (Drilling) and WBS 1.2.3.5 and 1.2.3.6 (Monitoring) of the EarthScope Facility PEP.

2) Duke University: Stage 1 and Stage 2 monitoring array, PI Peter Malin, Amount \$445K

Duke was contracted to develop the Stage 1 (Pilot Hole) Monitoring array and the seismic part of the Stage 2 (Main Hole) monitoring array. The Stage 1 array system had two sensors downhole: a gimballed, Galperin 3-Component 4.5 Hz Seismometer and a MEMS SciFlex3000L accelerometer. The surface equipment included the wireline, cablehead, and GeoSpace GeoRes data logger. A Gladwin strainmeter was proposed to be included with this system, but significant engineering difficulties led to the abandonment of that sensor. The components of the Stage 2 array consisted of two GeoSpace DS250 3-component 15 Hz seismometers, a Pinnacle tiltmeter, and 16,000 ft fiber optic cable and GeoSpace cablehead. We were able to modify the Stage 1 GeoRes data logger to incorporate data streams from the Pilot Hole and Main Hole systems. The Stage 2 system was deployed numerous times, although some deployments did not include a tiltmeter. The budget details for this subaward are presented under WBS 1.2.3.2 (stage 1) and WBS 1.2.3.3.1 (Stage 2) of the EarthScope Facility PEP.

3) Pinnacle Technologies: Stage 2 and Stage 3 monitoring array, Project manager Etienne Sampson, Amt \$179K

The Stage 2 system was developed by Peter Malin (then at Duke), working with Pinnacle Technologies (Pinnacle) for engineering support. After Duke had successfully deployed the Stage 2 monitoring array in the Main Hole it became clear that environmental conditions in the well (especially methane-series gases from the Great Valley Formation) were causing failure of the instrument systems. Consequently, Pinnacle Technologies received the subaward to construct the Stage 3 (Permanent) monitoring array. Pinnacle ran all instrument deployments from MH007 to MH018 and PH004 to PH006, as shown in the Table on page 9.

Pinnacle built the first permanent array for SAFOD, which was installed in September 2008 and consists of 5 pods and is described in more detail above. Three pods have GeoSpace DS150 3-component seismometers and 3-component MEMS accelerometers, two pods have Pinnacle tiltmeters. One of the seismic pods also includes the EM tool constructed by Peter Malin (University of Auckland, N.Z.) with support from NASA.

The budget details for this subaward are presented under WBS 1.2.3.4 of the EarthScope Facility PEP.

4) Northern California Earthquake Data Center (at UC Berkeley): Seismic data storage, processing, QA/QC and distribution, PI Barbara Romanowicz, Amount \$225K.

The NCEDC has played a critical role in the handling of the SAFOD time series data. The NCEDC converts the seismic waveform data from the native, multiplexed, SEG-2 file format to single channel MiniSEED files (one file per hour) using agreed-upon SEED Station Network Channel Location (SNCL) names.. They also create the SEED metadata file. NCEDC also provides QC feedback to SAFOD concerning the state of the sensors, data channels, remote computers and telemetry. The NCEDC makes the waveform data and associated metadata available openly through the NCEDC archive, as well as transmitting the data files to IRIS for long term archiving. NCEDC also will convert the tilt and strain data into SEED format. The table below shows how much of each data type have been collected and made available to the EarthScope community through the NCEDC data acquisition and dissemination system.

Table 6: Data Volume at NCEDC

Data Type	Data Volume
Seismic	1,534 Gbytes
Strain	540 GBytes
Tilt	167 MBytes

The budget details for this subaward are presented under WBS 1.2.4.2.2 of the EarthScope Facility PEP.

5) Univ. California at San Diego: Fiber optic strain meter in Main Hole, PI Mark Zumberge, Amount \$339K

Following Phase 1 drilling, three optical fiber cables were cemented in place in the vertical section of the borehole in the annular space between casings. These cables terminate at depths of 782 m, 864 m and 1320 m below ground surface. The two shallower cables are tensioned optical fiber loops; the deep cable terminates in a Mach-Zehnder interferometer spanning the interval between 1280 m and 1320 m. Optical tools monitor the change in lengths of the fibers over these distance intervals, which allows us to measure strains of 10^{-11} to 10^{-10} over short time periods. To achieve this precision, an ultra-stable, custom-built laser operating in a single mode between 1300 nm and 1500 nm is required. The laser measurement system samples the interference fringe pattern at 100,000 samples per second, solves for optical phase and decimates the result to a recorded sample rate of 200 samples per second. The budget for details for this subaward are presented under WBS 1.2.3.3.2 (construction) and WBS 1.2.4.2.3 (Data System) of the EarthScope Facility PEP.

6) Integrated Ocean Drilling Program's Gulf Coast Core Repository: Core handling and curation, PI John Firth, Amt \$45K

After extensively evaluating a number of options for curation of SAFOD core, cuttings, and fluid samples, we selected the GCR at Texas A&M University as the long-term storage facility for all SAFOD samples. This facility was selected for a variety of reasons:

- 1) The GCR has the facilities to store SAFOD core samples in their original fluid saturation state and under constant refrigeration.
- 2) The GCR has a state-of-the-art facility for sample examination, preparation, and distribution.
- 3) The technical staff and management of the GCR have several decades of experience in handling precious rock and sediment core samples.

The GCR is currently storing all SAFOD core, cuttings and fluid samples in refrigerated storage lockers at 4°C. They have already distributed numerous cuttings, core and mud samples from Phases 1 and 2 and have just begun to prepare and distribute Phase 3 core, cuttings and fluid subsamples to principal investigators in the United States and abroad in response to sample requests approved by the NSF EarthScope Program Director and the SAFOD Sample Committee. They are also maintaining records of core, cuttings, and fluid sample requests filled, as described above. The budget details for this subaward are presented under WBS 1.2.4.3.1 of the EarthScope Facility PEP.

7) International Continental Drilling Program: Web Services Development to support EarthScope Data Portal, PI U. Harms, Amt \$101K

Because the ICDP is the primary data archive for drilling, downhole logging and samples-related data from the SAFOD project, it is essential that ICDP be able to deliver these data to the EarthScope Data Portal. The ICDP will be responsible for developing the web services that can interact with the EarthScope Data Portal. The central node of the data portal will be hosted at UNAVCO, and data providers will be hosted at three distinct data centers: SAFOD-ICDP, USArray-IRIS, and PBO-UNAVCO.

Two primary web services were developed by the ICDP in support of the EarthScope Data Portal:

- 1) “Station” discovery. The purpose of this web service is to describe what the data holdings from SAFOD are that are held at the ICDP.
- 2) “Data” discovery/delivery. The purpose of this web service is make specified data readily available via the Internet

The data types that ICDP has made available to the Data Portal include the geophysical logging data obtained at SAFOD and photographs of the physical samples (cuttings, core and mud samples).

The budget details for this subaward are presented under WBS 1.2.4.4 of the EarthScope Facility PEP.

Risk Management Plan

The on-going operations of the San Andreas Fault Observatory face many risks. In order to help the new management better support SAFOD, we have identified the most apparent risks, but the actual problems faced during the O&M period maybe quite different

Table 7: Risk Matrix for O&M Phase

WBS	Title	Impact	Probability	Overall	Brief summary
2.2.1	SAFOD Management	Significant	50%	Low	PBO will takeover SAFOD operations and maintenance, and subcontract with Berkeley and the GCR to handle much of the operations. The new management structure and new personnel could impact the operations of the observatory.
2.2.2.1	Fiber optic Strain Meter	Significant	50%	Low	No funds are budgeted for repair or replacement of laser, should this become necessary.
2.2.2.1	Fiber optic Strain Meter	Significant	50%	Low	The downhole fiber optic loop was installed in 2004 and cannot be replaced. Only one of 3 fiber optic loops remains in operation. Repairs can only be made to the surface portion of the optical path.
2.2.2.2	Permanent Array: Cables	Critical	25%	Low	The cables are encapsulated in stainless steel tubes and designed for long-term deployment. They should last for the design lifetime of 3 years.
2.2.2.2	Permanent Array: Seismic sensors	Critical	50%	Moderate	The sensors being deployed have been temperature and pressure tested, but none have been run continuously for 3 years at the elevated temperatures in SAFOD.
2.2.2.2	Permanent Array: Tilt sensors	Critical	50%	Moderate	A new type of tilt sensor is being deployed. While it has been temperature and pressure tested, it has not been run continuously for 3 years at the elevated temperatures in SAFOD.
2.2.2.3	Retrieval/Deployment of instruments: equipment retrieval and repair	Critical	50%	Moderate	Many of the components in the current deployment will be needed for the next deployment. If they fail or are damaged, then repair or replacement of components not currently in the O&M budget may become necessary.
2.2.2.3	Retrieval/Deployment of instruments: cost of services	critical	50%	Moderate	Costs for retrieval and deployment are subject to prevailing costs in the petroleum industry, which can fluctuate greatly in response to the price of oil.

2.2.2	Instrumentation system	Significant	50%	Low	The Permanent Array designer, manufacture and system integrator, Pinnacle Technologies, is being acquired by Halliburton' The future of their involvement is thus uncertain. Alternative sources of technical support from industry, academia or government may need to be found.
2.2.3.1	Site Infrastructure: hole conditions	significant	100%	High	Current hole conditions do not allow for fluid pressure monitoring within the active fault zone. A clean-out trip will be required to remove fill (cement residue, etc.) in the bottom 100 ft of the cased hole.
2.2.3.1	Site Infrastructure: data logger	significant	25%	Low	The current datalogger is 6 years old. It has recently been inspected and serviced by the manufacturer, and should last for another 3 years.
2.2.3.1	Site Infrastructure: power supply	significant	25%	Low	All data systems are on UPS and have emergency back up power that should last 12 hours or more. A longer outage of line power could cause loss of data
2.2.3.2	Real-Time Data Subset	marginal	25%	Low	System performance is monitored at all times as part of USGS operations. Potential for data loss due to prolonged power/internet outage might occur.
2.2.3.3	continuous and triggered full-sample data	marginal	25%	Low	USGS Parkfield staff collects and mail data tapes on bi-weekly basis. Latency may increase if USGS staffing changes.
2.2.4.1	Long-Term Sample Curation	marginal	25%	Low	Sample and data handling at the Gulf Coast repository (GCR) could be impacted by factors such as difficulties encountered in sub-sampling of the core, unexpectedly high demand for SAFOD samples, and reductions in staffing or general support provided by the Integrated Ocean Drilling Program.
	ICDP Support	Significant	10%	Low	The International Continental Scientific Drilling Program (ICDP) is the primary data warehouse for SAFOD borehole logging data. If ICDP losses support for long-term data archiving, then data access and recoverability could suffer.
	Data Portal	Significant	50%	Low	There are no long-terms fund for continued ICDP support of the EarthScope Data Portal, or for continued integration of SAFOD data into the data portal

Ongoing and/or planned research activities at the SAFOD site and core/samples research underway

There are two research projects that are using the SAFOD boreholes.

- 1) The Carnegie Institute of Washington and Lawrence Berkeley Lab group have installed a seismometer in the Main Hole at depth of approx 1.1 km during the installation of the permanent array in September of 2008. At a later time, they will deploy a source in the Pilot hole and conduct a cross bore hole experiment to measure stress changes in the crust.
- 2) Guralp Systems has installed a broadband seismometer and strong motion sensor in the Pilot Hole. This is research and development project for Guralp Systems LTD, but the data are being made available to the public via NCEDC and IRIS.

There are a large number of SAFOD-related research activities being conducted by individual investigators at institutions around the world, especially related to conducting research on the physical samples exhumed from SAFOD. The research efforts focus on mineralogy, deformation mechanisms, rheology and geochemistry. Samples allocated for these studies along with results from these investigations will be made available through the EarthScope and ICDP web sites.

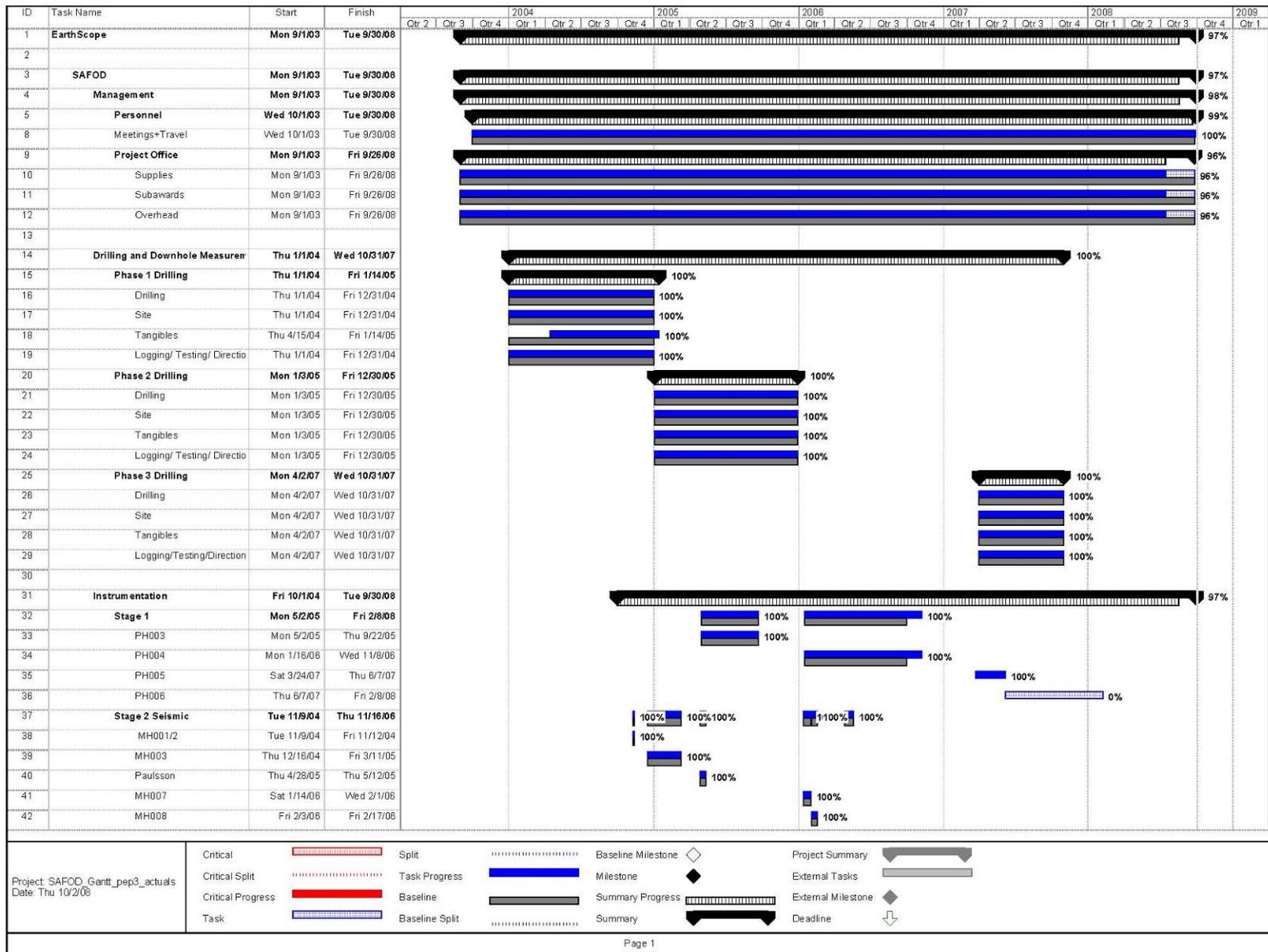


Figure 12a: Final Gantt chart

			Sheets	Charts	SmartArt Graphics	WordArt	
◇	A	B	C	D		E	
1	Deployment ID	Deployment ID	Sensor Type	Lifespan		Fate	
2	1	20041109	passive	1 day?		Moved up in hole	
3	2	20041113	passive	1 month		Pulled w/operating instruments	
4	3	20041215	active?	40 days		Failed	
5	4	20050429	80-level	?		?	
6	5	20050430	80-level	?		?	
7	6	20050430	80-level	?		?	
8	7	20060114	tilt + active	~2 weeks		?	
9	8	20060203	tilt + active	<1 week		Failed	
10	9	20060428	tilt + active	~2 weeks		Failed	
11	10	20060711	tilt + active	5 days		Failed	
12	11	20060802	tilt + active	5 days (tilt), 6 weeks (seismic)		Failed	
13	12	20061024	tilt + active	1 day		Failed	
14	13	20061026	tilt + active	1 hour		Failed	
15	14	20061031	tilt + active	2 days		Problems?	
16	15	20061101	same				
17	16	20061109	tilt + active	< ~10 days		failed	
18	17	20070111	active	10 days		failed	
19	18	20070324	active	single shot			
20	19	20080927	active	overnight run			
21	20						
22	21	20081204	passive	?		OK	
23	22	20090506	passive	16 months		OK	
24	23	20101209	passive	-			
25							

EarthScope Project Change Request

Change Request Number: SAFOD-029

Date: 20 Nov 08

WBS Element and Title: 1.2.3.4.2 Stage 3 Monitoring Final Array

Originator: Charley Weiland (650) 723-8367

Technical Change Description: The Stage 3 monitoring array was successfully installed on Sept 28, 2008. The final design with deployment depths is shown in Figure 1. Note that the array was deployed on EUE tubing 2 7/8 inch diameter. There were approximately 360 joints of the tubing. Also, there were two control lines, one for the seismic components (pods 1, 3, and 5) and one for the tiltmeters (pods 2 and 4). The tiltmeter in Pod 4 stopped working on the way down the hole, probably due to a short in the control line. The rest of the instruments work quite well for the next 4 days.

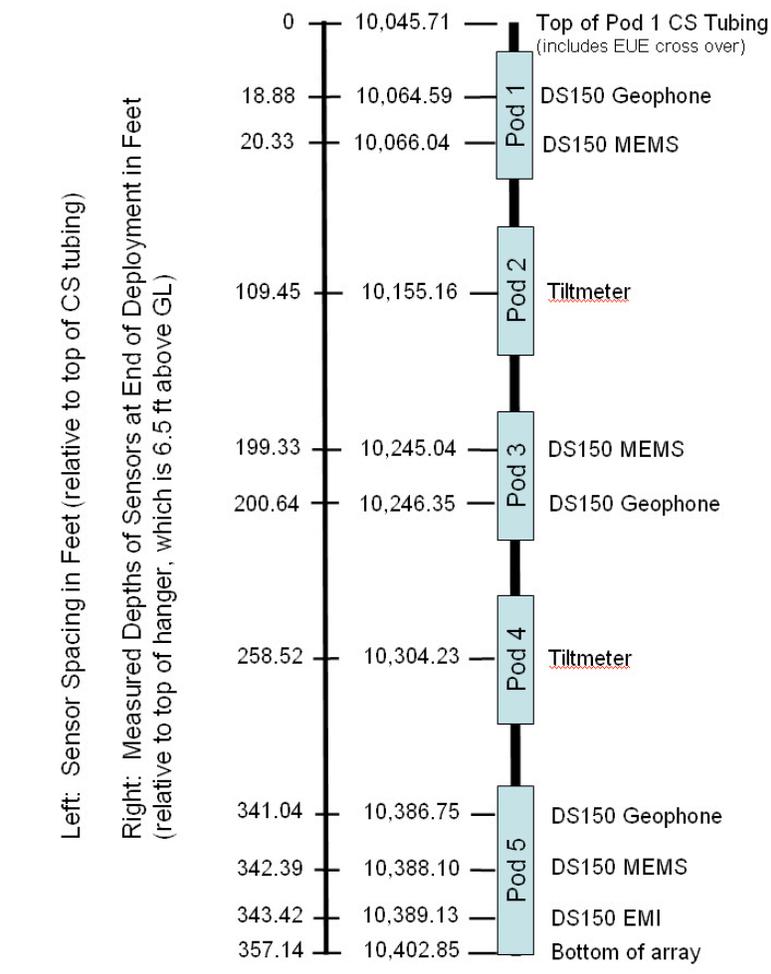


Figure 1: Final Instrument Configuration and Depths

Figure 2 shows an example of the data recorded by all 21 channels of the array from a M 1.3 event that occurred about 3 km from the instruments. The data are organized by "pod" from the top of the instrument string (Pod 1) to bottom (Pod 5). Also indicated are the sensor type and

position. The seismometer channels are the standard 15 Hz geophone that comes with the DS150 instrument and the output is proportional to velocity in this plot. The accelerometer channels are from the MEMS accelerometers that replaced the geophones and output is proportional to acceleration. The last 3 traces are from the large ferrite coil that Peter Malin deployed with support from NASA.

September 30, 2008 04:15:51 M 1.3

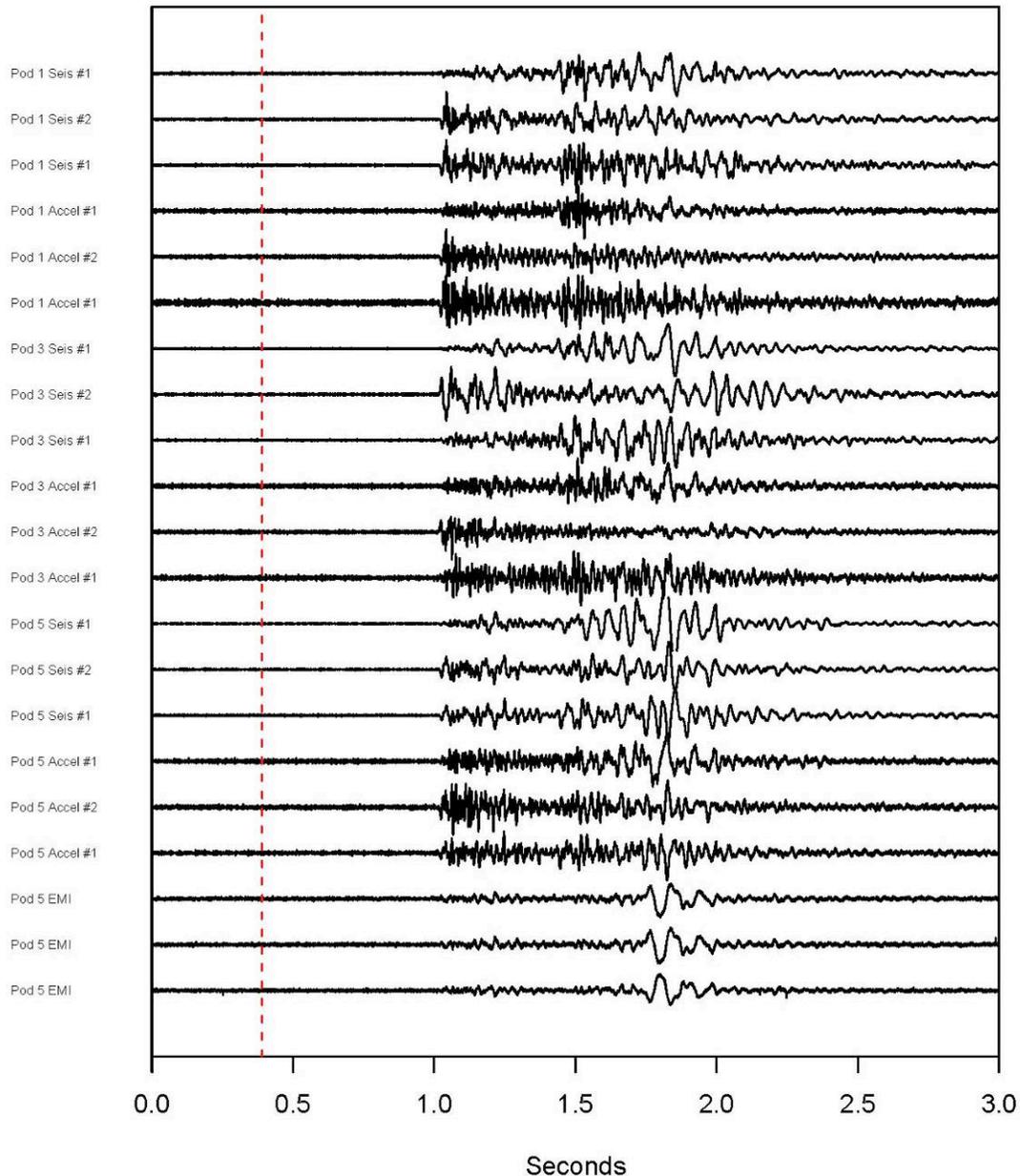


Figure 2: Waveforms from Permanent Array

There are several things of note in this recording. The data bandwidth is excellent up to the highest frequencies transmitted by the earth, or about 500 Hz in this case. The waveforms contain a large fault zone guided S wave arrival at roughly 0.75 s after P (1.75 s on the horizontal axis). This guided wave is strongest at Pod 5 and barely visible on Pod 1. A preliminary

interpretation is that this wave is travelling in the low velocity waveguide associated with the 10480 ft. fault.

We also see a strong response on the EMI coil to the seismic waves. There isn't an obvious response at the instant when the earthquake happened (vertical red line). Of course, it is far too early to draw any conclusion about this at this time, as this will be the subject of Peter Malin's research.

However, difficulties with instrumentation appeared gradually after several days of operation. The other tiltmeter was providing excellent data until a problem with its accelerometers (used to level the tool) occurred, and we are no longer getting much from it.

On the seismic string the problems started with communications between the 7 seismic modules. The problems showed a clear daily pattern that we could not easily explain which initiated several trips to SAFOD to investigate possible uphole problems with power supplies, the GeoRes computer, etc. By October 10, we had lost communication with all but the top instrument, and the decision was made to continue recording it with the hope that additional work would allow us to bring back the other 6 instruments. Unfortunately, this was not to be the case.

After 4 days of flawless operation, the last surviving instrument went into a spasm of drop-outs, spikes and reboots that ultimately led to no data coming from the tool. A team from the USGS made a final attempt at powering down and rebooting the system. The effort was unsuccessful. Our current understanding is that we have a downhole short that has rendered the instruments inoperable; however, retrieving instruments and cables to surface will be required to complete a full forensic evaluation of the system failure.

This change request is to modify plan for the permanent array. In order to further eliminate the seams, splices, and other points of failure, we propose to retrieve the current system, and redeploy using only the pod 4 (tiltmeter) and pod 5, (cablehead, seismometer, accelerometer, and EMI coil).

Budget Impact:

Retrieve Array	Rate	Number	Total
Rig to retrieve array			\$120,000.00
Forklift and crane rental	\$1,000	5	\$5,000.00
Heavy equip operator and labor	\$2,200	4	\$8,800.00
Casing tongs/elevators	\$2,400	4	\$9,600.00
Wellhead work	\$1,000	1	\$1,000.00
Site maintenance	\$1,000	4	\$4,000.00
Spooling units	\$ 500	4	\$2,000.00
Pinnacle crew	\$1,000	4	\$4,000.00
Company man	\$1,000	6	\$6,000.00
Total			\$160,400.00

Forensics and Repair

Modify Pod 5 to include cablehead	\$3,000	1	\$3,000.00
Pinnacle crew	\$1,000	5	\$5,000.00
shipping	\$5,000	2	\$10,000.00
Splice kits	\$2,500	2	\$5,000.00
Total			\$ 23,000.00
Install	Rate	Number	Total
Rig to install array			\$120,000.00
Forklift and crane rental	\$1,000	6	\$6,000.00
Heavy equip operator and labor	\$2,200	5	\$11,000.00
Casing tongs/elevators	\$2,400	5	\$12,000.00
Wellhead work	\$1,000	1	\$1,000.00
Site maintenance	\$1,000	5	\$5,000.00
Spooling uints	\$ 500	5	\$2,500.00
Pinnacle crew	\$1,000	5	\$5,000.00
Company man	\$1,000	6	\$6,000.00
Total			\$168,500.00
Grand Total			\$351,900.00

Schedule Impact:

Justification: Key science objectives of SAFOD related to directly studying the physical and that control earthquakes and earthquake generation cannot be met without the Stage 3 monitoring array.

Operations and Maintenance Impact: none

Assessment (Component): *(circle one)* Approved Denied

Signature and date, Director of appropriate component.

Assessment (EMT): *(circle one)* Approved Denied

Signature and date, non-component EMT member

Assessment (NSF): *(circle one)* Approved Denied

Signature and date, Program Director (if necessary).

SAFOD Documentation

Include:

Pod Bill of Materials...break down per Pod
Assembly Procedure

Design Decisions

Nitronic

Vam FJL

Benoit

CerroTru

Carbo Prop 20/40

Motor Oil

Swagelok Fittings

Modified DS150 Interconnects

Modified Gen III Cable Heads

Pod 5 Bull Plugs

Pods 1-4 Bull Plugs

CS Tubing and Crossovers (design flaw)

Cannon Clamps, Midjoints, Centralizers

Gemoco (Weatherford) "De"centralizers

Welding and Fabrication

Pod 1 Hinge Design - 1" Rod (1/2" Drill and .5156" Reamer) x 1/2" Rod

Abstract

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Abstract

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Introduction

The overall goal of the San Andreas Fault Observation at Depth (SAFOD) is to monitor earthquakes before, during, and after they happen with the hopes that those results might one day assist in warning us about a future earthquake. A major issue in the past has been the high temperature, highly corrosive gas environment of the SAFOD well. The goal for this installation was to address those issues while deploying tiltmeters, geophones/MEMS, and an EMI coil.

Previous runs with tools on wireline failed because the highly corrosive gas in the well was able to eventually penetrate and destroy the o-rings used to protect the tools from the well conditions. Our goal for this project installation was to bypass the use of o-ring seals all together and replace them with gas tight metal to metal seals throughout the entire system. For this reason alone, standard wireline cable could not be used. Instead, stainless steel tubing was used to house the conductor wire and fiber optics run to the tools from the surface.

Another major issue with electronics is heat. The USGS intends for this installation to last at least 3 years. None of the tiltmeters or geophones/MEMS have ever been run anywhere close to that length of time, especially not at that temperature. Temperature currently poses the biggest threat to the lifetime of this installation. While the tools are rated to the temperatures downhole, the length of time the tools are used will be the deciding factor in project success.

Methods – Mechanical Design

Background

The mechanical housings for the tools that went down hole were organized into pods, each of which was sealed with metal to metal gas tight connections. The design was to be run in 7" 26# casing with a 6.151" drift diameter. The tool string was to run on a 2-3/8" 4.7# EUE tubing string with 30' joints.

Wiring

From the surface, two 1/4" stainless steel tubings with a polypropylene coating are run to the tool string, one to the top of pod 1 and one to the top of pod 2. The 1/4" line to pod 1 contains 2 conductor wires and 4 fiber optic lines, only 2 of which are used. The 1/4" line to pod 2 contains a coaxial wire. There is another 1/4" coaxial line running from the bottom of pod 2 to the top of pod 4. The line from the bottom of pod 1 to the top of pod 3 and from the bottom of pod 3 to the top of pod 5 is larger 5/16" stainless steel tubing with no polypropylene coating that has 7 conductor wires, 4 of which are used. The wires used are brown, black, red, and green. The wires that are not used are blue, yellow, and white.

With the exception of the top of pod 1, all 1/4" and 5/16" stainless steel tubing is terminated at a modified connector that attaches to the tool string. These tool strings are normally run on wireline or rigid interconnects. They are not normally run on 1/4" and 5/16" stainless steel tubing because the lines are not capable of sustaining that type of loading. For that reason, there are no standard connectors available to terminate the lines and crossover to the tubing string. For all of the 5/16" tubing terminations in pods 1, 3, and 5, a modified wireline interconnect was used to terminate the wires. An unmodified wireline interconnect can be seen in Figure #. For all of the 1/4" terminations in pods 2 and 4, a modified Gen III cable head was used to terminate the coaxial wires for the tiltmeters. An unmodified Gen III cable head can be seen in Figure #.



Figure #: Down hole (top) / Up hole (bottom) of Unmodified Wireline Interconnect



Figure #: Down hole (top) / Up hole (bottom) of Unmodified Gen III Cable Head

Short lengths of standard wireline terminated with DS150 interconnects were purchased, and the ends were cut off. The wireline itself was then removed, and the connector was disassembled. A 1/2" NPT thread was tapped into the end of the connector in which the wireline would normally terminate. Gen III cable heads also had the wireline removed from their ends, and a 1/4" NPT thread was tapped in its place. If the interconnect was to go on the up hole end of the tool string, extra lengths 1/4" or 5/16" tubing would be needed about the interconnect (over 40 feet). For this reason, the fittings with ferrules and the upper bull plugs for the pods would need to be run over the line before assembly of the interconnect itself. An example can be seen in Figure #.



Figure #: Swagelok® fittings and Bull Plug run over the line before Interconnect

Swagelok® Fittings

With the importance of metal to metal seals for the pods, the fittings are a critical leak path when connecting to the pods. There are a number of different fittings that provide a metal to metal seal, but the decision was made to use Swagelok® fittings for sealing against the ¼” and 5/16” tubing lines. With cost always an issue, it is much cheaper and faster to tap NPT (tapered pipe threads) into the terminations and sealing portions of the tool string at pod entrances and exits. A list of the Swagelok® fittings that were used and where they were used can be seen in Table #.

Table #: Swagelok® Fitting Part Numbers and Use Occurrences

Pods							
Qty.	Fitting Type	Part #	Bull Plugs Upper & Lower	Gen III Cable Head	DS150 Interconnect	DS250 Cable Head	Pod 4 Lower Bull Plug
7	¼” NPT x ¼” Tubing	SS-400-1-4-BT	4	3			
4	¼” NPT Female x ½” NPT	SS-8-RB-4			4		
8	¼” NPT x 5/16” Tubing	SS-500-1-4-BT	4		4		
1	3/8” NPT x ¼” Tubing	SS-400-1-6-BT				1	
1	¼” NPT Plug	SS-4-P					1
Splice Housings (spares not included)							
Qty.	Fitting Type	Part #	¼” Coaxial Line		5/16” Conductor Line		
4	½” x 3/8” Reducer	SS-810-R-6			4		
4	3/8” x 5/16” Reducing Union	SS-600-6-5			4		
8	½” x ¼” Reducing Union	SS-810-6-4-BT	6				
6	½” Tubing x 7” x .049” Wall	SS-T8-S-049-20	3		2		

Multiple splices of control line needed to be made between pods. A splice of the 5/16” line was made below pod 1 and below pod 3. A splice of the ¼” line was made above pod 2 and below pod 2. A mistake was made in the splice below pod 2, so two splices were made in that location while running the tool string down hole. Splice housings were created for this project using ½” tubing and reducing unions to the ¼” and 5/16” tubing. Bore thru fittings were optimal if they were available. This provided the ability to make the splice, then slide the ½” tube over the splice and swage where needed. The procedure needs to be done in a specific order to prevent seal failure. It’s best to test the system before, during, and after splicing to make sure no errors are being made and to make sure the connections are good.

If at all possible, pressure testable fittings are the most desirable fittings to use. The cost of these fittings is much higher than a standard Swagelok® connection, but the pressure testability of the fittings plays a critical role in trouble shooting.

Pod Design

Each of the pods 1 through 4 was made primarily of a pup joint with bull plugs on each end. Although the size varied from pod to pod, a BTS-8 box by pin pup joint was ordered from Benoit and sent to a machine shop for further work. The data sheet, torque requirements, and blanking dimensions for Benoit BTS-8 thread connections can be found in Appendix 2. These are standard, off the shelf pup joints that are mass produced. The box end of the pup joint had the box thread cut off, and the lower, down hole end, bull plug was welded into place matching the upset OD of the pup joint itself. The outlet at the bottom of the bull plug was sloped toward the 2-3/8" tubing to avoid catching on anything while being run down hole. Each pod was internally pressure tested to 6,000 psi. to make sure the weld of the lower bull plug onto the pup joint could hold pressure. The test was conducted with water using a hand pump to build pressure. The lower bull plug was plugged for testing. Pressure testing setup can be seen in Figures 3 and 4. The test was a pass/fail through visual inspection. Failure of the weld would have been visible through water seepage, and a pressure drop would have been noticed on the pressure gauge. Communication of pressure to and from the pump was locked off by a valve on the pump side of the pressure gauge.



Figure 3: Pod 1 during pressure testing



Figure #: Lower Bull Plug of Pod 1 plugged for pressure testing

Another critical design specification was coupling the pods to the 7" casing as much as possible, also coupling the tool string inside of the pods to the pods themselves as much as possible to get better results from the tool string. The only tool for which coupling was not an issue was the EMI coil in pod 5.

The coupling method that was chosen for better coupling the pods to the casing involves centralizers which were purchased from Weatherford Gemoco. Centralizers are normally used to centralize tubing inside of casing. The design of the bow springs for the centralizer deals with casing size and weight, and the centralizers are generally an 'off the shelf' part. The problem with that, however, is that we want to DE-centralize our pods so that the tubing is actually firmly coupled to the casing. Centralizers are also generally run on one piece of tubing, whereas we essentially have two pieces of tubing welded together side by side. The way they calculate and rate bow spring forces is as an average of all bow spring forces acting on the casing from one centralizer at any given time. This makes it hard to know how much restoring force will be acting on the casing in our case because we take one centralizer with 6 bow springs spaced 60° apart, and we cut the centralizer to only utilize 2 bow springs. Ultimately, we are running the centralizer in a non-standard application, so the restoring force is really more of a theoretical number in the design. Centralizer bow springs were only used on pods 1-4. An example of what the bow springs look like attached to a pod, which is then attached to the 2-3/8" tubing can be seen in Figures # and #.



Figure #: De-centralizer on one of the pods



Figure #: All pods had modified Centralizers welded on, except for pod 5

The De-centralizers were all welded on the up hole end and were held close to the pods by guide rails on the down hole end. The up hole end was welded, which can be seen in Figure #, so that tool string could always be pulled up and out of the hole. The guide rails were also welded onto the pods, and all sharp edges were ground off so that no sharp edges might catch when running down hole. The purpose for the guide rails is to relieve added stress on the bow springs by allowing them movement up and down along the pod once the springs make contact with the 7" casing. An example of a guide rail can be seen in Figure #. Drawings from Weather Gemoco of the centralizers used can be found in Appendix ?.



Figure #: Bow Spring Guide Rails with sharp corners ground off

While the pods and tubing on which the pods were run were coupled to the casing using bow springs, the tool strings inside of the pods needed to be coupled to the ID of the pod using another method. The pup joints chosen for the tools did not allow enough room for bow springs to be added to the tool strings inside of the pods. Instead the decision was made to use a low melt alloy that could provide coupling to the pod wall. The company Bolton Metal Products, also Cerro Metal Products, was contacted to find out information on different properties of the low melt alloys that they could provide. After reviewing data sheets from more than one alloy, an alloy called CerroTru® was decided upon. CerroTru® happened to be one of their most popular low melt alloys, and well as one with the least environment/health effects. The key factor in the decision was the temperature range in which we were working. The metal would need to liquefy at a temperature higher than that of the well conditions so it didn't melt down hole and lower than that of the maximum temperature range of the electronics inside the tools. CerroTru® is sold by weight and comes in bars that can be seen in Figure #.



Figure #: Bar of CerroTru® Low Melt Alloy

Unfortunately, as with any project, cost was an issue, and filling every pod up to the top with CerroTru® would have cost too much. This and other reasons drove the search for a filler material that could be used between layers of CerroTru®. A number of tests were done to find the best material to use as a filler. The first test was just run with the nearest plain sand and dirt from the ground outside of the test lab. Those results can be seen in Figure #. The liquid CerroTru® went right through it and was not supported at all. As Pinnacle was owned by Carbo Ceramics at the time, there was extra proppant lying around in the fabrication shop. The second filler test was done with CarboLite® 20/40 as a filler, and it proved to be much more effective in retaining the CerroTru®. The result can be seen in Figure #. While it was more promising than regular dirt and sand, it still did not produce the most optimal results. Before accepting it as the filler material, the decision was made to use a higher density proppant to see if there would be a difference. The last filler test was done with CarboProp® 20/40. This test proved to be the most successful, and the result can be seen in Figure #. The decision was then made to use a standard 10W-30 motor oil as a filler liquid. This made sense because motor oil is non-conductive, and it would prevent water from seeping into the electronics if the metal to metal seals of the pod ever failed and pressure equalized. The data sheet for the CerroTru®, as well as marketing information on CarboProp® 20/40, can be found in Appendix ?.



Figure #: CerroTru® Test using dirt as filler medium



Figure #: CerruTru® Test using CarboLite® 20/40 as filler medium



Figure #: CerroTru® Test using CarboProp® 20/40 with oil as filler medium

Pod 1

Pod 1 was the most challenging pod to design around because it received the fiber optic cable from the surface. A DS250 cable head from Geospace was used as a housing for terminating the fiber optics. While the geophones/MEMS and DS150 interconnect all have a 1-5/8" OD, the DS250 cable head has a diameter of 2.5". You can see the larger diameter of the cable head crossover to 1-5/8" diameter in Figure #.



Figure #: 2.5" diameter Crossover to 1-5/8" tool string for Pod 1

The most cost effective way to accommodate the tool string is to have it placed in a sealed pup joint. Due to the 2.5" OD of the DS250 cable head, the closest pup joint size was 3.5" 9.3# tubing. The tool string for pod 1 is just over 8 feet long, so the pup joint purchased was 10 feet long. The extra length would help allow for the 1/4" tubing to move more freely during assembly without putting a bind on the line.

One of the most critical components of the pod is the type of thread used between the bull plug at the top, or up hole end, of the pod and the pup joint. Because of space restrictions set by the drift diameter, a flush joint is the most desired type connection. This means that the box thread and pin thread have the exact same OD and ID dimensions. The thread itself must provide a gas tight seal. For this reason, a Hydril® type of thread was used. The thread used was a 3.5" 9.3# BTS-8 thread machined by Benoit out of Houma, LA. A 10 foot long, 3.5" 9.3#, BTS-8 box by pin pup joint is a standard off the shelf item, and one was purchased and sent to a machine shop.

The 3.5" 9.3# pup joint has an upset on each end that gives a maximum OD of 3.915" on the ends. We were unable to mount the pup joint for pod 1 on a standard 2-3/8" 4.7# tubing because the tool string would not be able to pass into the 7" casing. Instead, a different type of tubing was selecting for mounting pod 1. We needed something with a smaller OD with close to the same strength as the 2 3/8" tubing. Eventually, it was decided that a 1-1/4" 3.02# CS Hydril® tubing be used. The OD of the body to which it would be mounted was 1.660" and would provide plenty of clearance into the 7" casing. Two crossovers were ordered and used on either end of the 30' long CS tubing to connect back to the 2-3/8" 4.7# tubing joints. A picture of the crossovers can be seen in Figure #. The crossover diameter matched the upset diameter of the 2-3/8" 4.3# tubing, so the cannon centralizers, which can be seen in Figure #, were not placed over the collars themselves. Instead, a centralizer was added below the lower tubing collar and above the upper tubing collar to provide protection for the lines near the collar as the string was run down hole.



Figure #: Lower Crossover (top) and Upper Crossover with tubing Collar (bottom)
2-3/8" 4.3# EUE 8 Round to 1-1/4" 3.02# CS Hydril® Tubing



Figure #: Cannon Tubing Centralizers for 2-3/8" Tubing

Another major issue with pod 1 was the fiber optics. We were able to weld pods 2-4 to the tubing joints on which they were run because a mechanical splice of the 1/4" line was possible above and below the pods themselves. However, with pod 1, the 1/4" line that had to be terminated inside the DS250 cable head. This means that an entire spool of 1/4" line would remain attached to the top of pod 1 during transport and installation. It is impractical to thread the joint on which pod 1 is mounted into the tubing string because the spool of wire would need to rotate with the pod on the rig floor as it is threaded. An example of a spool can be seen in Figure #. Pod 1 was assembled in Houston and shipped to the site connected to the 1/4" tubing. Pod 1 can be seen attached to the spool in Figure #. As that was not a feasible option, a different design was necessary so that the CS tubing could be threaded into place before attaching pod 1 to the tubing string. A concept similar to that of hinges on a door was suggested. The mounting of pod 1 to the CS Tubing using a rod and hinge can be seen in Figure #. It emphasized the alternation between welding a hinge to the pod, then the tubing, then the pod, etc. This shows how the weight of the pod is on the welds of the hinges and not the rods as the assembly is run down hole. There are two rod and hinge placements, one on each side of the tubing. This would be equivalent to having a hinge on two opposite sides of a door. The door would not move.



Figure #: 1/4" Tubing with Polypropylene Coating on Spools



Figure #: Pod 1 was shipped from Houston attached to a Spool



Figure #: Pod 1 also Hinged to CS Tubing for Shipping (down hole to the right)

There were design challenges when dealing with a hinge type connection. The hinges themselves needed to closely match the material of the CS Tubing and 2-3/8" EUE Tubing onto which the hinges would be welded. Similar materials are always desired when welding two pieces of metal together. For this reason, 4142 heat treated and stress free rod was chosen for both the hinges and the rods running between hinges. The rod running through the hinges is a standard 1/2" rod. The hinges themselves started as a 1" rod, and the middle of the rod was drilled out with a 1/2" bit. The ID of the 1" rod was then reamed with a .5156" reamer. The rods were 6' long, while the hinges were just under 8" in length each. Four of the 1" reamed rods were tapped on one end with a 3/4"-10 UNC thread 3/4" deep. This was so the a 3/4"-10 set screw 3/4" long would be used to hold the rod in place as a safety measure on both ends of the 1/2" rod.

After reaming the 1" rod, the hinges slid freely over the 1/2" rods without too much off axis movement. Sliding easily along the rod was desirable because the hinges would move and draw during the welding process. The reason for a 1/4" wall thickness on the 1" hinge was also made to avoid too much draw of the hinge onto the tubing from the welding as well as to avoid affecting the concentricity of the reamed ID. The rods were run through the hinges with set screws in place on either end while the hinges were tack welded to the 2-3/8" Tubing and CS Tubing. The rods were then removed to finish the welding process. Hinges were mounted in an alternating pattern so that a hinge welded to pod 1 would rest on a hinge on the CS Tubing as it is run down hole, thus supporting the weight of the pod without creating additional stress on the 1/2" rod. A close up of the welding on pod 1 can be seen in Figure #.



Figure #: Close Up View of Hinges Welded to Pod 1

Pods 2-4

Pods 2-4 were very similar in design to pod 1 with respect to the bull plugs and pup joints. The difference, however, is that they were run on the 2-3/8" tubing, and therefore had to be smaller in diameter than pod 1 so it could pass through the 7" casing. With no fiber optic terminations in any of the lower pods, a regular DS150 interconnect was used as a termination in pod 3, and a Gen III cable head was used as a termination in pods 2 and 4. Both the DS150 tool string and Tiltmeters fit perfectly inside the ID of a 2-3/8" 4.7# pup joint. Bull plugs were ordered with a 2-3/8" 4.7# BTS-8 metal to metal sealing box thread from Benoit to match the up hole end of the pup joints that were also ordered from Benoit. Two 10' pup joints with box by pin 2-3/8" 4.7# BTS-8 threads were ordered for use with the tiltmeter tool strings in pods 2 and 4, and one 6' pup joint was ordered with the same thread configuration for the tool string in pod 3.

Pod 5

Pod 5, like pod 1, had many design challenges that were unique only to that pod. For instance, pod 5 was at the very bottom of the tubing string. It needed to include a large EMI (Electro-Magnetic Induction) Coil which had an OD of approximately 3.41". A 4.5" piece of casing was chosen to house the EMI coil. A request was made for the housing of the EMI coil itself to be non-magnetic. For this reason, the material Nitronic 50 was chosen to run along the outside of the EMI coil. The EMI coil is approximately 10.5' long, but the tool string, interconnect, and EMI crossover about that were another 7.5' long. With the cost of Nitronic 50 being so high, the decision was made for only 10' of Nitronic 50 to be used to house the EMI coil, and another 10' piece of L80 tubing be used to house the rest of the tool string.

Pod 5 was the termination of the tubing string. This means that the very bottom of pod 5 is the first thing in the hole. For this reason, the bottom of the bull plug on the down hole end of pod 5 is completely hemispherical. A large hole was also drilled into this bull plug just in case there was a need to suspend the pod for any reason. The bottom bull plug can be seen in Figure #.



Figure #: Bottom Bull Plug of Pod 5

The threads chosen for pod 5 were also a flush joint thread, but there is no upset in the tubing. Vam FJL 4.5" 12.6# threads were used to connect the bull plug to the Nitronic 50, the Nitronic 50 to the L80 Tubing, and the L80 Tubing to the Top bull plug. The data sheet, torque requirements, and blanking dimensions for Vam FJL 4.5" 12.6# thread connections can be found in Appendix ?.

Another major issue with pod 5 involved running the 5/16" control line through the top bull plug and terminating it at the DS150 interconnect inside of the pod. The 1/4" and 5/16" lines running through the tops of pods 1-4 were run through the middle of the bull plug so that the bull plug could be threaded onto the pup joint without disturbing the line before the Swagelok® ferrules were ever engaged. The line for pod 5, however, could not be run through the center of the upper bull plug because the bull plug was connected to the tubing string using a coupling plug. The coupling plug is like any other collar in the string, but it is long with extra metal in the middle to act as a plug. It has 2-3/8" 4.7# box by box EUE threads. The coupling plug can be seen attached to the upper bull plug in Figure #.

With the line coming out of the side of the upper bull plug, the design needed to compensate for the Swagelok® fitting that would penetrate the bull plug at an angle. This also created a problem with assembly because the fittings and bull plug had to be run over the line before assembling the DS150 Interconnect that would attach to the tool string. The line and fitting protruding from the bull plug can be seen in Figure #. Assembly of pod 5 began with assembly the L80 tubing to the Nitronic 50 tubing and torquing the two together. The lower bull plug was then torqued onto the lower end of the Nitronic 50 tubing. Then, the fittings were run over the 5/16" line, then the bull plug. The DS150 Interconnect was assembled, and the tool string was connected and tested. The tool string was then inserted into its housing, and the housing was rotated as it was threaded to the upper bull plug. The coupling plug was left off in order to add the CarboProp®, motor oil, and CerroTru® through a 1.5" hole left in the center of the upper bull plug. The CarboProp® and motor oil were added first until they reached the top of the EMI crossover. It would be undesirable for the CerroTru® to harden around the EMI coil itself.

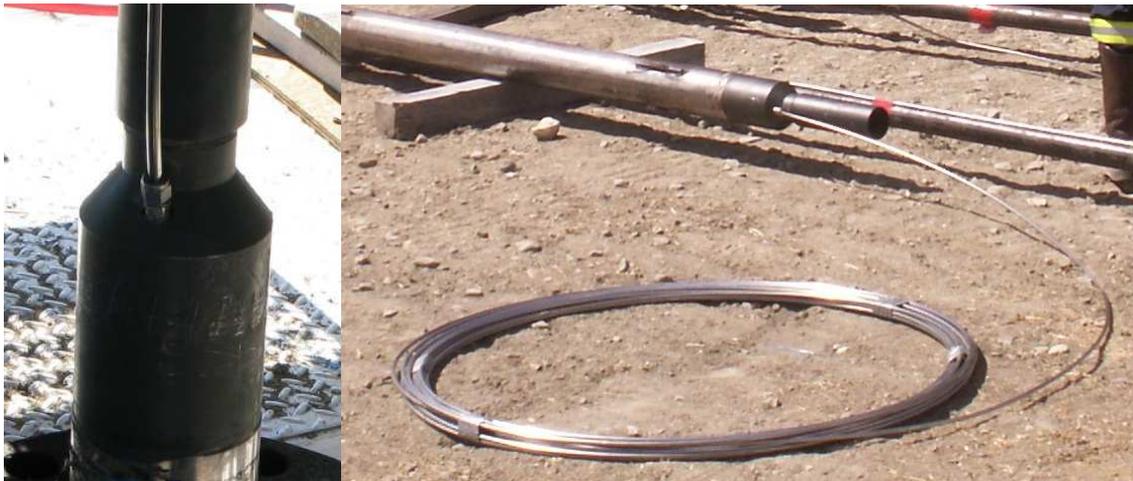


Figure #: Upper Bull Plug of Pod 5 with Line, Fittings, and Coupling Plug

While centralizers were ordered for pod 5, two hurricanes in the southern states created a problem with the manufacturing facility that would have provided the centralizers. There was an issue with the possibility that the tubing might roll and affect the readings from the geophones and MEMS tools. Two prevent rolling, 1/2" rods were welded to the L80 tubing. The rods were cut 6" in length, and were lines up axially with

the tubing. They were 3 of them 120° apart in 3 places spread equally along the 10' pod. An example over how they are aligned can be seen in Figure #. The rods were then ground down to an angle so that they would not catch on anything while being run down hole. This can be seen in Figure #.



Figure #: Alignment of Rods welded to Pod 5



Figure #: Rods Before (top) and After (bottom) grinding of angles

Assembly & Installation

Pod Assembly

- Tool Assembly required
- Tool Testing
- Pod Pressure Testing of Weld
- Running fitting and bull plug over line before assembling interconnect
- Run string with nut, then connected tool string
- Swage bottom line/bull plug
- Test tool string in series
- Add carboprop and cerrotru
- Tighten upper bull plug with torque
- Tighten upper swage
- Test tool

Shipping

- How was it shipped?

Proposed schedule

Onsite procedure

- Test tools on arrival
- Run in procedure
- Tool Testing while running
- Control line handling while running
- Pup joints between pods
 - Diagram
- Splice time and procedure 5/16" line
 - Tool testing
- Cannon clamp use
 - Midjoints and centralizers
 - Initial lack of line tension
- Splice time and procedure 1/4" line
 - Tool testing
- Pod 1 assembly
 - Post assembly splice
- Running with the sheave wheel
 - Tie off of wireline
 - Sheave wheel lowered and raised daily
- Setting spool tension
- Tiltmeter monitoring at > 5° tilt
- Addition of peter malin's tool
 - Third line with manual tension needed
- Completing the well
 - Shut down monitoring
 - Cut lines with 250 extra feet
 - Procedure with running lines through bolts and wellhead and order

Discussion

Future improvements

Mistakes made?

What would you do next time?

Pressure Testability

Appendices

SAFOD Main Hole Instrument Deployments 2004 – 2011
Bill Ellsworth and Steve Hickman

******Main Hole Deployments separated by asterisks******

MH001 November 9, 2004
 Galperin seismometer
 m.d. 9899 ft

Deployment by Duke University (Peter Malin and Eylon Shalev). Instruments were a collaborative effort of Duke and Oyo Geospace and based on the Geospace DS-350 borehole seismometer. The instruments were clamped to the borehole using a motor-driven hole lock (DS-325). Data digitized downhole and transmitted on OF to Geores computer at the surface. The Galperin suspension was being tested to determine if gimbaled “low frequency” (2 Hz) geophones could be used in the inclined hole.

Sonde in place for shots at PASO stations. Good data for the shots was obtained.

MH002 November 13, 2004
 Galperin seismometer
 m.d.6216 ft

Deployment by Duke University (Peter Malin and Eylon Shalev)

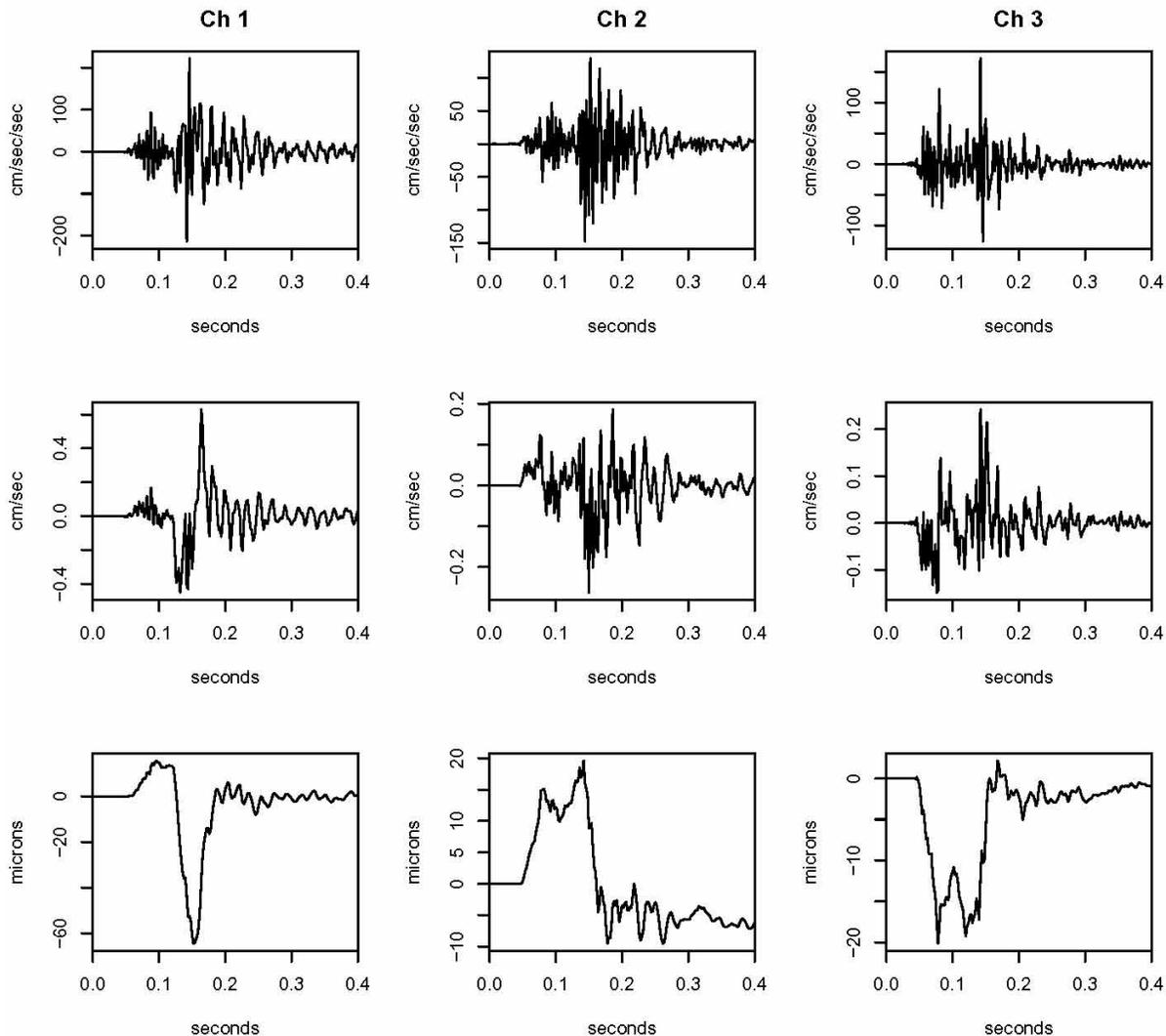
Sonde repositioned for additional shots at PASO stations. Good data for the shots was obtained. Instruments were functioning correctly when removed to prepare for MH003.

MH003 December 15, 2004
 Galperin + DS325/MEMS
 m.d. 9868

Deployment by Duke University (Peter Malin and Eylon Shalev)

This was the initial test of the Colybris Si-Flex SF3000L MEMS accelerometer. Instruments were a collaborative effort of Duke University and Oyo Geospace and based on the Geospace DS-350 borehole seismometer. The instruments were clamped to the borehole using a motor-driven hole lock (DS-325). The instruments operated until January 25, 2005. Details of failure mode are not known.

The accelerometer produced excellent data, including the recording of the L.A. target earthquake repeat on January 23, 2005. The nearfield motions were well recorded, and a static offset of 5 microns was obtained by double integration of the accelerogram (see below).



MH004 April 29, 2005
 PGSI 240 channel, 80 level, 3-component geophone array

This was a joint project of Paulsson Geophysical Services Inc. (PGSI, who provided the array), Geometrics, Inc (who supplied the data loggers) and SAFOD (who provided a workover rig for installation). The seismometers were Oyo SMC-1850 15 Hz omni directional moving coil geophones. Each geophone is connected to the surface data logger by a twisted shielded pair of copper wires. The seismometers were mounted in a special cradle attached to EUE tubing (see below). An inflatable bladder next to each seismometer was used to clamp the geophones to the casing.

This deployment (MH004) represents the initial array position in SAFOD after all geophones were installed.



MH005 April 30, 2005
PGSI 240 channel, 80 level, 3-component geophone array
Middle position during trip-in.

MH006 April 30, 2005
PGSI 240 channel, 80 level, 3-component geophone array
m.d. 9001 ft

Final position in well. Instruments were removed on April 12, 2005.

The PGSI array provided good data for low-amplitude signals. We found, however, that the clamping force was not sufficient to prevent crosstalk between the channels for higher-amplitude signals and concluded that the inflatable bladder would not provide adequate clamping, particularly for the recording of target events.

MH007 January 14, 2006
DS250 + tiltmeter + DS325/MEMS
m.d. 9643 ft

Installation by Pinnacle, Duke and USGS. This was the first deployment of the Pinnacle tiltmeter at SAFOD.

This was also the first deployment in the Phase 2 hole. The hole had been turned over to Paul Silver for his cross-hole experiment following the completion of drilling in September 2005. We were unsuccessful in running the tool to the target depth, because of a slight lip (1-2 mm) on the

7" SAFOD Phase 2 liner hanger that caught an edge of the DS325 sonde (see photo below). Consequently, the tool was positioned just above liner hanger. All of the tools died soon after installation. We concluded that we needed to switch to the DS250 seismometer, since it and the tiltmeter were of uniform diameter with no external upset. This would give us the best chance of getting past the liner lap.



Tools recovered February 2 by Pinnacle and USGS. Gas pressure of over 700 psi has built-up on well. (Note that this gas pressure cannot simply be converted into a downhole pressure because of two-phase fluid in SAFOD and resulting uncertainty in mean fluid density between the wellhead and bottom of the Phase 2 hole, which was open to the Great Valley Formation.)



MH008 February 3, 2006
 DS250 + tiltmeter + DS250
 m.d. 10738 ft

Installation by Pinnacle and USGS. Lots of gas vented from wellhead.

DS250 having intermittent problems during surface test, which Pinnacle attributes to board in fiber optic cable head. Water found in cable head, so they replace board and got it to work after some tinkering. Installation successful with tools placed below liner lap.

Sensors working next day, but with sporadic signals on tilt and geophones. Signals cleaned up by unclamping and reclamping arms. Internal sonde temperatures 115 to 121° C.

The lower DS250 failed on February 10. The upper DS250 failed on February 16.

Examination of the tools at the surface revealed moisture on the pins of the loop back connector (terminator) at the bottom of the tool string. We were unable to diagnose further the failure mode of seismometers in the field. Tools taken by Pinnacle for repair of boards.

Tiltmeters failed with a dead short. Pinnacle found that the unit had been invaded by wellbore gas and there was internal corrosion of electronics. Need to improve resistance to gas in wellbore fluid by better O-rings, welded connections and metal-metal seals.

MH009 April 28, 2006
 DS250 + tiltmeter + DS250
 m.d. 10738 ft

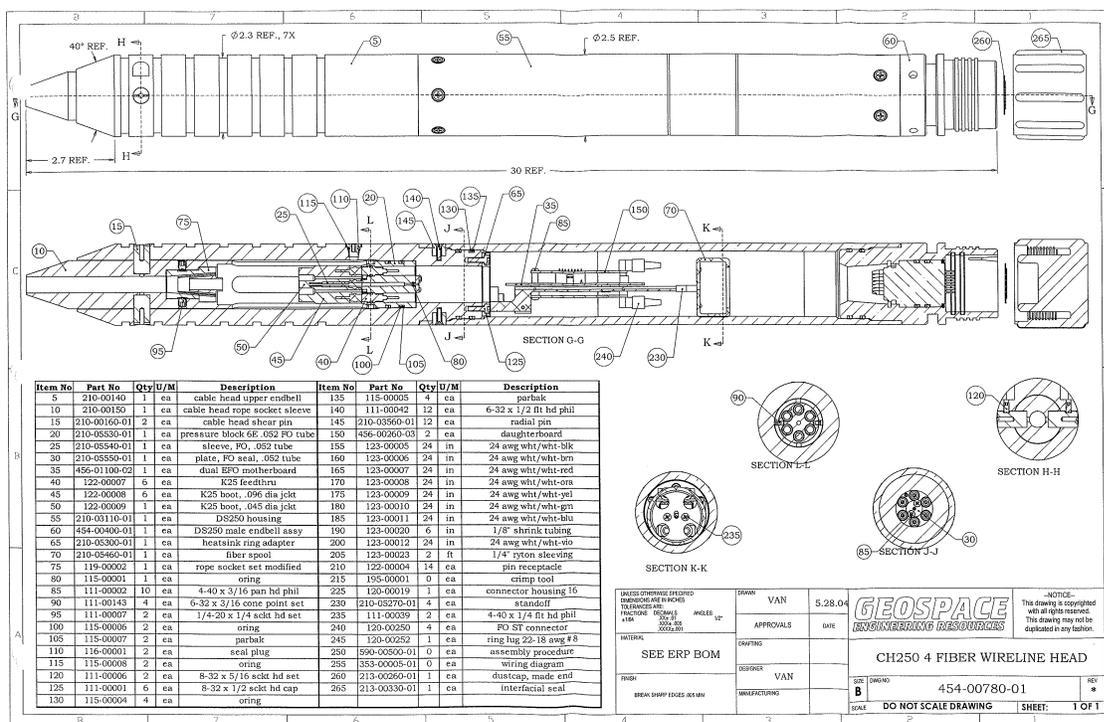
Installation by Pinnacle, Duke and USGS.

Wellhead pressure in excess of 550 psi – vented 2 days before installation, but rebuilt to 310 psi in 40 hours. At the recommendation of Pinnacle, we replaced Viton Duro 70 O-rings with (very expensive) Kalrez O-rings. The latter are very resistant to gas.

There was also concern about damage to the cable due to exposure in the well. We cut 162 ft of cable to get to better copper on electrical conductors.

Instruments ran until May 14, and were removed from SAFOD May 23 (see tool recovery notes, below). Failure occurred from short in cable head (cable head engineering drawing below).

Cable head examined in detail at site, and tiltmeter tested in Pinnacle San Francisco and DS250s sent to Pinnacle San Francisco.



USGS cut several hundred more feet of cable and tested for continuity on June 6.

SAFOD Tool Recovery – May 23 2006

Field Crew: Ralf Krug, Mike Spradlin, Joe Svitek, Andy Snyder, Fred Grubb.
Arrived on site at 08:00

The well was found leaking fluid out of the rubber plug. The gas monitor (“GasAlertMax” monitoring H₂S, CO, O₂ and Combustibles) was set up with its nozzle close to outlet of the lower valve. The valve was opened which resulted in a short surge of fluid (probably the amount inside the well head). The gas monitor did not register gases, O₂ remained at 20.9%. The gas monitor remained at the valve outlet during the operation. Around 10:00 (before the tool string was pulled) it issued a short CO/Combustibles alarm. No other alarms were recorded during the rest of the operation.

The tiltmeter was found drawing 100mA – but no communication was possible. The DS250s could not be woken up. At 8:45 we closed the arms: 260V/0.5A for ~20sec before dropping down to 240V/0.5A.

Pulling started at 10:15 – the load cell showed a reading of 4.0

When the instrument string surfaced around 13:00 small gas bubbles were visible coming out of the upper part of the cablehead (seal approx. 2in below the upper end) and the wireline (right on top of the cablehead) through a greasy, clear substance.

The locking arm of the upper DS250s was only half way retracted. The locking arm of the lower DS250 was completely retracted. The connection between the upper DS250 and the tiltmeter had some moisture in it (all other connectors were found dry)



The tool string was laid out on the surface for these tests:

1. complete instrument string (as in the well): Only the arm of the upper DS250 could be moved. Waking up the DS250s was not successful. Tiltmeter showed excessive current draw (120mA compared to 80mA), communication was not possible
2. Cablehead – upper DS250 (S/N 109) – lower DS250 (S/N 108): both arms could be moved in and out – wake up was not successful.
3. Cablehead –lower DS250 (S/N 108): arm could be moved in and out – wake up was not successful.
4. Cablehead – tiltmeter: excessive current draw, communication was not possible
5. Cablehead – upper DS250 (S/N 109): arm could be moved in and out – wake up was not successful.
6. Cablehead alone: Even if no tiltmeter was connected, the tiltmeter power supply showed a current draw of 26mA

Note: Due to these tests the bottom loop back connector is currently attached to the upper DS250 (S/N 109)

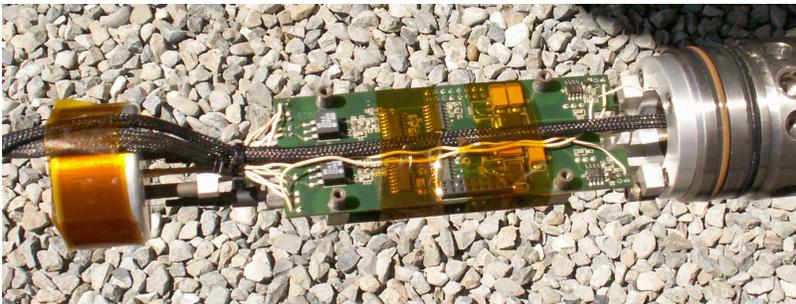
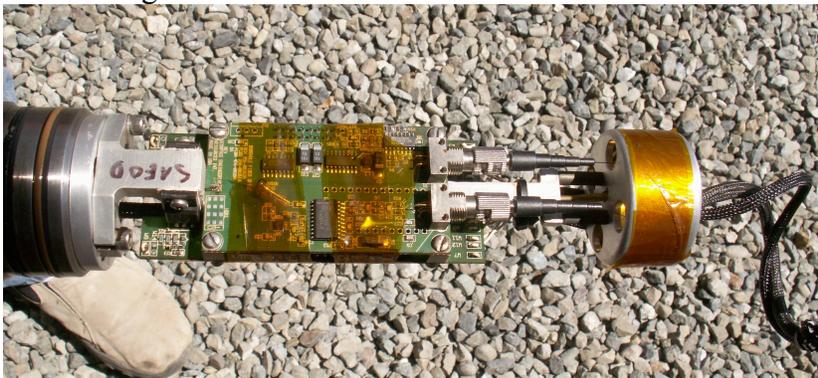
At this point the decision was made not to redeploy. Instead the cablehead was brought into the science trailer for inspection.

The pressure plug of the cable head (lower part including the fiber optic converter) was opened with the nozzle of the gas monitor held close to the pressure plug. The inside was not pressurized but the gas monitor found extreme high concentration of CO (went off scale) while showing traces of H₂S, and combustibles. Everyone agreed on a strong “burnt” smell when the bottom connector was removed. The wires leading to the bottom connector were found wrapped in a brown paper insulation which looked burnt.



Maybe the paper insulation did not withstand the high temperature and oxidized over time thus releasing CO into the cable head.

No moisture was found inside the lower part of the cable head. The electronic boards seemed to be undamaged.



After the white/brown wire was removed from connection point W5 of the board the 6 leads of the wireline were tested with a megaohm meter (Amprobe AMB-3, 500V). All 6 leads show 0 M Ω resistance to armor. The same test was done with a regular multimeter:

	Color Code	Resistance to armor
Tool Power +ve	Wht/Brn	160 Ω
Tool Power -ve	Wht/Red	136 Ω
Arm Power +ve	Wht/Ora	12M Ω
Arm Power -ve	Wht/Yel	Inconsistent (negative)

CCL +ve (unused)	Wht/Grn	350k Ω
CCL -ve (Tiltmeter)	Wht/Blue	2k Ω

At this point the decision was made not to cut the cable head since there was no apparent damage to the bottom part (not pressurized side). The cable head was left unassembled (secured with duct tape) in the science trailer for future repair.

We left the site around 16:30

Back in the lab in San Francisco the tiltmeter was tested electrically. It worked fine (no excess current), all connection between the DS250s were tested good (no conductivity of all 12 leads to the housing, full conductivity of all 12 leads between top and bottom connector).

All three instruments will be brought to Menlo Park on May 24 to take a gas samples when the pressure plugs will be opened.

After this test the DS250s will be sent to Pinnacles office in Houston to check if they are working. It has to be decided what to do with the lower DS250 (S/N 108) since it showed a resonance at the 15Hz eigenfrequency of the sensors.

Angus Duthie assumes that *“the cablehead will probably need to be cut. Looks like the grease pack and the boots did not hold up”*.

Ralf Krug, Pinnacle, San Francisco

MH010 July 11, 2006
 DS250 + tiltmeter + DS250
 m.d. 10704 ft

Installation by Pinnacle and USGS, after rebuilding of all components.

Kalrez O-rings were used on all on tool joints on high-pressure side, Viton on low-pressure side. Instead of grease used previously, for this deployment the wet side of cable head was filled with Krytox oil, which is the standard water block used in high-temperature geothermal cable head applications. Krytox is a low viscosity, high-specific-gravity oil that is designed to remain contained without broaching in a cable head that is sealed (e.g., with O-rings) from below.

All instruments working the next day, except some communications problems with tiltmeters (two DS250s working OK). Successful recording of PASO shots on July 13.

Electronic noise on seismometers found to be caused by tiltmeter modem transmissions.

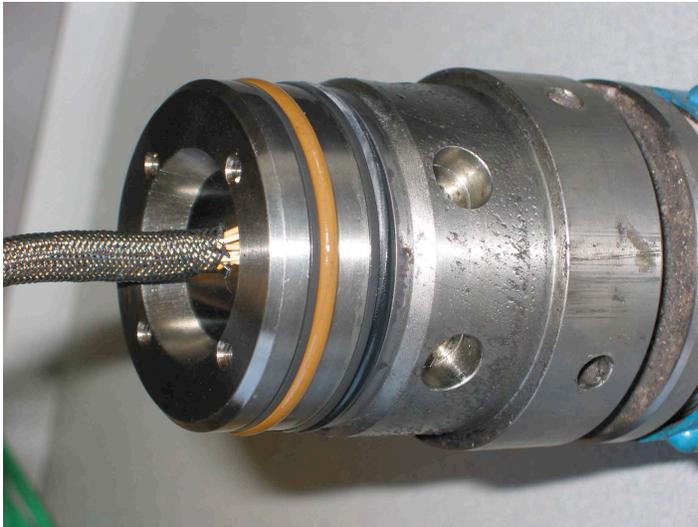
Tools experienced sudden electronic failure on July 16, and were removed from SAFOD and inspected July 19 and 20.

When the tool string arrived at the surface, a substance was hissing out of the wire line for the last couple of meters above the cable head. The picture below was taken one hour later when the substance had dried out.



Gas pressure was noted in the cable head when it was taken apart at the wellhead. When opened, a number of O-rings were found to have been damaged. It does not appear, however, that liquid had time to enter the pressure vessels, as all tools tested OK once separated from the cable head. Further testing after severing the cable head from the cable revealed that there was a short in the cable head – clearly the failure point. Although there were doubts about how much Krytox oil was in the cable head when the tools were recovered, draining of the cable head overnight recovered about 100 ml of Krytox oil, which showed no signs of degradation or discoloration. The remaining Krytox might have leaked out or been replaced by the gas-charged wellbore fluid. Corrosion in rope socket supports this view. The Viton O-ring in the cable head interconnect was observed to be swollen (see photo below), but the Kalrez O-ring showed no sign of damage. Similar swelling was seen in the Viton O-ring in the in the cable head bottom bulkhead, but not in the Kalrez O-ring. No O-ring swelling was observed in the interconnects between the DS250s and the tiltmeters.





Cable head shipped to Houston for repair. Evidence found of burning on pins 1 & 2, possibly due to burning of boot due to high current. Considerable discussion of options for potting the wet side of the cable head. Decision made to try grease recommended by Oil Center Research, as the DC111 grease that we have been using has proven inadequate to the task. Will also research high-temperature epoxy as another alternative.

Additional research on O-rings suggests that some of the Kalrez and most of the Viton O-rings used in MH010 were not suitable for 110 deg C applications. Better (and much more costly) formulations of Kalrez O-rings purchased for next installation.

MH011 August 2, 2006
 DS250 + tiltmeter + DS250
 m.d. 10740 ft

Installation by Pinnacle, USGS and Stanford.

New O-rings installed in cable head and the DS250s. Could not open pressure port on tiltmeter, so it was left as-is. The potting grease recommended by Oil Center Research as having better gas resistance, as well as a different boot with better gas resistance recommended by Kemlon was used in this installation.

The tiltmeter failed after 4 days. Later analysis showed that the tiltmeter lines shorted in the boot. We were lucky that it didn't take out the DS250s as well.

This proved to be the longest-running of all of the DS250 deployments in the SAFOD main hole. The instruments ran until September 13 when they experienced a sudden electronic failure. Tools were removed on September 18.

The grease we used this time performed marginally better than the previous compound. Considerable discussion about what to do for the upcoming PASO shots that we need to record as close to the target events as possible. One option is to use the same grease, since the time frame is short. The alternative is to use epoxy, although doing so will sacrifice cable head parts. There are also concerns about the large void space to fill and the heat produced while curing.

MH012 October 24, 2006
 DS250 + tiltmeter + DS250
 m.d. 11196 ft

Installation by Pinnacle and USGS.

Used same grease as last time in cable head. Tool repositioned multiple times to put clamping arm on high side. Tools died next day. They were recovered and re-headed for installation the next day (swapping out the fibers used in the cable head, and repolishing the fiber terminations) to record the PASO shots.

MH013 October 26, 2006
 DS250 + tiltmeter + DS250
 m.d. 11213 ft

Tool repositioned twice to put clamping arm on top. Tool began to fail after just 1 hour. We were able to nurse it along just long enough to record two shots. Cancelled the remainder of the shots for now.

MH014 October 31, 2006
 DS250 + tiltmeter + DS250
 m.d. 10719 ft

Installation by Pinnacle and USGS.

Data intermittent, lots of drop outs. Pulled up tool to cool off several times, but it did not solve problem. Fibers shot with OTDR, found to be OK. Tools pulled out of hole.

Tool repaired and re-installed. Six PASO shots successfully recorded on November 1.

MH015 November 1, 2006 (same deployment as MH14; i.e., tool not pulled from hole)
 DS250 + tiltmeter + DS250
 m.d. 11209 ft

Tool repositioned to deeper depth for next set of PASO shots. All six shots successfully recorded.

Tool kept in hole overnight, which was fortuitous, as we caught an L.A. repeat. Pulled out of hole the next day to leave it free for PMIT log the following week.

MH016 November 9, 2006
 DS250 + tiltmeter + DS250
 m.d. 11202 ft

*Reinstallation after running PMIT log day before.

*Instruments working OK at that time

*11/20/06: we return to site to remove dead instrument from hole. No notes on why instrument died.

MH017 January 11, 2007
 2x DS250
 m.d. 11194 ft

Installation by Pinnacle and USGS.

Tiltmeter was not available, so decided to go with just the pair of DS250s. For this deployment, the cable head was filled with the high-temperature epoxy.

Tools died a week and a half later, and was removed from the hole on January 24. Below is the e-mail from Etienne Samson reporting Pinnacle's investigation of the failure.

All,
First, the DS250 was tested. It draws current but does not communicate. It is now at GERI for repair. Our guess is that the Vcxo chip and been damage somehow. This type of behavior is something we see very often in our tool. What we call the Vcxo chip is a little circuit that has been hybridized and package in one metal box. The metal box had 4 legs for thru hole mounts.

Problems we see with that chip range from broken legs, to crack solder joints and loose components in the metal case. There are 2 different board revisions. A green board (old) and red board (new). The green board has surface mount pad to mount that chip, the red board had thru holes to mount it which solved many problems (See Vcso and Vcxo_1 picture). From memory, I think both tools have green boards but not exactly sure. The cablehead was cut. No fluid was found inside. It's not very easy to draw a conclusion from the parts because the heat generated by the cut degraded the epoxy around the feed thru. The voids could have been created by the heat or could have been there all along (Picture 0).



In "Picture 1", if you zoom in on the feed thru, you'll notice bubbles or a path on the feed thru where it looks like the epoxy was delaminated from the feed thru. It looks like water could've come from the bottom side of the epoxy and made its way back up along the feed thru. If that happened, it would explain the short between conductors and ground. It looks like the epoxy bonded well with the copper tubes (Picture 2).



All the parts were degreased and the surface of the pressure block (part that holds the feed thru) was rough up with a file. It looks like that may not have been enough to allow the epoxy to bond well with the metals. If we try the epoxy again, I would suggest that we sandblast the metal parts and feed thru and chemically etch the polypropylene on the conductors.

Etienne Samson
Pinnacle Technologies

MH018 March 24, 2007
 2x DS250
 m.d. 10709 ft

Installation by Pinnacle and USGS.

This installation was done for the sole purpose of repeating a PASO shot at PIGH that was not well-recorded earlier.

MH019 September 27, 2008
 Observatory (overnight run during deployment)
 m.d. 8989 ft

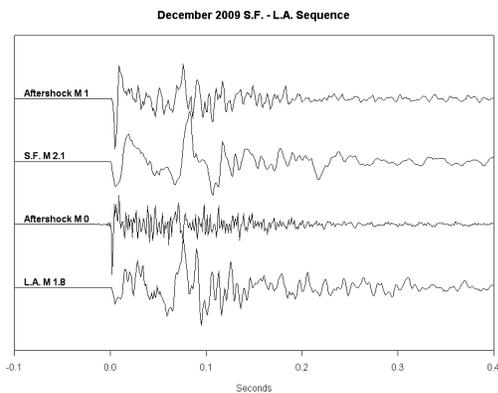
MH020 September 2008
 Observatory
 m.d. 10389 ft

MH021 December 4, 2008
 Mini-mini-me
 m.d. 10064 ft

Installation by USGS.

This was the first deployment of a passive instrument in the SAFOD main hole since the PGSI array was briefly installed in 2005. The instrument has an O.D. of 1.5 in and was lowered down the inside of the EUE tubing to land on the cross over between the EUE and CS tubing. The seismometers are the same as used in the DS250. The old wireline was used, after cutting of a considerable amount of cable to get to good copper. The cable head was filled with the same epoxy as used in MH017. A Reftek 130 was used to digitize data at 1000 sps.

This deployment returned beautiful data at the start, including spectacular recordings of S.F. and L.A. repeats.



As time went by, we saw an increase in the pick-up of 60/180 Hz noise from the AC power. We believe that this was due to the slow failure of the cable, as when removed, the cable head was intact. This is not surprising, as this cable had been in the well for a long time at this point.

The tool was finally removed

MH022 May 6, 2009
 Mini-mini-me
 m.d. 10066 ft

Installation by University of Auckland and USGS.

This was an identical instrument to MH021, except that we filled the cable head with Krytox oil. We did find, however, that we only had 5 good conductors in the old wireline and as a consequence deployed this as a 2-component seismometer. The performance of this tool was the best to date. It ran between May 2009 and September 2010, when it was removed to prepare for the recovery of the MH020 observatory.

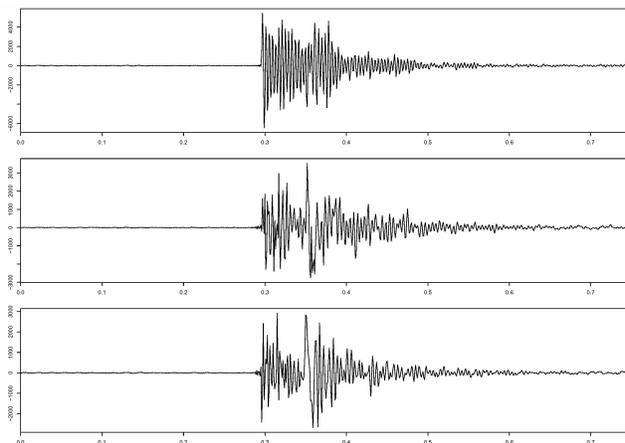
We did observe a steady increase in 60/180 Hz noise on this instrument, which we attribute to the further failure of the wireline.

MH023 December 9, 2010
 Mini-mini-me
 m.d. 10056 ft

Installation by USGS.

A new off-the-shelf 7-conductor logging cable was purchased to replace the SAFOD wireline. The new cable was connected to the MH022 sensor, with the cable head filled with Krytox oil. Deployment was in the open hole to approximately the same depth as MH021/MH022.

Although we continue to be plagued by 60/180 Hz noise, the data is otherwise of excellent quality (and the AC noise can be removed by predictive filtering). An example of a recent event is show (February 8, 2011).



The 60/180 Hz noise problem is not insurmountable. We have had excellent experience in the 2700 m deep Long Valley Exploratory Well in eastern California running 2 Hz 3-C geophones

on a cable with individual twisted shielded pairs of conductors since 2003 at an ambient temperature of 105 C.

It is clear, however, that we are missing important data by recording at 1000 sps instead of 4000 sps that was standard with the Geores. We are currently investigating higher-sample-rate digitizers, such as the Geometrics Geode that was used with the PGSI array at 4000 sps.

We may also miss critical data when the M~2 target earthquakes occur because the signals may exceed the dynamic range of the recording system. We have already seen this in a M 1.0 earthquake in the Hawaii target zone that just clipped one component of MH022. The 15 Hz geophones also limit the data bandwidth. It is unlikely that we will be able to recover static displacements with them, as we did with the MEMS sensors.

Related Instrumentation Development Activities

Pilot Hole

The SAFOD pilot hole was also used for the testing of sensors. In particular, DS250 and Galperin seismometers were run for periods of up to 11 months without problem at 1050 m depth and an ambient temperature of 60 C.

Guralp Systems, Ltd. also ran a broad band seismometer at the same depth for over 1 year (PH008), again without incident.

Bench Tests

DS150 #6118 was run in a continuous high temperature test in Menlo Park between June 27, 2008 and August 20, 2008. The instrument was kept in an oven at a temperature of 120 C, which resulted in an internal module temperature reading of 129 C. Although the acquisition spontaneously aborted several times, the problems were traced to the Geores software and firmware in the module. After reset, the tool woke-up successfully each time. Software patch fixed the overflow problem that had been killing acquisition.

DS150 #10576 was modified by Pinnacle and their consultant Mike Abrams by replacing the geophones with the Colybris SiFlex 1500 MEMS. It was shipped to Menlo Park on August 20th. The oven test was resumed on August 21 with both module #6811 (top) and #10576 in the oven at a temperature of 107.7 C. The internal temperature of the tools read 118 C. The tests revealed that the way that the MEMS was connected to the DS150 digitizer limited the range to less than 2 g. Discussions with Pinnacle and their consultant determined that by using a different output pin from the SF 1500 the full 3 g range could be recorded. The tool was returned to Pinnacle for modification on August 26th.

PROJECT SUMMARY

This is a proposal to re-instrument the main borehole of the San Andreas Fault Observatory at Depth (SAFOD) with a new monitoring array that meets the original science goals of the SAFOD project. These goals include: 1) monitoring of fluid pressure within the San Andreas Fault Zone, 2) wide dynamic range recording of microearthquakes at distances of 100 m or less, and 3) monitoring for transient deformation within the fault zone.

Under this proposal, the instrumentation installed in SAFOD at the conclusion of the EarthScope MREFC phase in September 2008 would be replaced. The new instrumentation and observatory design is based on commercially available hardware. The observatory will be deployed in a manner that will simplify the future retrieval, repair and reinstallation of the array under existing EarthScope O&M funding.

This proposal is in response to two unanimous recommendations made by the newly empanelled SAFOD Advisory Committee to the UNAVCO Board of Directors (<http://www.unavco.org/community/governance/committees/committees.html#sac>) during a meeting held on May 11 and 12, 2009 at the EarthScope National Meeting. The overall recommendation of the committee was: "It is critical to maintain continuity of recording amid the well-chosen nest of repeating earthquakes within a few hundred meters of the recording location at 2.5 km depth inside the San Andreas Fault." They recommended a two-phase process.

Phase 1 would involve replacing the failing USGS MH022 analog instrument with a temporary array of two digital DS-150 seismometers, which would be installed in the current EUE tubing. The temporary array and wireline will be purchased and assembled from a third party vendor and the installation will take place with an existing winch by UNAVCO and USGS personnel. Funds for purchase, assembly, installation, and data handling activities will come from existing and accumulating SAFOD O&M funds. Phase 1 is very low risk in term of instrumentation and installation and will temporarily restore seismic data continuity to capture repeating earthquakes deep in the hole. The full cost of phase 1 is \$268,785.00 and work can commence after October 2009 or sooner based on prespending authority. Some of the materials to be purchased under Phase 1 – such as the logging cable, and two seismometers – will also be used in Phase 2. It must be emphasized that Phase 1 is only a temporary solution, as past experience has taught us that gasses dissolved in the SAFOD borehole fluid pose a serious threat to long-term operation of seismic instrumentation at depth. Solution of this problem, by creating a benign oil-filled environment in which to install the full SAFOD observatory, is the goal of Phase 2.

Phase 2, addressed in this proposal, is divided into 4 separate steps: 1) Removal of the inoperable observatory instrumentation installed in September 2008; 2) Well remediation and installation of pressure sensors; 3) Fabrication and testing of the new equipment; and 4) Redeployment of the SAFOD observatory. The full cost of this proposal is \$2,722,105 (Sum of Phase 2A-D of budget) and is based on a bottom-up estimate of all expenses

including subcontractors, drilling, equipment, and schedule risk. In addition this proposal provides a more sustainable and cost effective plan for future SAFOD maintenance under the existing O&M budget. For example, instead of deploying the instruments and control lines directly inside the water-filled casing on tubing as was done during the initial deployment, this proposal would deploy them on wireline inside a new, 4 inch EUE tubing string that is sealed at the bottom and filled with a non-corrosive, non-conducting fluid. This will provide a non-caustic environment for the instruments and allow rapid and inexpensive retrieval (no drill rig required) of the instruments in the event of failure.

BACKGROUND

The San Andreas Fault Observatory at Depth (SAFOD) was constructed as a component of the EarthScope Program of the National Science Foundation between 2003 and 2008. The facility includes a cased borehole that is 3200 m MD (measured depth along the well trajectory) and terminates inside the active trace of the San Andreas Fault at a true vertical depth of 2.6 km. The scientific rationale for installing an observatory of seismic, pressure and deformation sensors within the actively deforming San Andreas Fault zone has been presented previously in the 2003 EarthScope MREFC Proposal and the 2007 EarthScope O&M proposal (available at www.earthscope.org). In brief, the SAFOD observatory offers the unique opportunity to observe variations in deformation, fluid pressure, microseismicity and radiated seismic energy within and adjacent to recurring earthquake rupture patches over multiple earthquake cycles. Acting in concert with studies on recovered samples, SAFOD monitoring will thus make it possible to observe directly a number of time-dependant processes related to earthquake nucleation, propagation, and arrest, including: (1) the possible role of temporal variations in fluid pressure within the fault zone in controlling earthquake periodicity and rupture propagation and arrest, (2) the interplay between aseismic and seismic fault slip in the nucleation process for repeating microearthquakes, (3) the time scales and physical processes through which stress and strain interactions occur between nearby earthquakes, and (4) the manner in which earthquake energy is partitioned among seismic radiation, frictional dissipation, grain-size reduction, and chemical reactions.

The scientific experiment being conducted at SAFOD is unique. Never before have detailed measurements of the seismic and aseismic fault movement and related processes been attempted under the conditions encountered inside a major plate boundary fault at depths where earthquakes nucleate. The challenge facing the long-term SAFOD observatory is to build and install a robust system directly within the fault and operate it continuously at temperatures of ~125 °C and fluid pressures of 30 MPa.

The harsh conditions under which SAFOD instruments must operate are complicated by the presence of hydrocarbons in the borehole. After the completion of the Phase II drilling in 2005 it was found that the wellbore fluid contained natural gas and light weight liquid-phase hydrocarbons, coming primarily from sedimentary formations northeast of the San Andreas Fault. The presence of gas and light hydrocarbons in the wellbore fluid created major problems for prototype deployments of seismic and tilt

instruments in SAFOD. A bridge plug was installed and cement in the casing in 2006 in an attempt to isolate the hydrocarbons, but this operation was unsuccessful.

The SAFOD MREFC construction team worked closely with the prime contractor for the SAFOD observatory, Pinnacle Technologies, to develop a monitoring system to cope with the harsh temperature, pressure and chemical conditions downhole. The construction team also obtained advice from the SAFOD Monitoring Instrumentation Technical Panel, experts associated with Integrated Ocean Drilling Program (IODP) and International Continental Scientific Drilling Program (ICDP), and the Geothermal Instrumentation Group at Sandia National Labs. These experts recommended the following practices for SAFOD observatory instrumentation:

1. Employ instruments that allow long-term operation at elevated temperature and pressure in a corrosive environment. Replace polymer O-ring seals with metal-to-metal seals. Use only high-temperature electronic components. Encapsulate electrically conducting cables and optical fibers inside seamless stainless steel tubes connected to instrumentation pods through welded or metal-to-metal seals.
2. Plan for SAFOD monitoring instrumentation to be replaced every three years.
3. Deploy instrumentation on rigid, large-diameter tubing to facilitate accurate sensor placement and good coupling to the formation. At a later date, this tubing would also be used to install a bridge plug at the bottom of the hole for long-term monitoring of fluid pressure within the fault zone.

The observatory installed in September 2008 at the conclusion of the MREFC phase (Figure 1) fully complied with these recommendations and consisted of two independent systems: one for the tiltmeters and one for the seismic and electromagnetic sensors attached to the outside of 2-3/8-in-diameter EUE tubing. Power and telemetry for each of these systems was accomplished through two continuous, plastic-encapsulated 1/4-inch-diameter stainless steel tubes (“control lines”) strapped to the outside of the EUE tubing, extending from the array to recording instruments at the surface. The construction team used best industry practice to protect the control lines during installation, including the use of protective clamps at every joint between pieces of EUE tubing and at every mid-joint. Centralizers were also used to keep the control lines away from the casing in the inclined portion of the well. Despite best efforts, contact was lost with one of the tiltmeters before it reached bottom. The other tiltmeter arrived on bottom in good condition. However, about 2 weeks later it, too, began to have problems and ultimately stopped working on October 14.

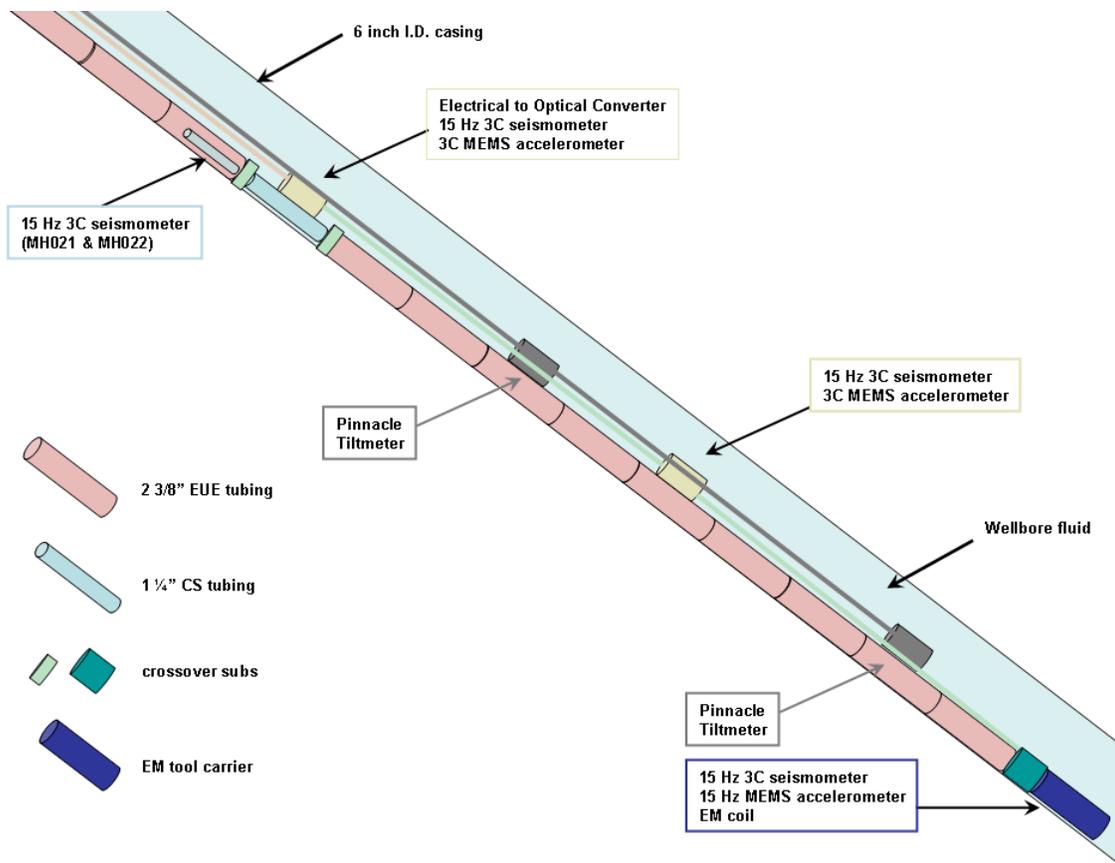


Figure 1. Layout of instrument section of the SAFOD observatory deployed in September 2008. The five instrument pods are rigidly attached to the supporting EUE tubing, and coupled to the inside of the casing by bow springs located on the top side of the pods. Oyo Geospace DS250 digital borehole seismometers are located in the 1st, 3rd and 5th pods. One DS250 contains 15 Hz geophones and the other Colybris MEMS accelerometers. Pod 5 also contains a 3rd DS250 connected to a large EM coil provided by funding from NASA under a grant to Duke University. Pods 2 and 4 contain Pinnacle Technologies tiltmeters. The location of the currently operating analog seismometer (MH022) is shown.

The seismic array arrived on bottom in fully functional condition. Difficulties with the seismic data, however, began to appear after several days of operation in the form of communication problems between the 7 modules. This initiated several trips to SAFOD to investigate possible problems with power supplies, the GeoRes (data recording) computer, and other components. On October 10 communication was lost with all but the top instrument, and the decision was made to continue recording it in the hope that additional work would allow us to restore the other 6 instruments. Unfortunately, this was not to be the case. After an additional four days of operation, the last surviving instrument went into a spasm of drop-outs, spikes and reboots that ultimately led to no data coming from the tool.

Despite this setback, a primary science objective of SAFOD continues to be observation of the microearthquakes located nearest to the instruments (i.e., the “target” earthquakes) and the drilling plan was designed from the beginning to come as close as possible to these events. These target earthquakes are repeating earthquakes that re-rupture the same area of the fault in nearly identical earthquakes. The rupture areas of these events have been stable since at least 1984, when digital waveforms from the regional seismic network first became available. Figure 2 shows the location of the target earthquakes relative to the SAFOD well at the completion of Phase II drilling in 2005. The current cased hole terminates just beyond the “3190 m” fault. The “Hawaii” target earthquake is located approximately 100 m below the well, and the “S.F.” and “L.A.” target earthquakes are located approximately 300 m above and northeast of the well. The most recent occurrence of the target events were in August 2008 (Hawaii) and December 2008 (S.F. and L.A.). Their recurrence intervals are currently lengthening following the increase in fault creep rate caused by the 2004 Parkfield earthquake. The next recurrences of all three sequences will likely be in 2010.

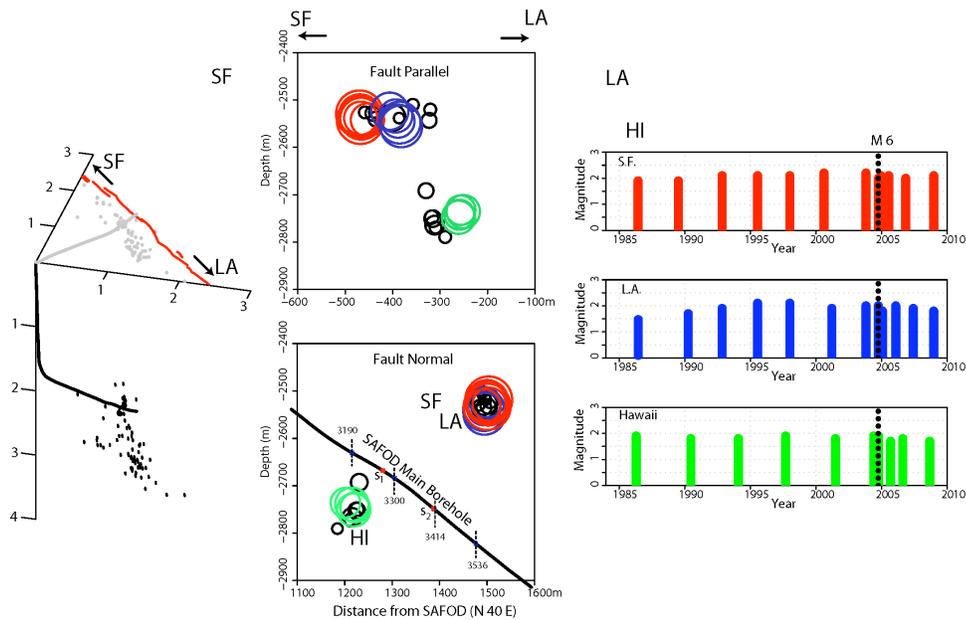


Figure 2. Left) Perspective view of microearthquakes occurring on the San Andreas Fault in the vicinity of the SAFOD drillsite and the trajectory of the SAFOD mainhole. Center Top) View of the plane of the San Andreas Fault at ~2.7 km depth. The red, blue and green circles represent seismogenic patches of the San Andreas Fault that produce the regularly repeating target microearthquakes discussed in the text. Center Bottom) Cross-sectional view of the target earthquakes, the trajectory of the SAFOD borehole and some of the most significant faults encountered during drilling. Right) Time sequence of the repeating earthquakes.

PROPOSAL FOR A NEW OBSERVATORY

The premature failure of the instruments in October 2008 came as a severe disappointment to everyone involved in the project. However, the scientific justification for operating an observatory inside the San Andreas Fault at SAFOD remains as strong as ever. The problems that must be overcome are almost certainly related to problems with isolating the instrumentation from contact with the wellbore fluid. At this time, there is no evidence to suggest that there are problems with the instrument themselves, as all are qualified at temperatures above those encountered in SAFOD. However, this point must be examined carefully when the instruments are recovered from the well. Assuming that this is the case, a new solution needs to be found for protecting the instruments and their associated control lines.

There is an alternative way to install the same types of sensors that solves the problem of the wellbore fluid. Instead of deploying the instruments and control lines directly inside the water-filled casing, the SAFOD O&M team propose to deploy them inside a new, 4 inch EUE tubing string that is sealed at the bottom and filled with a non-corrosive, non-conducting fluid. By placing all of the seismic and tilt instruments in a benign environment, we eliminate the source of the problem by entirely removing water from the environment. We also eliminate one possible cause of failure at control line splices by using a standard electrical/optical wireline from the surface to the array and rigid interconnects between the array components.

We propose to use off-the-shelf instruments for the seismic and tilt array, all of which are used routinely by Pinnacle Technologies in monitoring of oil fields. The digital seismometer modules are manufactured by Oyo Geospace and have a screw-driven locking arm that mechanically clamps the instrument to the inside of the tubing. The tubing, in turn, would be equipped with rigid stand offs to ensure good coupling to the inside of the cemented casing. Some of the seismometer modules would be modified by replacing the 15 Hz geophones with MEMS accelerometers. The SAFOD MREFC construction team made the same modification to a different model of Oyo Geospace digital seismometer for the observatory installed in 2008 and have confidence in the design. The tiltmeters are identical to those installed in 2008 and are manufactured by Pinnacle Technologies. Although they did not collect a great deal of data in 2008, Pinnacle said it was the quietest tilt data they had ever collected in a borehole. The number of tiltmeters is being increased from 2 to 3 so that it will be possible to measure the curvature of the tilt field, which is critical for the interpretation of tilt signals. Two tiltmeters were installed in 2008 solely to stay within the available budget

A major addition to the proposed observatory is a system for monitoring fluid pressure in the fault zone. This will be accomplished by installing a bridge plug in the existing casing below the instrumentation interval to isolate the fault zone from the wellbore above. A “stab in” connection will be used to allow quartz pressure transducers attached to the base of the 4-inch EUE tubing string to monitor fluid pressure in the fault zone. This fluid pressure monitoring system employs a solid rubber packer, polished bore receptacle, stinger tool and quartz pressure transducers used routinely for zonal isolation

and pressure monitoring at comparable conditions in the oil field. From the beginning of the SAFOD project there was an opportunity to monitor the fluid pressure in the fault zone as one of the key science drivers of the experiment. This goal was temporarily abandoned in 2008 due to problems with the well. Following the Phase III drilling in 2007, it was discovered that the bottom 30 m of the well was not cleaned out properly and that it would be necessary to remediate the well before a bridge plug could be deployed. There were insufficient funds at that time to pay for this operation. As part of the down hole instrumentation refurbishment we now propose to perform remediation operations before the bridge plug is deployed, as explained below. In addition, to ensure good pressure communication with the actively deforming fault, after remediation we will run a casing deformation/cement bond log and then shoot a dense spread of perforations through the cemented casing and into the 3190 m fault.

The layout of the proposed SAFOD observatory is shown in Figure 3. Working up from the bottom, a bridge plug will be permanently installed inside the existing 6 in I.D. casing to hydraulically isolate the fault zone from the rest of the wellbore. A 4 in, internally flush (EUE) tubing string with stand-offs (for coupling to the casing) and a closed bottom will be lowered into the well and “stabbed in” to the bridge plug. Two separate quartz pressure transducers (for redundancy) will be attached to the bottom of this tubing string and control lines for the pressure transducers will be attached to the outside of the EUE tubing. The inside of the EUE tubing will then be filled with a non-conducting environmentally benign oil. The seismic tools (geophones and accelerometers) and tiltmeters will be connected together using rigid interconnects and the entire system will be lowered into the well on a electrical/optical wireline using the winch already at the SAFOD site. Once the instruments are at the desired depth, the screw-driven locking arms will be deployed to couple the instruments to the tubing.

The proposed seismic layout contains 12 Oyo Geospace DS250 digital seismometers arranged to make an array with 9 levels. Each DS250 has a motor-driven locking arm that provides the coupling force between the instrument and the tubing. Half of the seismometers are equipped with standard Oyo Geospace digital grade 15 Hz geophones that come installed in the DS250 instrument. We will replace the geophones in every other instrument with Colybris MEMS accelerometers. Both sensors have been deployed successfully in SAFOD. The top, 6th and 9th elements of the array will contain both geophones and MEMS accelerometers, with a Pinnacle high-temperature borehole tiltmeter inserted between them. The construction team successfully deployed this tiltmeter between a pair of DS250 seismometers multiple times at SAFOD. This configuration of intermixed Oyo Geospace DS250 seismometers and Pinnacle Tiltmeters with rigid interconnects between levels and a wireline at the top is standard operating procedure for Pinnacle Technologies field operations.

As part of the refurbishment we propose to increase the number of seismic levels from 3 to 9 to address the valid concerns about array aperture and sensor coverage expressed by the EarthScope Management Team in the 2007 annual review of SAFOD. If desired, in the future it would be possible to expand the array to include up to 24 seismometers and 7 tiltmeters.

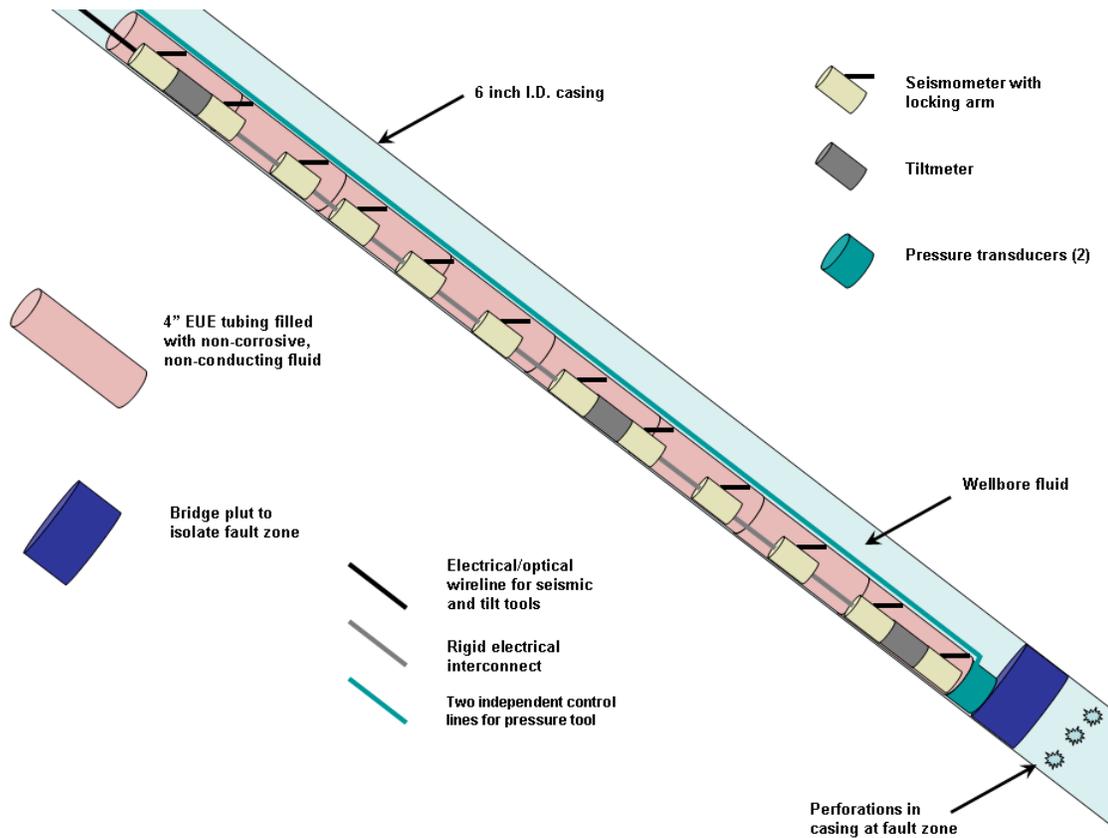


Figure 3. Layout of new SAFOD observatory (see text for details).

The performance of the instruments is illustrated by recordings obtained with the now inoperable array of an M 1.3 microearthquake located approximately 4 km from the instruments (Figure 4). This example shows clear evidence of fault zone guided waves on the sensors located just outside the 3190 m fault (Pod 5, also see Figure 5). These waves are smaller at Pod 3 and almost absent at Pod 1. The waves are very sensitive to the geometry and velocity contrast within and adjacent to the fault and its associate damage zone, and can be used to study the internal structure of the fault over distances of several kilometers from the instruments. Earthquakes of similar size occur daily near SAFOD. Much smaller earthquakes are also routinely detected at SAFOD, and events as small as M -3.5 have been detected using the off-the-shelf DS250 instruments in the past. Hence, the array will provide a very extensive and rich data set for analysis by the seismological community.

The bottom three traces in Figure 4 show the response of the large EM coil to the earthquake. The response appears to be entirely driven by the movement of the instrument in the Earth's magnetic field caused by the passage of the seismic waves. In this example, we do not see any evidence of EM radiation from the source (it would arrive well before the seismic waves), but additional observations are needed. This

instrument was deployed at SAFOD as part of a NASA-funded investigation. It will be possible to incorporate an EM coil in the proposed design, if additional funding is available from NASA and if this addition is approved through the EarthScope Change Control process. It will also be possible to include other add-on science projects to the system, as was done when the array was deployed in September 2008. For example, the LBL accelerometer that was attached to the outside of the EUE tubing and deployed at approximately 1 km depth as part of Carnegie's crosshole seismic monitoring experiment could be re-deployed when the new instruments are installed.

September 30, 2008 04:15:51 M 1.3

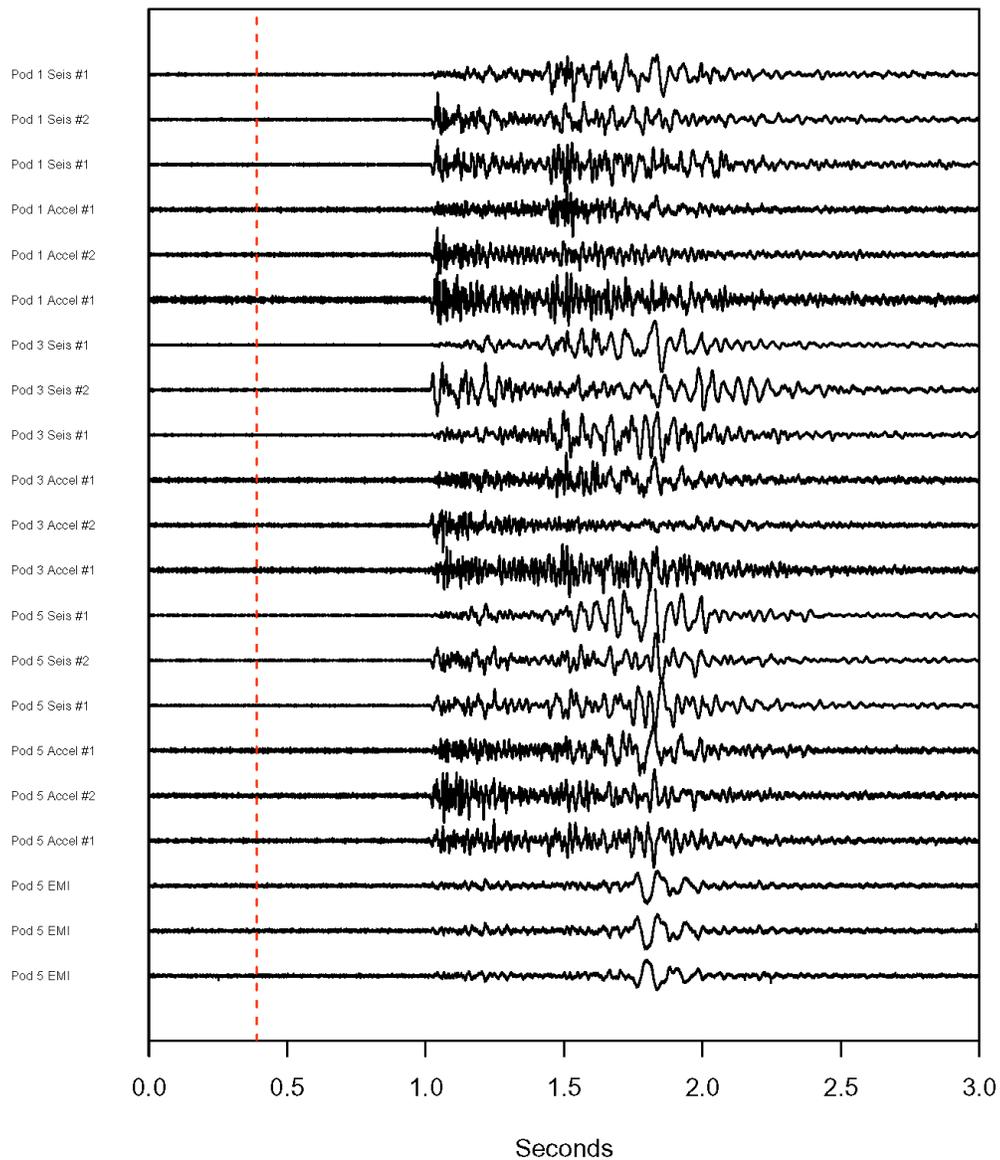


Figure 4. Microearthquake recorded on the SAFOD observatory seismic and EM sensors. Origin time of the earthquake marked by red dashed line.

Finally, there is one aspect of the new design that has major implications for the operation of the array in the O&M phase of the EarthScope project. According to the new plan outlined above, the entire seismic/tilt system could be deployed and removed by UNAVCO and USGS personnel with modest assistance from Pinnacle Technologies. In contrast, a drill rig and large crew is required to remove or reinstall the instruments currently in SAFOD. If the proposed observatory is implemented as proposed, then it will be possible to readily operate it within the existing operations and maintenance budget for SAFOD.

PROJECT PLAN

The project is divided into 4 steps: 1) Removal of the inoperable observatory instrumentation; 2) Well remediation and installation of pressure sensors; 3) Fabrication and testing of the new equipment; and 4) Redeployment of the SAFOD observatory.

Step 1. Removal of the inoperable observatory instrumentation. This will require the use of a drill rig to pull the tubing now in SAFOD, spooling units to recover the control lines, and an industry crew experienced with recovery of borehole instrumentation. After the inoperable observatory instrumentation has been removed from the well, we will re-deploy a seismometer on wireline in the cased hole to maintain continuity of recording. The recovered observatory instruments will undergo a careful examination in the field to determine the points of failure and performance of all components. They will be opened in the lab to salvage as much hardware as possible.

We recommend that Step 1 occur as soon as practical. The weather window for working at SAFOD normally closes in late November and does not open again until late March.

Step 2. Well remediation and installation of pressure sensors. At the conclusion of the Phase 3 drilling in 2007, the bottom 30 m of the well was left in poor condition with cement cuttings in the hole. We will clean out the well so that pressure monitoring of the fault zone can be implemented as originally planned. This operation will be performed following standard industry procedures using a mud motor on coiled-tubing with a self-contained pumping and mud-control/shale-shaker system. Following cleanout, we will run cased-hole logs to examine the condition of the casing and cement and look for signs of casing deformation at the 3190 m fault and then perforate the casing to ensure hydraulic communication with the active fault. We will then deploy a bridge plug with a “stab-in” hydraulic connector just above the perforations to hydraulically isolate the fault zone (Figure 3). After the bridge plug is installed and tested, we will run a 4-inch tubing string in the hole with an integral hydraulic connector on bottom to mate with the bridge plug. The tubing string will be sealed and filled with a non-corrosive, non-conductive, environmentally benign fluid such as soy oil. The bottom of the tubing string will contain two redundant pressure gauges, enabling pressure monitoring directly within the San Andreas Fault Zone. Two separate control lines for the pressure gauges will be attached to the outside of the 4-inch tubing and protected with Canon clamps.

Step 3. Fabrication and testing of the new equipment. The instrumentation is based on commercially available equipment routinely used in the petroleum industry, as described above. These seismic and tilt instrument modules are the same ones used in SAFOD during instrument developments in 2005 - 2007. The instruments will be deployed on wireline inside the 4-inch tubing installed in Step 2. By placing the instruments in a non-corrosive and non-conducting fluid they will be isolated from the gas-saturated borehole fluids that have proven to be so difficult to overcome during past SAFOD installations.

Step 4. Redeployment of the SAFOD Observatory. The seismic and tilt observatory will be installed inside the 4-inch tubing on wireline using the winch already at SAFOD (Figure 3). A major advantage of this new system is that a drill rig is not needed for array installation or removal. Thus, the observatory can be readily retrieved and redeployed at a later date using a crane, which is typically a 1 day operation. This will allow us to service the instruments as needed and add additional components or instruments to the array, when approved through the EarthScope Change Control Process.

The observatory will be deployed in the cased hole left at the conclusion of Phase III drilling (Figure 5). The bridge plug (Step 3) will be deployed just above the 3190 m fault zone and will provide hydraulic isolation of the fault and damage zone for pressure monitoring. The deepest seismic and tilt instrumentation will be installed as close as is practical to the 3190 m fault to facilitate observation of fault zone guided waves. The rest of the seismic and tilt instruments would extend uphole from this location, crossing the Salinian Terrain boundary, to form a total aperture of approximately 200 m.

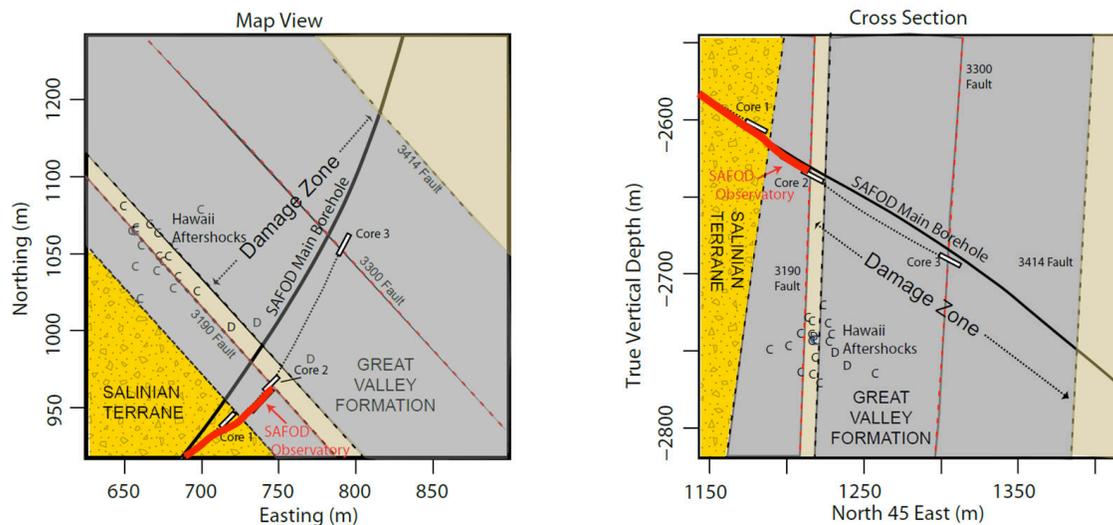


Figure 5. Map view (left) and cross-section (right) of the trajectory of the SAFOD main borehole, the generalized geology, the locations of the major faults (and damage zone) and the locations of the cores obtained in multi-lateral sidetracks. Note that the location of aftershocks of one of the Hawaii target earthquakes (shown by symbols C and D) correlates with the 3190 m shear zone. The position at which the SAFOD observatory is deployed is adjacent to the 3190 m shear zone, about 100m above Hawaii events.

BUDGET

See excel spreadsheet

Timeline of SAFOD Observatory Installation and Operation

Notes compiled by Steve Hickman, Ralf Krug and Bill Ellsworth (11/30/2010)

2008/09/23: Installation begins with pod 5 entering the hole. With pod 3 hanging in derrick, problem (a short) encountered with splice between pods 3 and 5. Problem due to pinched wire in splice housing, so splice had to be redone. Problem also discovered in splice between pods 2 and 4, which was then repaired (resulting in two splices).

2008/09/25: Pod 1 enters the hole. Tiltmeters are now continuously recording during installation.

2008/09/26: Seismic tools recorded overnight.

15:10 last data point recorded from bottom tiltmeter. Tests indicate that it must have shorted out (current spike when switch in top tiltmeter is closed) A flooded splice between top and bottom tiltmeter is suspected source of failure.

Top tiltmeter continued to record data

2008/09/27: Seismic tools recorded overnight.

2008/09/29: Installation is complete, 7 seismic and 1 tiltmeter tools are recording data.

5:1	-	6010	6010	0	1868	0	0	0	0	0
5:2	-	6122	6122	0	1868	0	0	0	0	0
5:3	-	10542	10542	0	1868	0	0	0	0	0
5:4	-	10576	10576	0	1868	0	0	0	0	0
5:5	-	8233	8233	0	1868	0	0	0	0	0
5:6	-	6118	6118	0	1868	0	0	0	0	0
5:7	-	10622	10622	0	1868	0	0	0	0	0



GeoRes-2.7.4.10 - [D5150 Demo 1 Line Project: Real-time display]

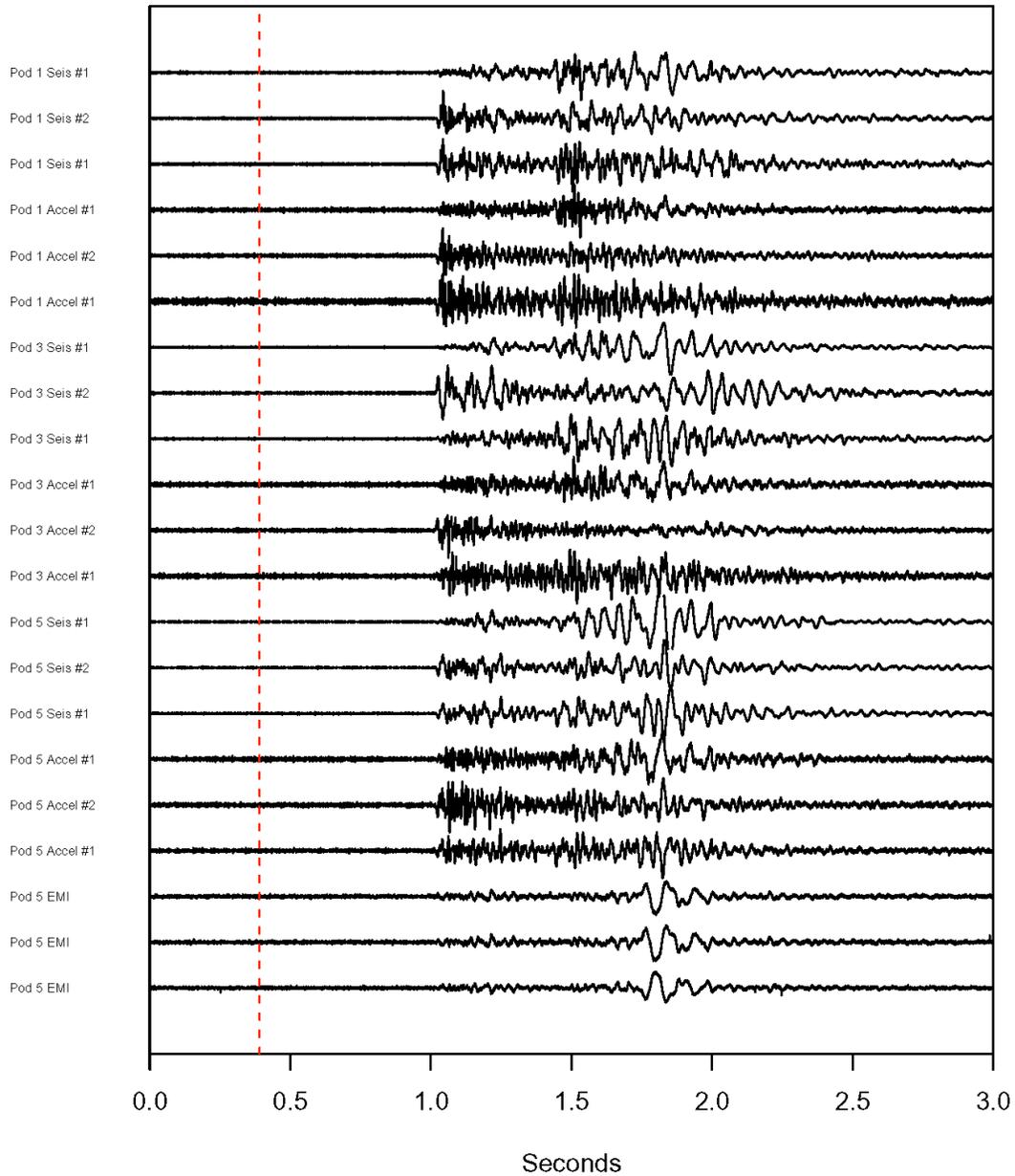
File Settings Operation Test View Window Help

GP NP 0

adF...	BadS...	XmitE...	Current	Core Volt	+3.3V	+5V	-5V	Vcxo Volt	Ground	Humidity	Module Temp
0	0	0	0.211	-	3.276	5.090	-	1.114	-	21.363	123.544
0	0	0	0.087	-	3.277	5.085	-	1.361	-	27.255	117.918
0	0	0	0.248	-	3.303	4.989	-	1.978	-	0.000	120.853
0	0	0	0.083	-	3.307	5.024	-	2.317	-	0.000	125.134
0	0	0	0.075	-	3.335	5.012	-	2.440	-	0.000	119.997
0	0	0	0.221	-	3.266	5.100	-	1.265	-	14.189	121.587
0	0	0	0.247	-	3.309	5.005	-	2.793	-	0.000	121.465

Surface Status Test Results Test Settings

September 30, 2008 04:15:51 M 1.3



2008/10/01: GeoRes configuration error fixed (we were losing a fraction of a second of data in each 10 s buffer due to the mistake).

2008/10/02: 1 Hz high-pass filter added to seismic data stream to fix drift problem with digitizer output. This resulted in a significant improvement in data quality.

Module	SerialNo	SYNC Err	MissBlkCnt	Current	+3.3V	+5V	Vcxo Volt	Humidity	Module Temp
5:1	6010	-	-	0.218	3.276	5.090	1.249	21.805	123.544

5:2	6122	-	-	0.080	3.277	5.085	1.438	27.758	117.918
5:3	10542	-	-	0.237	3.303	4.992	2.032	0.000	121.098
5:4	10576	-	-	0.070	3.305	5.023	2.367	0.000	125.256
5:5	8233	-	-	0.060	3.334	5.010	2.586	0.000	120.119
5:6	6118	-	-	0.207	3.266	5.100	1.364	14.341	121.587
5:7	10622	-	-	0.233	3.309	5.005	2.857	0.000	121.465

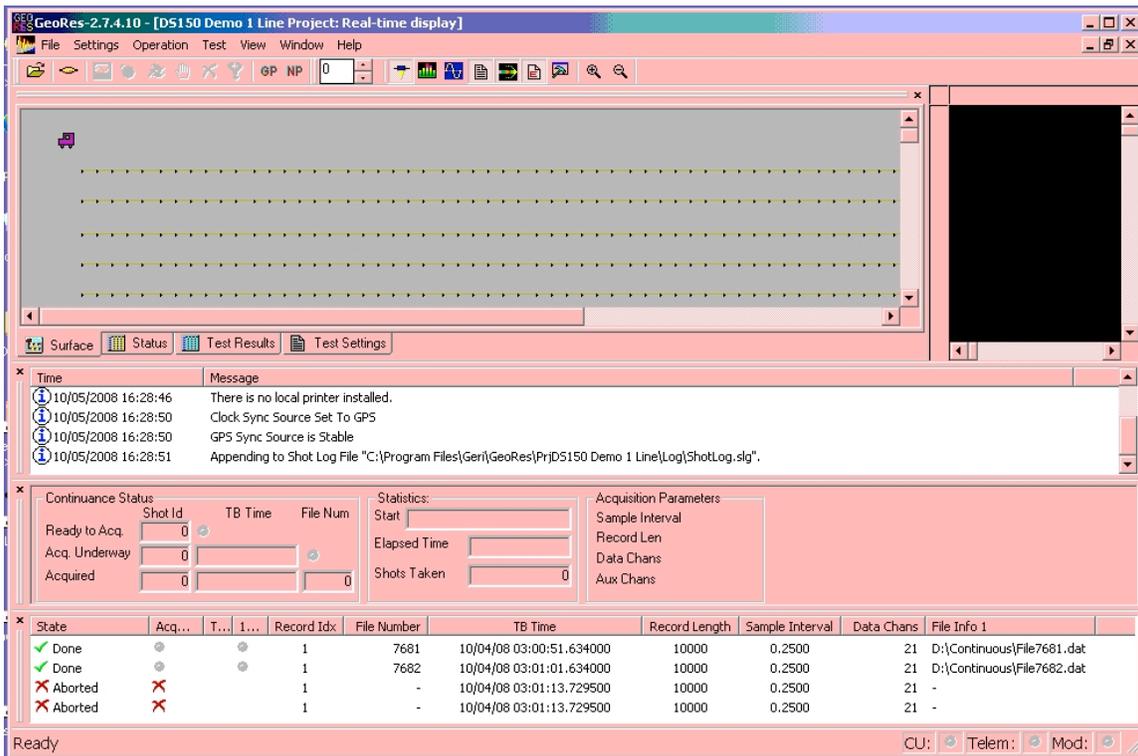
2008/10/03: Seismic data starts to show data spikes (with a strong diurnal signature) and an increase in "module status errors" reported by the GeoRes. The Sorensen power supply of the seismic instruments generates a lot of noise on the tilt lines.

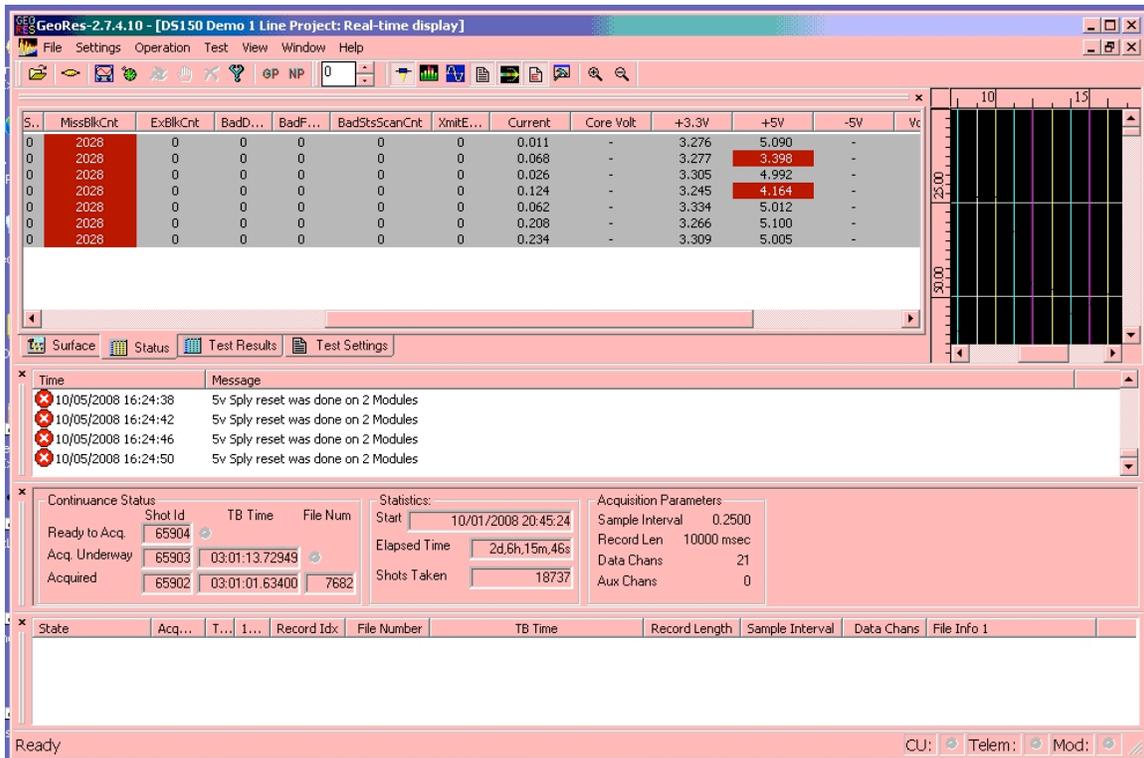
Two possible solutions:

- a) Use a Xantrex power supply (e.g. the one from the pilot hole tiltmeter which is currently unused).
- b) Attempt to isolate the tiltmeter from ground (we currently have a ground loop).

Module	SerialNo	SYNC Err	MissBlkCnt	Current	+3.3V	+5V	Vcxo Volt	Humidity	Module Temp
5:1	6010		0	0.218	3.276	5.090	1.249	21.878	123.544
5:2	6122		6	0.080	3.277	5.085	1.439	27.901	118.040
5:3	10542	x	9	0.238	3.304	4.992	2.031	0.000	121.098
5:4	10576		2029	0.124	3.245	4.164	2.298	0.000	125.012
5:5	8233		2029	0.062	3.334	5.012	2.594	0.000	120.119
5:6	6118		2029	0.208	3.266	5.100	1.367	14.341	121.587
5:7	10622		2029	0.234	3.309	5.005	2.857	0.000	121.587

2008/10/04: GeoRes and seismic tools powered down.



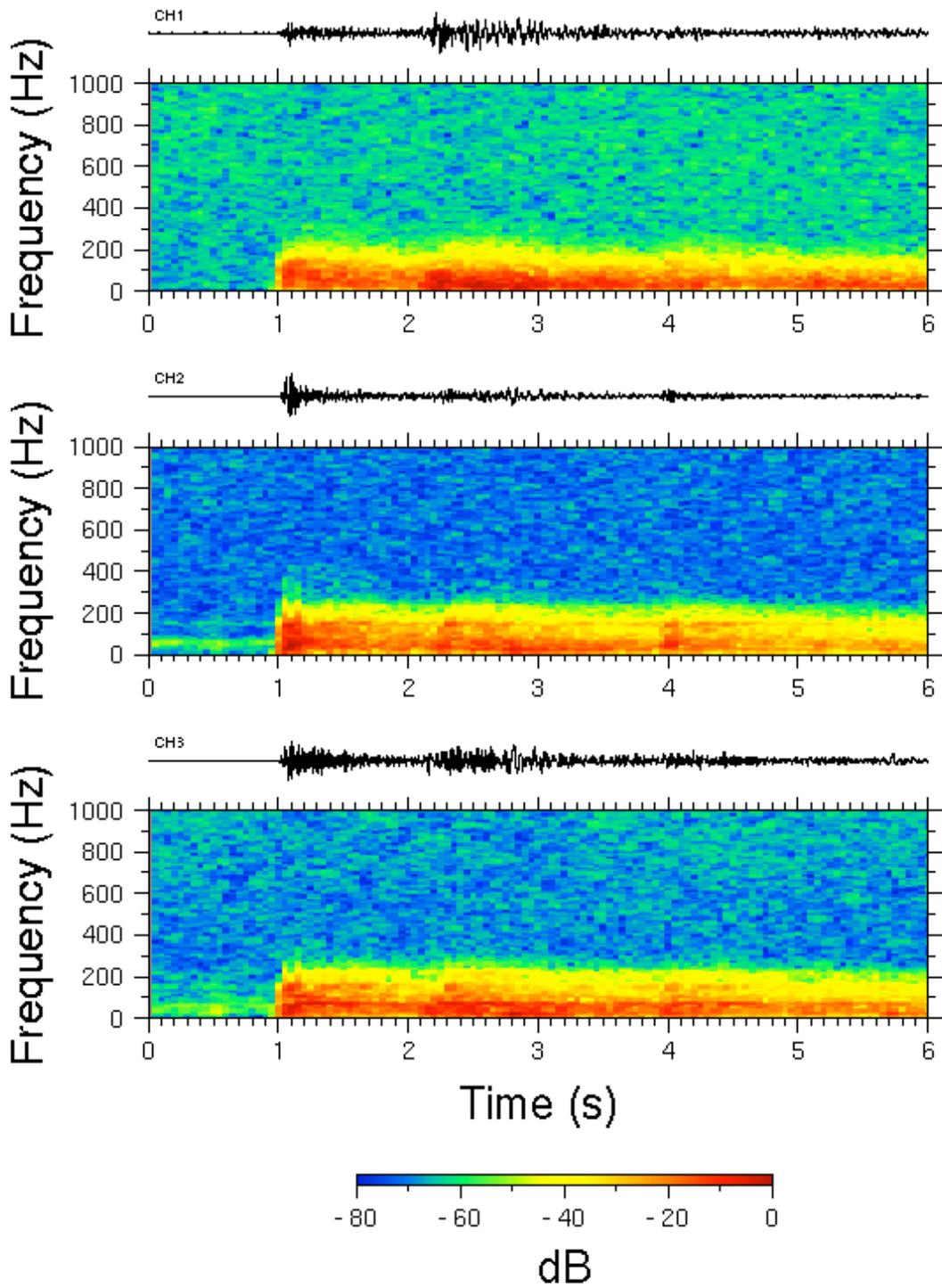


2008/10/09: Xantrex power supply replaces Sorensen power supply. Unable to wake-up bottom 3 DS150s despite repeated attempts. Began recording again with the top 4 DS150s. With the Xantrex was supplying 0.67 A at 198 V., the reserve current values on the 4 tools were 0.270, 0.133, 0.294 and 0.124 mA. After 2 hours, however, only the top DS150 is sending data. Restarted with just the top tool awake with Xantrex supplying 0.59 A at 179 V which gives the top tool a reserve current at 0.184 A.

During the switch of the power supply to the seismic system, the top tiltmeter tool ran on uncontrolled power for several hours. Y accel fails and takes down analog section.

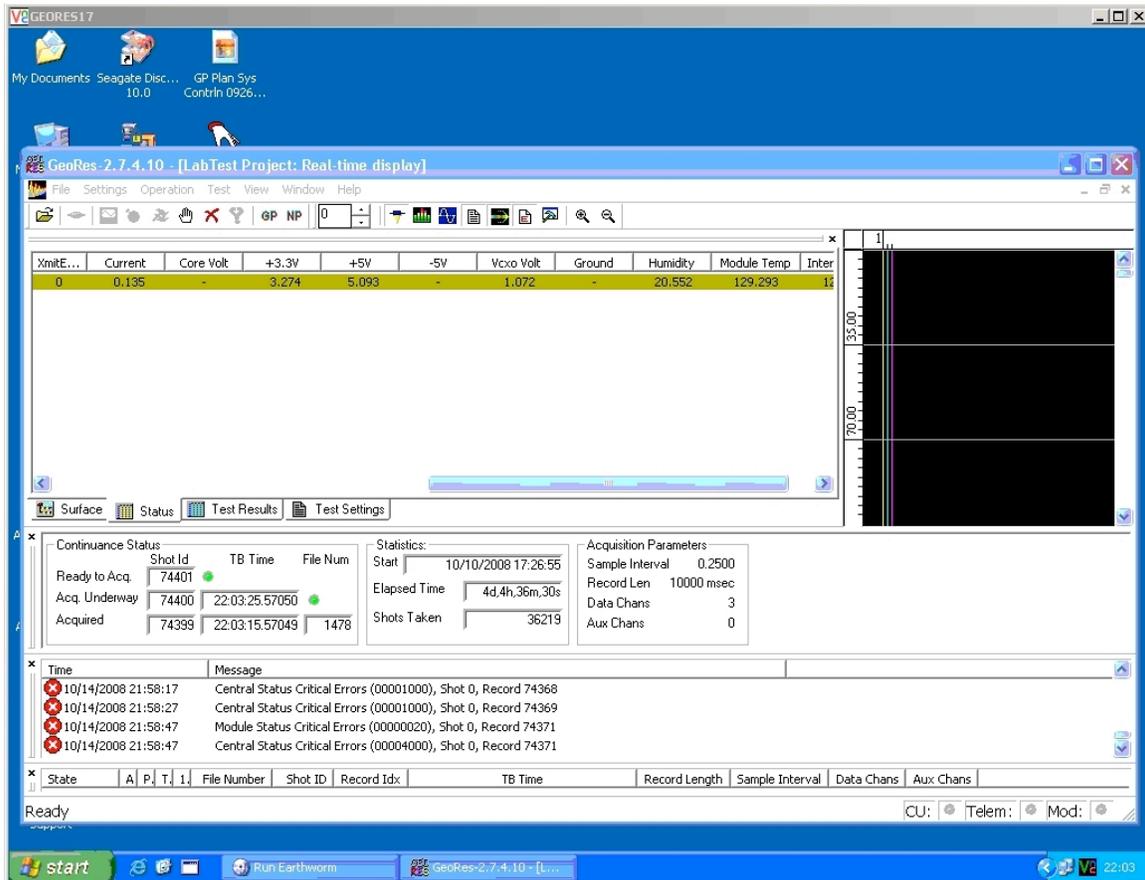
2008/10/10: Single remaining DS150 failed at 03:59:40 UTC with many "Module Status Critical Errors (00000020)". Power shut down for about 15 minutes and tool successfully restarted. Running again at 42 dB gain with very quiet data.

SAFOD MAIN HOLE 20081010-185255
TW= 0.1 TC= 0.05 FW = 10.0 NFFT = 512

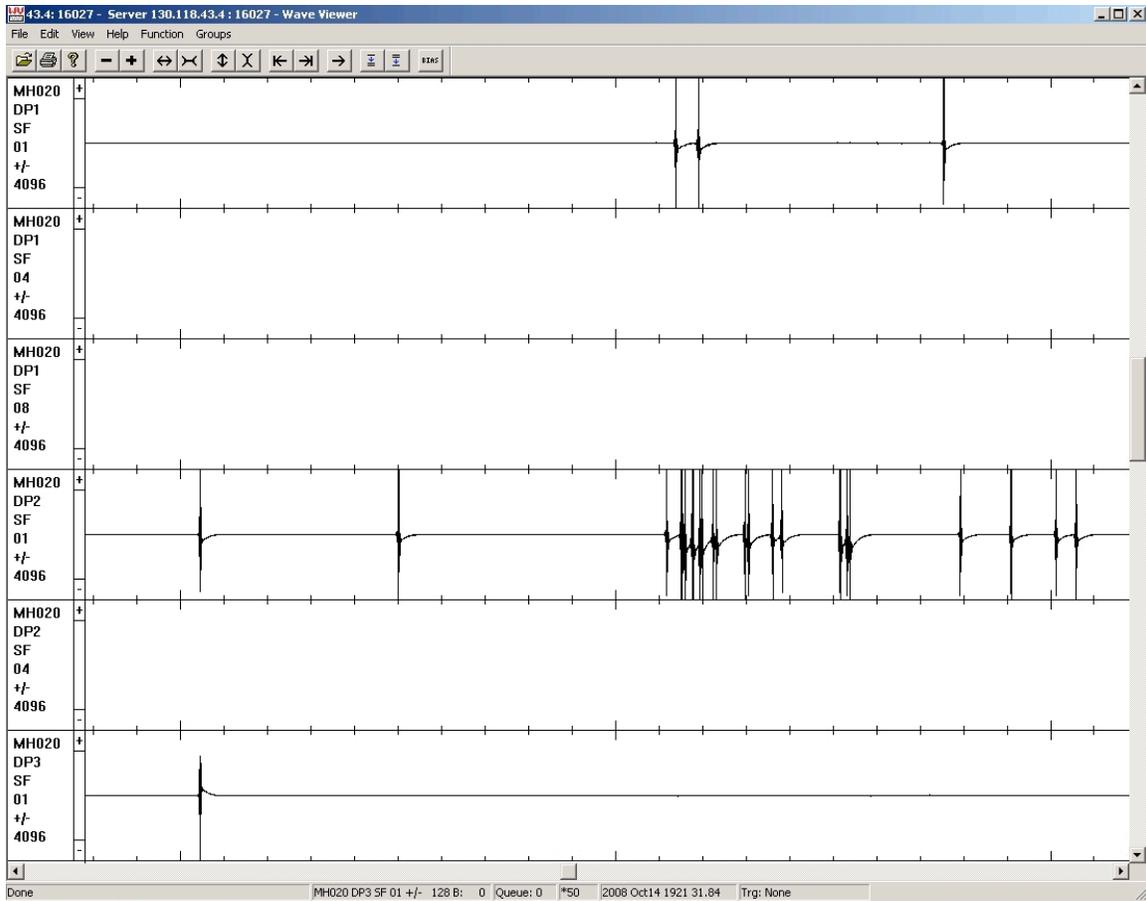


2008/10/13: Reserve current of the last running seismic tool decreases further and module temperature raises.

2008/10/14: After an error-free run of 4 days problems began to occur this afternoon with the lone remaining DS150. The screen shot shows some of the error messages as well as the tool's vital signs from midway into the troubles. Initially the only vital signs that was abnormal was a low reserve current of 0.135 mA, where it had been a steady 0.197 mA.



The errors started abruptly, and in the time domain appear as spikes in the data. The screen shot below shows the beginning of the problems. The data have been decimated from 4000/s to 250/s in this display.

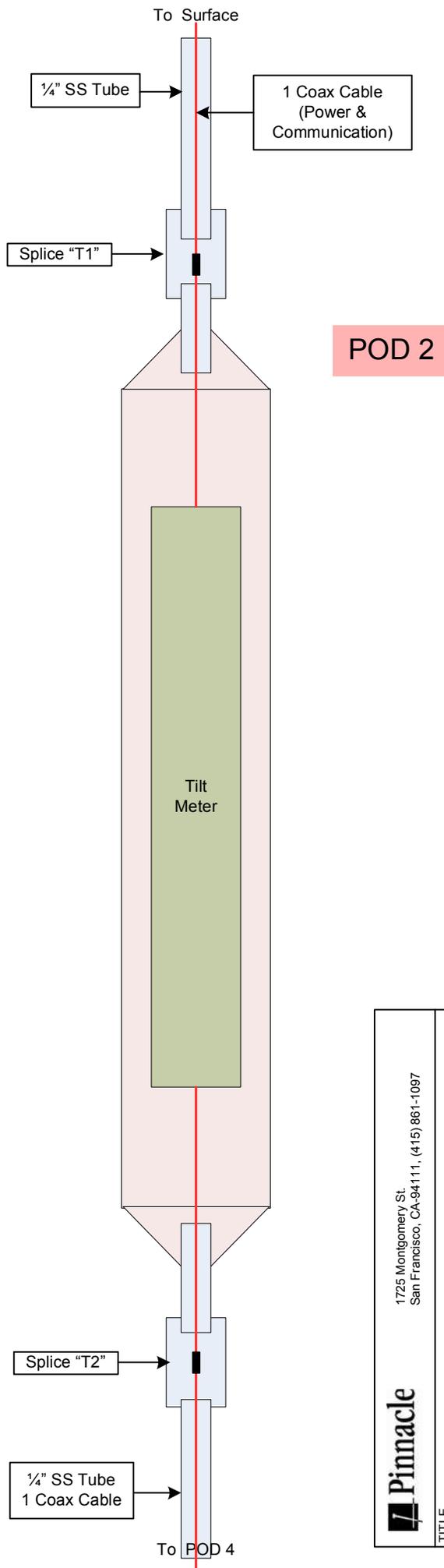
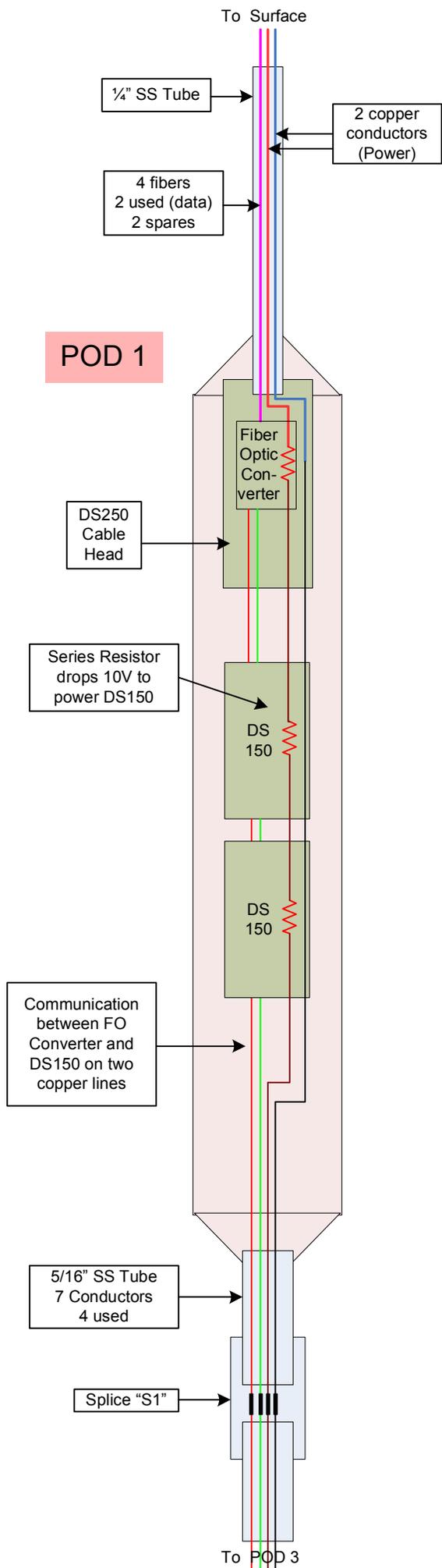


Things got much worse that this for a time and then went back to normal for about 2 hours, before the problems started again. Decision was made to halt acquisition and power down the tools as no useful data was flowing. When the plug was pulled the module temperature had climbed to 130.5 C. It was clearly overheating relative to its previous steady state temperature of 123 C.

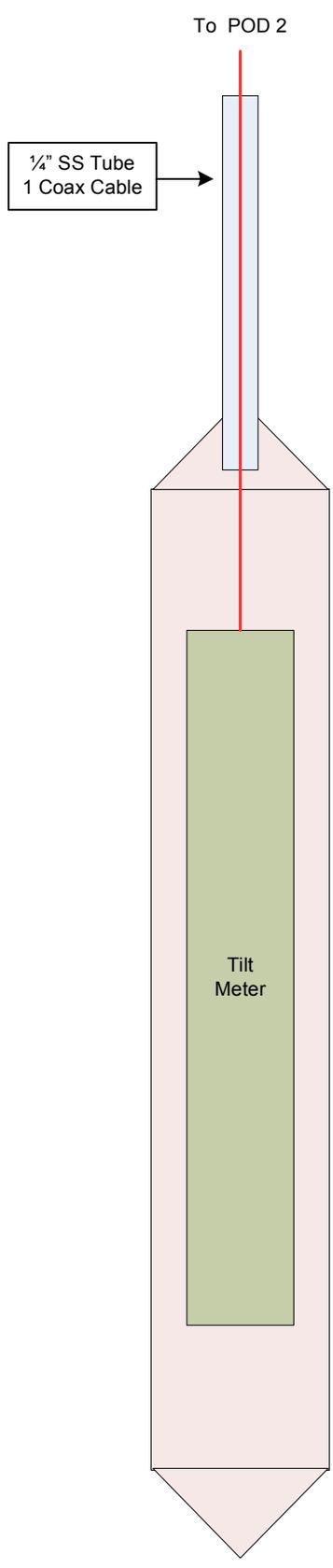
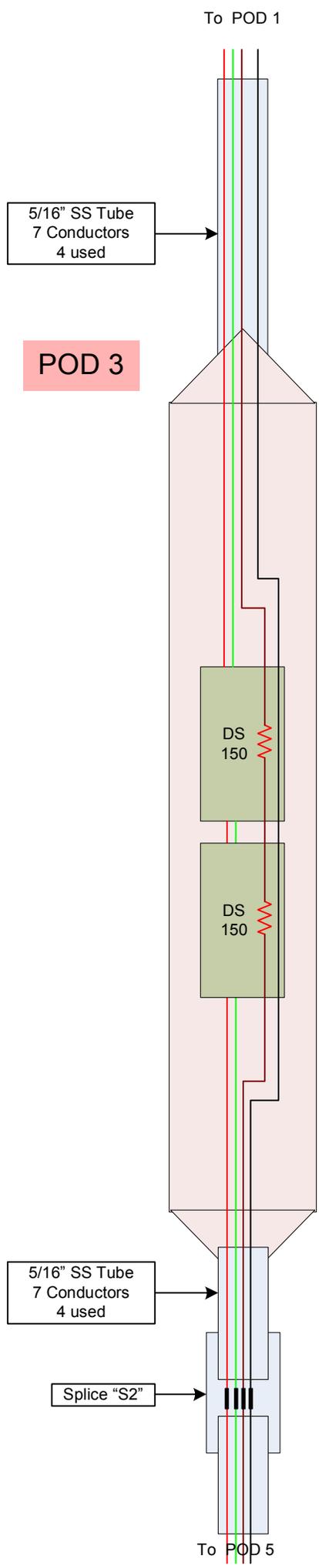
Many attempts were made in the following days to wake-up the tool, but all failed.

2008/10/18: Communication problems to top tiltmeter begin.

2008/10/24: Last communication to top tiltmeter. Tool current increased overtime until Xantrex current limit was hit. (flooded splice above top tiltmeter?).

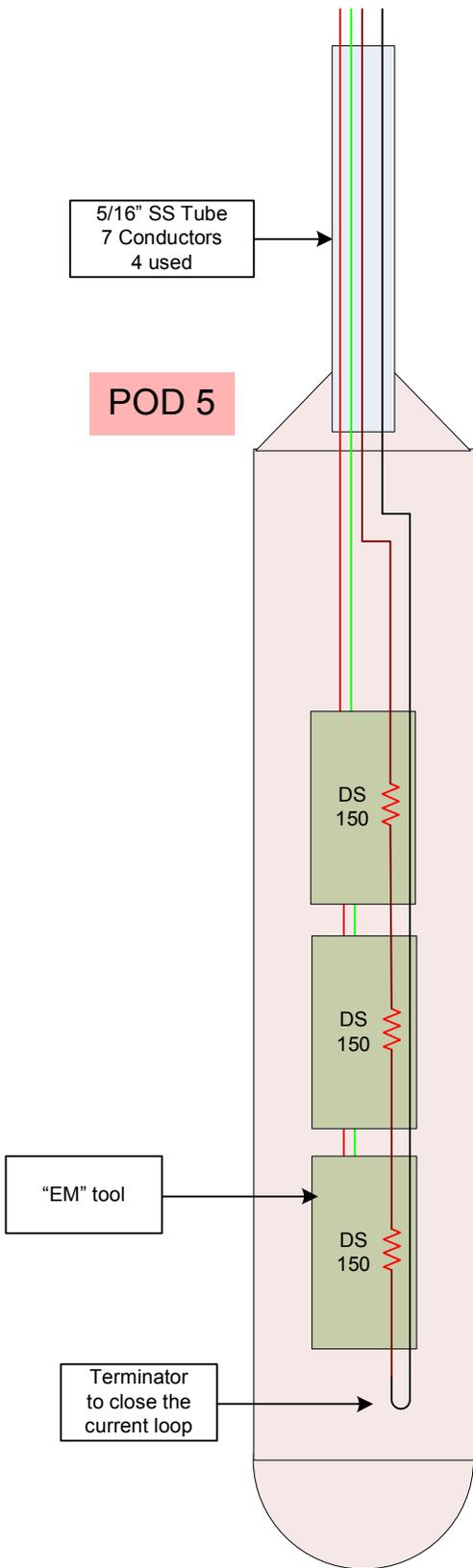


Pinnacle		1725 Montgomery St. San Francisco, CA-94111, (415) 861-1097	
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SCALE: N/A	DESCRIPTION: Block Diagram SAFOD PODs	REVISION: 1.0	
DRAWN BY: Ralf Krug	DATE: 10/12/2010	REVISED: 4/17/2009	PAGE: 1 OF 3
Filepath: c:\my documents\safod\2008\drawings\			



		1725 Montgomery St. San Francisco, CA 94111, (415) 861-1097	
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DRAWN BY Ralf Krug	DATE 10/12/2010	REVISED 4/17/2009	PAGE 2 OF 3
Filepath: c:\my documents\safod\2008\drawings\			

To POD 3



5/16" SS Tube
7 Conductors
4 used

POD 5

"EM" tool

Terminator
to close the
current loop

DS
150

DS
150

DS
150

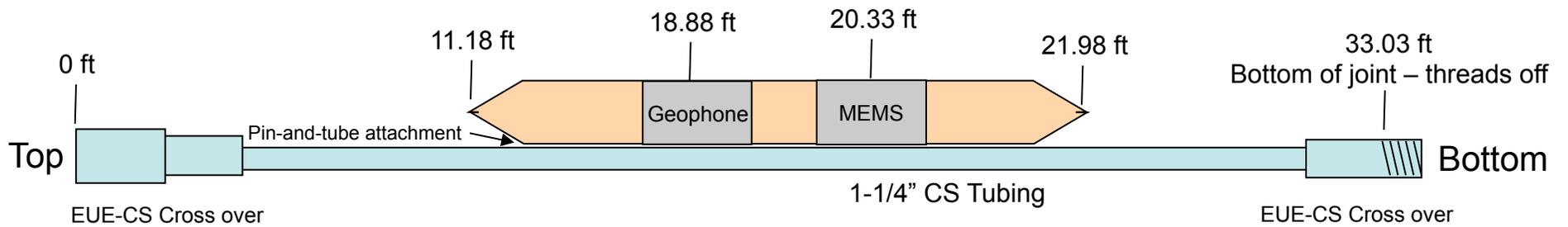
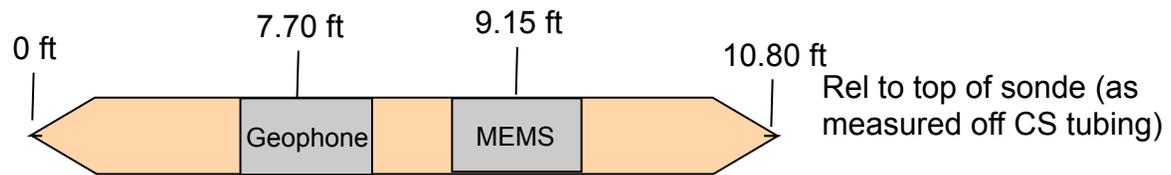
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DRAWN BY: Ralf Krug	DATE: 10/12/2010
REVISION: 1.0	REVISED: 4/17/2009
	PAGE: 3 OF 3
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SAFOD Monitoring Installation

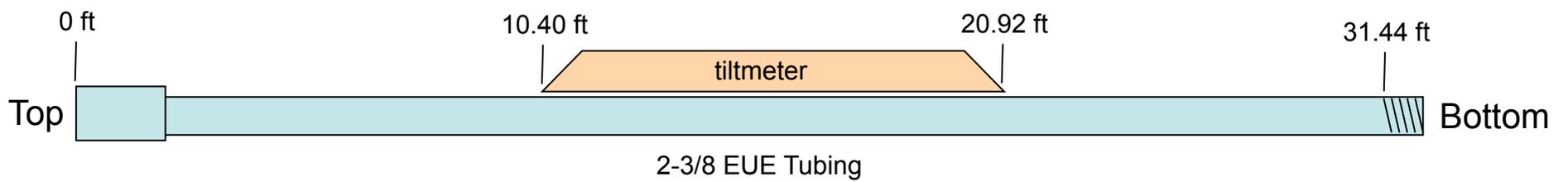
Sept 2008

Pod locations and sensor
positions

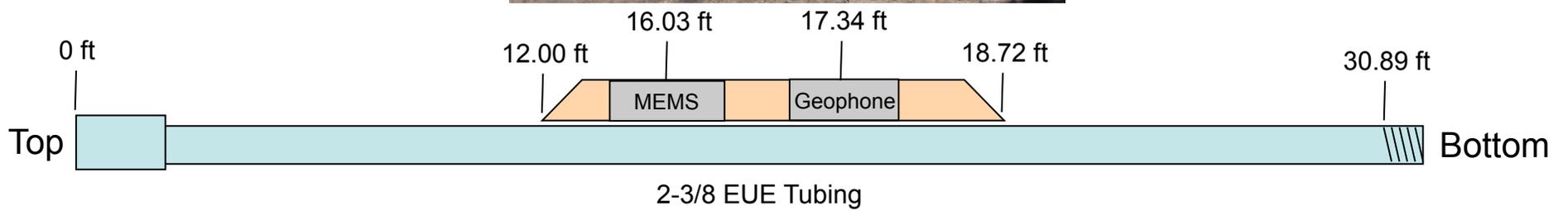
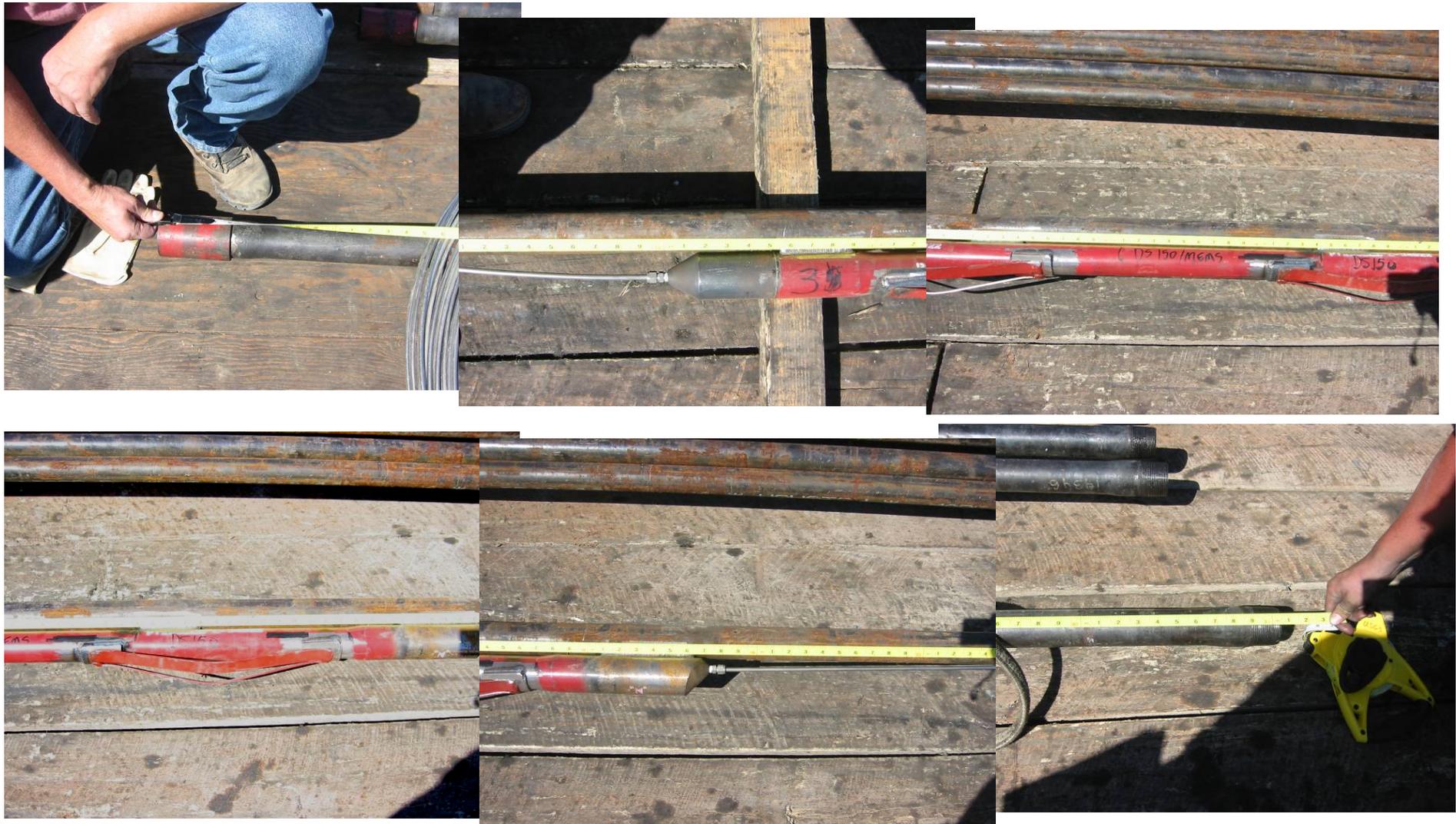
SAFOD Pod 1: Length and sensor location



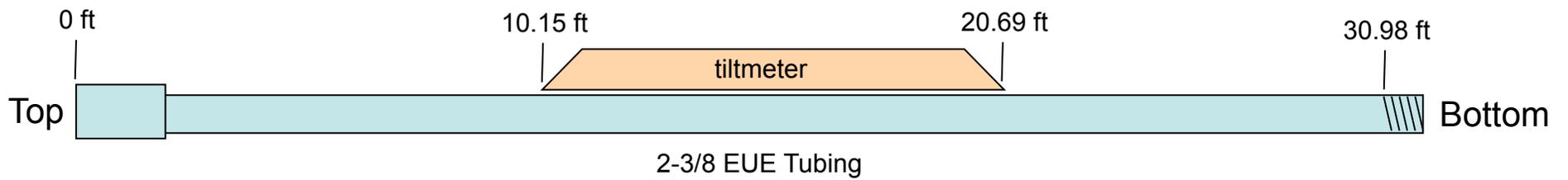
SAFOD Pod 2: Length and sensor location



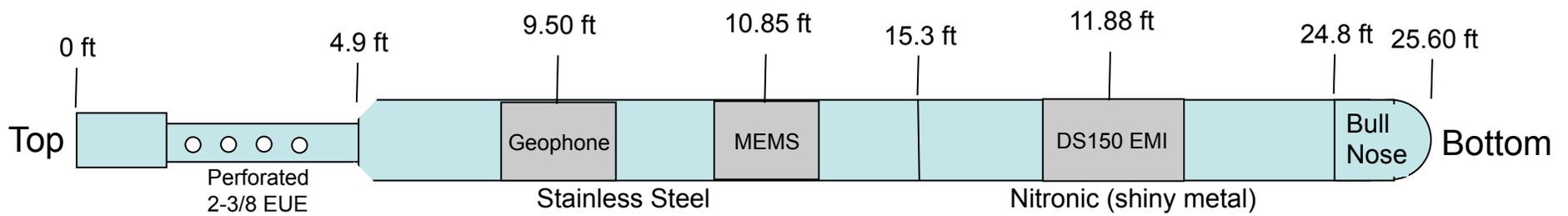
SAFOD Pod 3: Length and sensor location

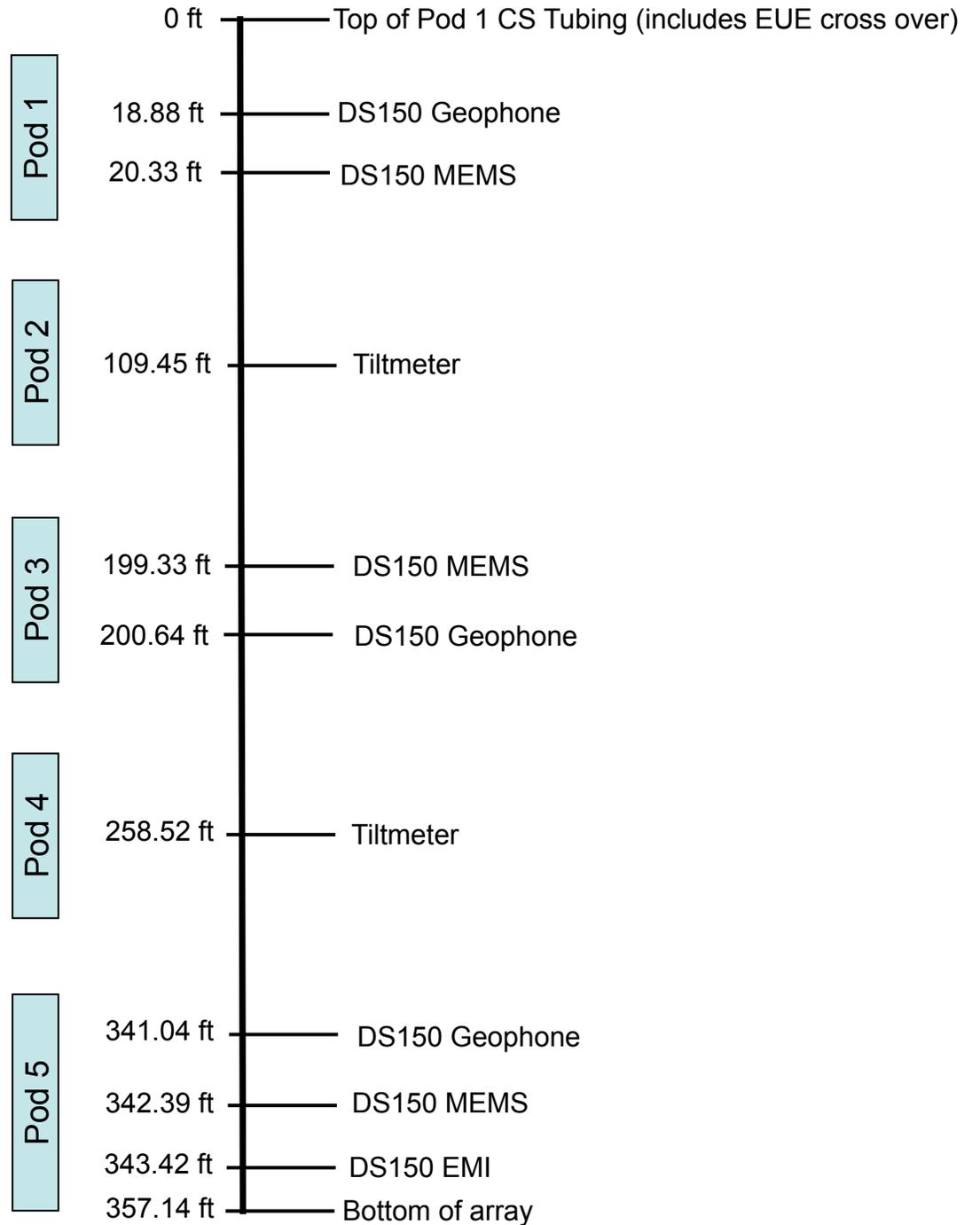
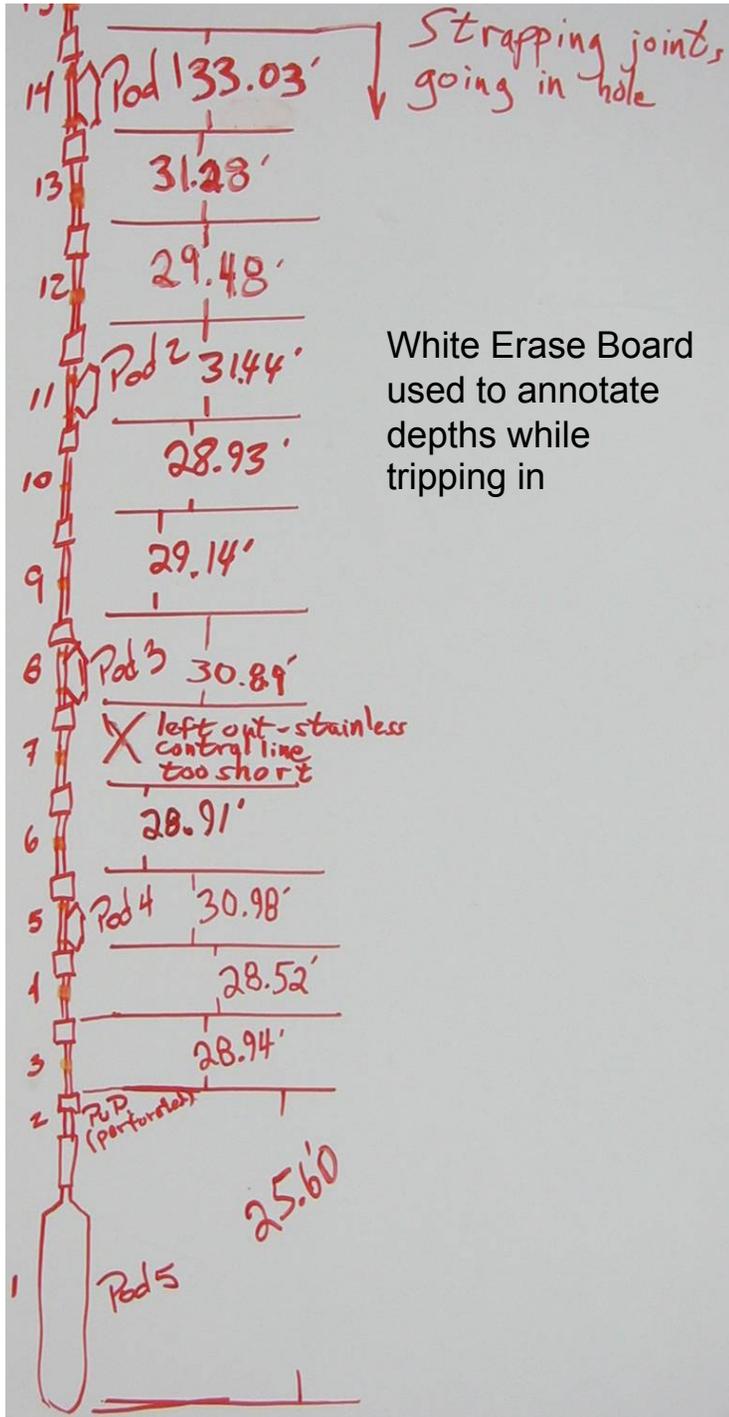


SAFOD Pod 4: Length and sensor location



SAFOD Pod 5: Length and sensor location





Risk Assessment: Using wireline tools in the open-cased hole at SAFOD

As a result of discussions with engineers at OYO Geospace beginning November 2009, PBO has assumed that wireline instruments can be reliably deployed in wells with SAFOD-like temperatures and depths for time periods of months to years. OYO Geospace manufactures the wireline (Fig. 2) and wireline instruments proposed in the SAFOD restoration proposal. It is a fact that specialized instruments containing no o-rings and with isolated tube encapsulated conductors and fiber (Fig. 1) have been successfully installed in deep wells for more than twenty years in similar harsh conditions.

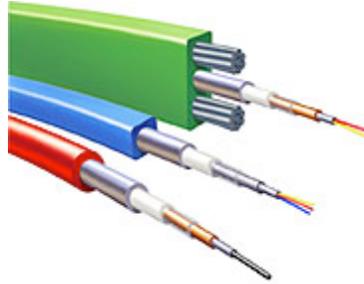


Fig. 1: Tube encapsulated conductors and fiber for permanent installation

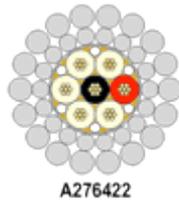


Fig. 2: Retrievable wireline

However, recent discussions with the engineers at Pinnacle that installed the original SAFOD temporary instruments highlight some unique factors that increase the risk of using wireline tools in the SAFOD well. Wireline tools of very similar nature to those proposed in this change order were temporarily installed in the SAFOD well “six to ten” times during construction of the well in an attempt to record seismic data during the SAFOD well construction phase. All these temporary installations failed. None of the instruments lasted longer than six weeks, failing on average in two to three weeks. Each subsequent installation was engineered with the previous failure mechanism factored in. Attempted remediation included the use of several kinds of o-rings and isolating the entire cable-head with epoxy. Wireline tools recovered to the surface were over-pressurized, indicating that they had been exposed to downhole well conditions. Corrosion of the copper conductors in the wireline at the cable-head was evident.

The issue with the SAFOD well is the presence of gas. Pinnacle owns and operates many 15-tool-arrays of microseismic instruments and have been running these instruments since 2001. When these instruments are deployed in cased wells, any gas leaks in the borehole are sealed with the use of packers, plugs or cement, if the instruments have to stay in place for extended period of times (few months).

Elastomers used for sealing and insulation are permeable to gas over time. As the temperature and the pressure are elevated, gas will migrate through the elastomer faster. Based on this principle, gas migrated inside the tools over time, elevating the internal tool pressure. This same principle is true for the conductors on the wireline. Over time, the gasses migrated through the electrical insulating material of the conductors, corroding the copper ultimately causing failure.

The SAFOD borehole crosses an active fault line. Several attempts have been made to seal off the gas entry with cement assuming it was coming from the very bottom near the fault. All attempts proved unsuccessful. Tests in the past were never able to identify the gas entry point. Sealing off the gas entry point also presented some conflicts with the scientific interests, specifically monitoring the borehole fluid pressure. Sealing off the bottom of the wellbore, above the fault line, while helping increase the survivability of the seismic instruments would eliminate the chance of monitoring borehole pressure.

Pinnacle engineers believe most probable failure mechanism was intrusion of gas/fluids into the wireline itself. The SAFOD well is atypical from other geophysical boreholes in that there is gas entering the well. **Pinnacle believes that any temporary installation of wireline tools that are not isolated from the SAFOD fluids will fail within weeks.**

The current proposed restoration of SAFOD, isolating the entire array with larger diameter EUE tubing, was originally proposed in response to these experiences. This placed the SAFOD community in a position of balancing survivability against what was considered insufficient coupling of the EUE tubing to the casing. With the failure of the observatory, this risk should be re-visited.

FAILURE ANALYSIS

POD 1 SEISMIC

Longest lasting of the seismic pods. No clear reason for failure.

POD 2 TILTMETER

Pod2 was the longest-lasting instrument, survived about 2 weeks. Instrument failed over time with increasing current levels - Jamie says this is not unusual in downhole instruments, often caused by wellbore fluid that gradually decreases the resistance as the amount of fluid increases. Pod2 had oily residue on the electronics board, fluid in lower cablehead, but no fluid in the upper cablehead. Also had highest pressure of all Pods once opened. Possible failure due to leak that eventually hit the cablehead? (NOTE: This seems unlikely after conversation with Ralf Krug.) Alternate idea -- this could be a failure of the electronics: capacitors were damaged, so when they applied voltage to communicate, this could have "killed" electronics downstream by hitting a current limit, then the tool is just out, and current draw goes down. Evidence for this: when first connection made before extraction, drawing high current (110 mA vs. max 75 mA); then within 5 minutes, dropped to ~20mA. (Seems more likely at this point.)

POD 3 SEISMIC

Fluid was found here - a slurry of water with some oil and other material, including clear gel-like substance. Threads on the upper endcap had a sticky substance, and Benoit analysis indicates less than ideal thread connection. Question - did fluid enter Pod3 separately from Pod5, through separate leak, or was it communicated via about 130-140' of tubing from Pod5, including a splice in between? Chemical analysis of Pod3 fluid indicates highest dissolved solid concentration of all samples, and chemical analysis indicates composition of fluid samples is most similar between splice S1 and seismic pod3.

POD 4 TILTMETER

Possible electrical short at connector at bottom of Pod2, inside the bottom bulkhead of tiltmeter tool, leading to the cable that runs between Pod2 and Pod4. Fluid leak at cable head under hydrostatic pressure? Potential leak point at the swagelock connector; Pod4 connector was cross-threaded at the Pod4 interconnect- non-pressure-bearing. Role of the splices is not yet clear. Some fluid was noted when Pod4 cablehead was opened in Houston. (NOTE: Henfling now believes this could be an internal electronic fault, not leak or short at the bottom of Pod2.)

POD 5 SEISMIC

Top DS150 started showing spikes first, then the other two. This Pod had the most fluid, highly gas charged. Threads on the bottom bullnose "broke" at lower torque than expected: 2000-2400 ft-lbs, rather than ~3000. Upper connector was EUE joint that

should have been either something else or should have been welded. Questions: do the spikes reflect power supply problems? Or are they a symptom of downhole instrument problems, possibly related to heat or to fluid entry? Noted diurnal variation made USGS feel likely an uphole problem perhaps with power supply or GeoRes system. Henfling: do we know fluid got into the cablehead?



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Checked by	

TITLE:		SAFOD PROJECT: DS150 FAILURE ANALYSIS RESULTS		
PINNACLE DOCUMENT No.				
CONTENTS:				
A		Test Procedure		
B		Test Results		
SUMMARY		This procedure details the test results and observations for failure analysis of DS150 tools deployed at the SAFOD Observatory.		
A	1/10/2011		M. Hochmeister	
REV	Date	NOC	AUTHOR	APPROVED
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A. Test Procedure

This procedure outlines the activities performed in the Pinnacle test lab for failure analysis of the DS150 tools removed from the SAFOD observatory.

- **DS150-Interconnects**
 - Open up interconnects (swagelock to bulkhead)
 - Note condition
 - Oil?
 - Water?
 - Corrosion (wires or pins)
 - Gas or other smells
 - Photos
 - Remove O-rings and note their condition
 - Single photo showing all parts with appropriate labeling of which pod and which connector
 - Place O-ring in small plastic bags and label bags with Pod#
 - Clean and inspect O-ring grooves
 - Clean and reassemble w/o O-rings
 - Repeat for all interconnects

- **DS150s**
 - Open up
 - Remove O-rings and note their condition
 - Single photo showing all parts with appropriate labeling of which pod and which DS150, which connector
 - Place O-ring in small plastic bags and label bags with Pod#, and DS150#
 - Remove electronics and visually inspect all boards
 - Note condition
 - Oil?
 - Water?
 - Corrosion (wires or pins)
 - Gas or other smells
 - Photos
 - Condition of individual components (cracked capacitors, transformers, etc.)
 - Check resistances on four transformers (primary to secondary windings)



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- Any other tests that may seem appropriate
- Clean and reassemble w/o O-rings
- Repeat on all DS150s

- **DS250-to-150 converter**
 - Open both ends
 - Remove O-rings and note their condition
 - Single photo showing all parts with appropriate labeling of which pod and which DS150, which connector
 - Place O-ring in small plastic bags and label bags with Pod#
 - Note condition
 - Oil?
 - Water?
 - Corrosion (wires or pins)
 - Gas or other smells
 - Photos
 - Clean and inspect O-ring grooves
 - Clean and reassemble w/o O-rings

- **Fiber Optic Converter**
 - (Same as DS250-to-150 converter)



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B. Test Results

Pod 1



- DS250 Cablehead- Documentation taken by SAFOD.
- DS250 to DS150 Crossover-
 - Would wake up tools.
 - Crossover had pressure built up inside, had same smell.
 - No water intrusion, small amount of oil film on inside where o’rings seat.
 - Corrosion on all connector pins inside case.
 - O-rings had typical seating impression.
- DS150 SN: 6122-MEMS Tool
 - Woke with errors, fails test calibrations.
 - Tool had pressure built up inside, had same smell.
 - No water intrusion, small amount of oil film on inside of tool where o-rings seat.
 - Corrosion on all connector pins inside tool.
 - O-rings had typical seating impression.



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- Transformers checked ok.
- DS150 SN: 6010-Geophone Tool
 - No wake up.
 - Tool had pressure built up inside, had same smell.
 - No water intrusion, small amount of oil film on inside of tool where o-rings seat.
 - O-rings had typical seating impression.
 - Corrosion on all connector pins inside tool.
 - T2 75ohm primary to secondary.
 - T4 and T5 shorted primary to secondary.
 - C6, 16 cracked on power supply board.
 - R75 burned on power supply board.
 - C55 on analog to digital board cracked.
 - Interconnect- DC111 found inside has broken down. Same smell inside. O-rings have seated.

Pod 3

- Interconnect- Documentation taken by SAFOD.
- DS150 SN: 10542- Documentation taken by SAFOD.
- DS150 SN: 10576- Documentation taken by SAFOD.
- Interconnect- Documentation taken by SAFOD.



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Pod 5

- Interconnect
 - Same smell inside.
 - No DC111 found.
 - O-rings have seated.





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- **DS150 SN: 8223 MEMS**



- Tool woke with errors.
- Failed calibration tests.
- Tool had pressure built up inside, had same smell.
- No water intrusion, small amount of oil film on inside of tool where o-rings seat.
- O-rings had typical seating impression.
- Corrosion on all connector pins inside tool.
- C6, 16 cracked on power supply board.
- C55 on analog to digital board cracked.



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- DS150 SN: 6118 Geophone



- No wakeup.
- Tool had pressure built up inside, had same smell.
- No water intrusion, small amount of oil film on inside of tool where o-rings seat.
- O-rings had typical seating impression.
- Corrosion on all connector pins inside tool.
- T2 shorted primary to secondary.
- T4 6.2ohm primary to secondary.
- C6, 16 cracked on power supply board.
- C55, 56, 57 cracked on analog to digital board.
- C71 cracked on logic board.



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- DS150 SN: 10622 Induction tool



- No wakeup.
- Tool had pressure built up inside, had same smell.
- No water intrusion, small amount of oil film on inside of tool where o-rings seat.
- O-rings had typical seating impression.
- Corrosion on all connector pins inside tool.
- Connectors stuck together inside tool, breaking P1.
- T1 shorted primary to secondary.
- C6, 16, 30, 33 cracked on power supply board.
- C55, 56, 57 cracked on analog to digital.
- C47, 48, 71 cracked on logic board.



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Instruments

- Top tiltmeter: S/N 22050 (POD2)
- Bottom tiltmeter: S/N 22051 (POD4)

Both tiltmeters were opened in Houston in December 2010 to briefly check their state.

The top tiltmeter was partially flooded with oil. The seal of the bottom tiltmeter seemed have stayed intact – no signs of liquids were found. Both tiltmeters showed no signs that they have been exposed to excess pressure.

This document describes the findings of the detailed post mortem analysis done in San Francisco, in January 2011

Bottom tiltmeter (S/N 22051 - was in POD 4)

Visual inspection after opening the instrument

- Top roller bearing is dirty (IMG_0143)
- Trim-Pot on Modem Board is discolored (IMG_0143, 0144)
- Processor is discolored (IMG_0146)
- One wire connecting the big inductor to the PCB was off the solder pad E1 (IMG_0149). It is unclear if the wire came off the solder pad when the instrument was opened in Houston in Dec 2010. When the instrument failed during the deployment in fall 2008, the failure mode was a short. The ripped off wire would result in an “open”
- The RTV (DOW CORNING® 3145 RTV MIL-A-46146 ADHESIVE/SEALANT - CLEAR) - supposed to give the large and heavy components like inductors and capacitors extra mechanical support - was brittle, felt oily, slightly discolored (yellowish) and detached easily (e.g. IMG_0150)
- White, powdery residue on bottom end of analog board (IMG_0155, 0161)
- Y-accelerometer has black mark, capacitors next to it seemed to be damaged as well (IMG_0156)
- Electrolytic capacitors (on all PCBs) look heavily corroded at positive end (IMG_0158, 0159, 0160)

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- When disconnecting bottom bulkhead to remove o-rings, the (yellow) insulation of the terminal rings broke on the first touch (IMG_0164 and 0165; compare to IMG_0163)
- The threads of the end cap were still filled with proppant (IMG_0167), the inside of the bottom bulkhead (after removing the end cap) was completely dry (IMG_0166)
- The o-rings of the bottom bulkhead were flat, but still elastic (IMG_0169). One o-ring broke during removal. The par-back (rightmost in IMG_0169, the one closest to the inside of the instrument) was no longer elastic and broke easily during removal

Removal of the Power Supply Board

- While removing the connector (wires to power supply board – see picture IMG_0143) the plastic mold of the connector was brittle and disintegrated on the first touch. However the 3 wires which are held in place by the plastic mold seem to have had still contact to the connector and did not touch each other (IMG_0170 – note the extensive corrosion on the nut which attaches the inductor to the PCB)
- All PCB-interconnects seem to be in good shape (IMG_0171, 0172)
- Supplied 20V to the board after re-attaching inductor wire.
 - Current draw: 3.8mA (ok).
 - First power supply chip (12V LDO, U2 LM2937ET-12V) is ok (11.95V at TP3)
 - 5V power supply (step-down converter U3 LTC1174HVCN8) is ok (5.06V at TP5)
 - 5Vmotor power supply (U1, same chip as U3) is not ok (8.57V instead of 5.0V at TP4 when U1.8 is held to H or left floating).
 - 3.3V power supply (U4, same chip as U3) is not ok (5.45V instead of 3.3V at TP6)
 - Voltage supervisor U7 is ok. Provides “H” signal to U3 and U4
 - Added a 50uF capacitor in parallel to the 2x50uF caps in the circuit of U4 – now TP6 shows 3.3V.
- Cut capacitors C19 (22μF/25V), C22 (47μF/10V) off the board and measured capacity. Capacity is less than 1nF. Capacitors are “BC Components, Series 123 SAL-A (Aluminum electrolytic capacitor, Solid Al, Axial). Datasheet is attached. According to datasheet the lifetime is 20,000h @ 125C. (2y = 17,500h). The crusty, burnt material of one capacitor was cleaned. IMG_0180 shows a

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comparison of a good new capacitor (on right PCB), a burnt one (on left PCB) and the cleaned one. It looks like that the red cap has been burnt, but the capacitor show no signs of leakage.

Both capacitors were placed in a sample bag.

- The 100 μ F/25V capacitors of Series118 (C30, C31) (4000h lifetime) looks visually good, but had no capacity left

Removal of the *Processor Board*

- To removing the board the connector which holds the wires from the sensor/motor pack and connects into the analog board had to be removed (IMG_0177). Same problem as earlier: The mold was extremely brittle (almost oxidized) and disintegrated. However all wires were hold in place in did not touch each other prior to the removal of the connector. The remnants of the connector were placed in a sample bag.
- The processor board in the inter-board connectors looked in good shape (IMG_0174, 0175, 0176).
- When power is applied, the processor board does not boot up (draws either excess or too little current on the 3.3V power).
- Attempt to clear the content of the CPLD via its JTAG interface: Communication with the CPLD was not possible. This indicates a bad CPLD (supplied by 3.3V). A bad CPLD is the most common failure mode of the processor board

Removal of the *Analog Board*

- When the attempt was made to power up the analog board, it drew excess current
- 4 electrolytic capacitors of type 123 showed the same sign of damage as on the power supply board
- The 100 μ F/25V capacitor of type 118 looks visually good, but has no capacity left

Inspection of *Sensor pack*

- In order to test the sensors pack (2 tilt sensors, 3 accelerometers, 2 motors) the wires (IMG_0177) were inserted into a new housing and connected to a new analog board. No response from any sensor (tilt, accel).
- Disconnected sensor pack from analog board.
- Tested Accelerometers (Colibrys MS7002). Current draw was ok. Output was stuck and did not change when position of instrument was changed
- Tested Motors: No current was flowing into each of the two the motors



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- Tested (ceramic) sensors: They did not respond position changes and had extreme high impedance. This is an indicator of sensor fluid loss.

Modem board

Since it contains two of the 100 μ F/25V capacitors of type 118 (which failed on the other boards) it can be assumed this board will not work. Thus it was not tested

Summary for tiltmeter S/N 22051

- The instrument was not flooded. All seals were intact. No excessive pressure was observed when the instrument was opened (in Dec 2010 in Houston). The metal cans of the crystals were not deformed (which is an indicator that the instrument was not exposed to overpressure).
- No excessive corrosion was observed. The first observation that the electrolytic capacitor might have leaked causing corrosion turned out to be some burnt plastic on the top end of the capacitor.
- All major components (electrolytic capacitors, CPLD, tilt sensors, accelerometers, motors) have failed.
- The components have failed even without even been powered up because the tiltmeter did get disconnected already during the installation. There is the possibility that the processor board (e.g. CPLD) might have been damaged when the instrument was powered up after it was brought back to the surface (the loss of capacitance of the electrolytic caps results in overvoltage).



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Top Tiltmeter (S/N 22050 - was in POD 2)

The instrument was initially opened in Houston , partially disassembled and cleaned.

Visual inspection after opening the instrument

The instrument showed similar signs of degradation as the bottom tiltmeter:

- Trim-Pot on Modem Board is discolored
- The RTV was brittle, felt oily, slightly discolored (yellowish) and detached easily
- Y-accelerometer has black mark, capacitors next to it seemed to be damaged as well
- Electrolytic capacitors (on all PCBs) look heavily corroded at positive end
- When disconnecting bottom bulkhead to remove o-rings, the (yellow) insulation of the terminal rings broke on the first touch. A loss of insulation on the terminal ring connecting to the bottom bulkhead could potentially result in a short and explain the failure mode of the bottom tiltmeter (sudden short). However the sudden short happened during the installation and it can be assumed that the insulator was still intact at this time
- The plastic mold of the two connectors (to power supply board and analog board) was brittle and disintegrated on the first touch

Removal of PCBs from the metal chassis

- Power Supply Board: IMG_0183 to 0186 (bottom side), IMG_0187 to 0190)
- Modem Board: IMG_0191 to 0193 (top, bottom side was clean and showed no signs of degradation)
- Analog Board: IMG_0194 to 0197 (bottom), IMG_0203 to 0205 (top)
- Processor Board: IMG_0198 to 0200 (bottom), IMG_0203 to 0205 (top)
- Some board-to-board connectors were in bad shape, one detached from power supply board because it was baked to the mating connector on modem board (IMG_0185, IMG_0213)

Chassis was cleaned with de-greaser; PCBs were cleaned with electronics cleaner

Top side of boards: IMG_0206 to 0210

Bottom side of boards: IMG_0211 to 0215



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Electrical Measurements

Power Supply Board

- Supplied 20V to the board.
- Current draw: 3.8mA (ok).
- First power supply chip (12V LDO, U2 LM2937ET-12V) is ok (11.95V at TP 3)
- 5V power supply (step-down converter U3 LTC1174HVCN8) is not ok (5.11V at TP5)
- 5Vmotor power supply (U1, same chip as U3) is not ok (4.85V instead of 5.0V at TP4 when U1.8 is hold to H or left floating).
- 3.3V power supply (U4, same chip as U3) is not ok (3.66V instead of 3.3V at TP6)
- Voltage supervisor U7 is ok. Provides “H” signal to U3 and U4
- Adding a 50uF capacitor in parallel to electrolytic caps brings output voltages to nominal values.
- Cut two capacitors to measure capacitance. Measurement was not possible, because some electrochemical reaction must be going inside the cap (acts like a battery and always puts out a DC voltage)

Processor board

- Supplied ext. power to the board.
- When power is supplied the current draw starts high and goes to nominal after a couple of seconds
- Connect to “TiltTalk2” software: Communication is possible.
- Board diagnostics indicate that 2 of the 8 copies of the code have been damaged (page 0 low and high). This explains the high current draw at boot time.
- Attempt to repair code flash pages was not successful and made the board unresponsive. Together with the high start current it indicates a defective code flash
- Reprogramming the CPLD was successful

Inspection of *Sensor pack*

- Tested Motors: No current was flowing into each of the two the motors (open)
- Tested Accelerometers. Current draw was ok. Output was stuck and did not change when position of instrument was changed
- Tested (ceramic) sensors: They did not respond position changes and had extreme high impedance. This is an indicator of sensor fluid loss.



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Summary for tiltmeter S/N 22050

- The instrument was partially flooded with an oily fluid. Judging by its apparent properties (viscosity, color, odor) it is the same oil which was used to fill the PODs. No defective seal (o-ring) or other passway for the fluid was found.
- No excessive pressure was observed when the instrument was opened (in Dec 2010 in Houston). The metal cans of the crystals were not deformed (which is an indicator that the instrument was not exposed to overpressure).
- No excessive corrosion was observed. The first observation that the electrolytic capacitor might have leaked causing corrosion turned out to be some burnt plastic on the top end of the capacitor.
- Damaged components: electrolytic capacitors, tilt sensors, accelerometers, motors.
- Processor board was working but failed while it was been tested. There is the possibility that the processor board (e.g. code flash memory) might have been damaged when the instrument was powered up after it was brought back to the surface (the loss of capacitance of the electrolytic caps results in overvoltage).

Conclusions (for both instruments)

- Loss of capacitance of electrolytic capacitors resulted in increase of voltage from the internal power supply and ultimately damaged the electronics it was powering. However the damage has most likely happened during the tests when the instruments have been brought up to the surface. It is unlikely that capacitors were responsible for the initial failure of the instruments (all boards were burnt-in at temperature to mitigate initial failure of components). Most likely the capacitors degraded during the time when the instruments were sitting in the well not been powered up.
- No indication was found inside the instrument S/N 22050 why POD2 slowly increased the current draw (failure mode about 3 weeks after the installation)
- No indication was found inside the instrument S/N 22050 that it was damaged while it was running on uncontrolled power for a couple of hours about 2 ½ weeks after the installation
- No indication was found inside the instrument S/N 22051 why POD4 created a sudden short (failure mode during the installation)
- All 6 accelerometers (3 per instrument) failed. However they did not show a short which was believed to cause the tilt Y channel to fail about two weeks into the installation



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- All 4 tilt sensors (2 per instrument) failed. The ceramic sensors used in these instrument have a blob of glue to hold the sensor wires in place (see the black blobs in IMG_0182). In 2009 (months after the installation of the SAFOD instrument) it was discovered that these blobs of glue expand at high temperature and deform the package causing the fluid to leak.
- All 4 motor (2 per instrument) failed and showed an open
- No indication was found why the S/N 22050 (POD2) leaked

Recommendation

Would the electrolytic capacitors not have failed, it can be assumed that electronics of the tiltmeters would still be working (the processor board of S/N 22050 proves that).

- Use capacitors with live up to their temperature specs
- Use extra power supply for accelerometers so that a failure of (one of) them does not affect the rest of the circuit (accelerometers are only needed to position the sensor initially. Should the accelerometers fail at a later time, the quality of the tilt data is not affected)
- Use improved ceramic sensors
- Use different motors
- Use connectors with a material that does not degrade
- Use terminal rings with insulator material which does not degrade



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Prepared by	John Maida

Summary

Before the SAFOD toolstring was recovered the two active fiber optic lines (CMD="tan", DATA="black") of the microseismic cable were shot on Oct 5, 2010 with an OTDR device (Module IFTB-7200D-12CD-EI for multimode tests and Module FTB-7400E-2347B-EI-VFL for single mode tests). At the time of the OTDR shots the cable was still in the well – only a some 100ft were coiled up on the surface.

From the drum end (at surface), telco-standard OTDR responses of the MMFs look good at ~0.6dB/km @ 1300nm and 2.5dB/km @ 850nm using the MM port of the OTDR. These are one way loss factors and are typical for 1300nm transmission over 50um and 62.5um multimode fiber (MMF).

Conclusions: Insignificant fiber transmission loss changes did not contribute to loss of signal telemetry at 1300nm.

Recommendations: Future cables should employ more expensive carbon-nanocoatings, over each glass fiber, to drive hydrogen permeation time constants to greater than 25years at expected 115C wellbore temperatures.

OTDR Analysis:

Loss profiles are mostly linear at 850nm and 1300nm optical transmission wavelengths, however, we can see the onset of hydrogen ingress, via permeation, at the SiOH overtone laser wavelength of 1383nm over the length span starting at about 2300m downward (loss slope knee at ~2300m re surface).

Other laser lines at 1550nm and 1625nm also show H₂ (gas-in-glass) and GeO₂ and P₂O₅ overtone absorption also using the singlemode port lasers of the OTDR.

To confirm OTDR agreement between MM and SM ports, the 1300/1310nm loss slopes are in agreement at about 0.6 to 0.8 dB/km in the 1300nm band, which is the actual transmission band for the digital-optical telemetry system employed.

However despite the degradation of the fiber because of the hydrogen ingress, the loss is still small. Assuming the degradation is linear with time (question: How much is the hydrogen absorption gel already saturated?) the cable has more than 10years left.

Since the 1625nm line shows no significant loss increases, no micro-bending has taken place, which would also be an indication that the cable could have survived for many more years – or could have even been redeployed.

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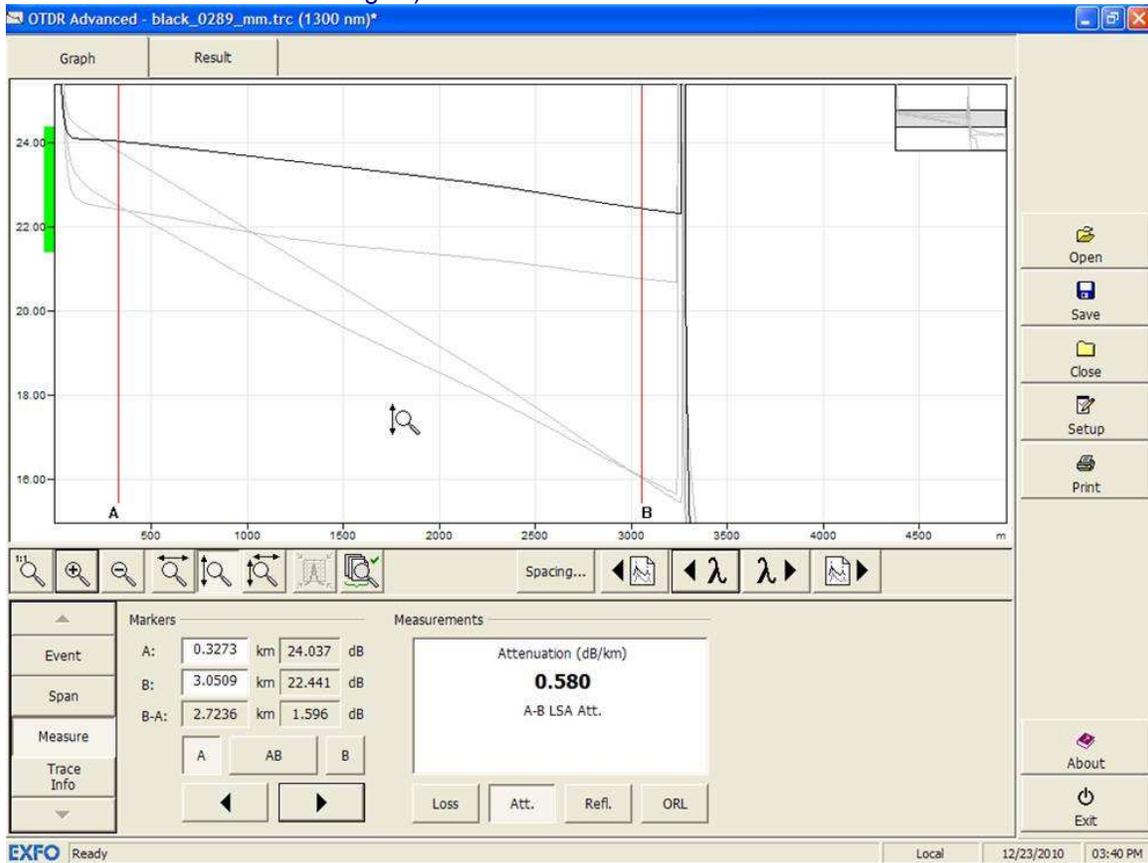
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OTDR Data Plots

Multimode Port Readings

Tan Fiber: 2.3dB/km @ 850nm and 0.58dB/km @ 1300nm

Black Fiber: 2.8dB/km @ 850nm and 0.58dB/km @ 1300nm (slightly more total loss compared with tan fiber at these wavelengths)





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Singlemode OTDR Port Readings

Black and Tan Fibers:

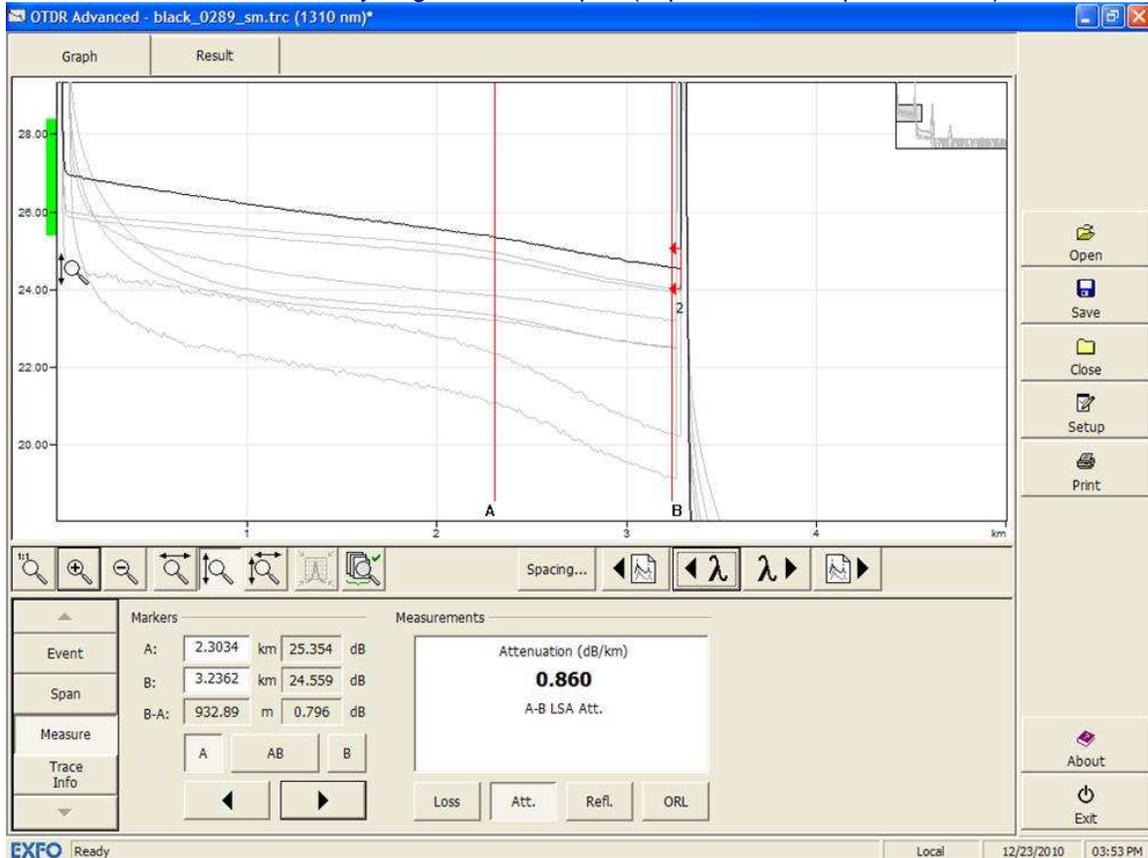
Losses measured over SM port

@ 1310nm: 0.7 dB/km over hydrogen-affected span (expected/average loss slope 0.6dB/km in agreement with MM port readings)

@ 1383nm: 2.4 dB/km over hydrogen-affected span (expected loss slope 0.7dB/km, definite indication of increased optical absorption activity with conversion of SiO₂ to SiOH)

@ 1550nm: 0.8 dB/km over hydrogen-affected span (expected loss slope 0.3dB/km)

@ 1625nm: 1.0 dB/km over hydrogen-affected span (expected loss slope 0.4dB/km)



Summary of the cable test results performed at SAFOD prior to pulling the toolstring on October 4th 2010.

Tested cables

- 1) 1-conductor Coax Cable connected to the top tiltmeter
- 2) 2-conductor, 4 fiber cable connected to the top FO-converter on top of the top seismometer

The third cable going to the LBL accelerometer pod at 3000ft was not tested

Tiltmeter Cable

Brief background

The tiltmeter runs on DC voltage. An operating tiltmeter draws about 75mA, supply voltage can be anywhere between 16V and 32 V. In order to compensate for the voltage drop on the line, the power supply at the surface has to be set to ~30V (constant voltage). There is no current loop – in case of a disconnected tiltmeter no current draw is expected. Communication to the tiltmeter is done by modems via a modulated AC signal on top of the DC power.

Failure mode

Supply current increased slowly until pre-set current limit of the power supply was hit. There was no more communication to the instrument after this time. This scenario can be explained by an added load – e.g. a short between the central conductor and the armor of the cable

Test results

When the power supply was connected to the cable and the voltage was slowly increased the current increased as well. The cable acted more or less as a load adhering to Ohms law. In contrast the tiltmeter does not act like an ohms load, it has a different characteristic.

The voltage increase was stopped at 20V because at this point the current was already at 110mA – more than the regular 75mA of the instrument and thus confirming the observations at the time of tool failure.

However about 5 minutes later the current draw had decreased to 40mA. The supply voltage was now increased to 35V resulting in a 70mA current.

At this point commands to the tiltmeter were issued via the modem but did not response was received.

5 minutes later the current had dropped to 30mA, about 30 minutes later it dropped down to 20mA. The voltage was left connected to the cable until the end of the complete test (another 60 minutes) but the current did not drop further.

The measured U vs. I characteristic resembled the one of an electrochemical cell. Also the fact that the power draw at the beginning was significant higher than at the end points towards a battery. This was confirmed when the DC power supply was disconnected. A voltage of 72mV was measured between the center conductor and the armor. This voltage slowly dropped – about 2 hours later it was still above 50mV.

Since a voltage above 35V would destroy the tiltmeter, the voltage was not increased to values above 35V.

Summary of the cable test results

performed at SAFOD prior to pulling the toolstring on October 4th 2010.

Conclusion

Since the cable has the characteristic of a battery, it is likely that at some point well fluid penetrated the cable. The cable consists of two metals (steel on the armor and copper as the central conductor) the well fluid could have formed a wet cell. It is unlikely that a failed tiltmeter would act in this way – unless it itself got flooded and acts now as a battery.

With this test it was not possible to determine at which depth the short occurred.

Seismometer Cable

Brief background

The seismometer runs on DC voltage. All 3 instruments are hooked up in series, the bottom instrument closes the current loop. Each seismometer needs a 10V voltage drop to operate and draws about 140mA. Excess current (“reserve current”) is dropped in the internal powersupply of the instruments. To operate the seismometers the DC power supply on the surface is set to constant current – minimum is 150mA, max is 630mA, a typical value is 500mA. A comparable high voltage is required to drive the current over the long cable – to drive 500mA down the line, usually around 140V are required.

In contrast to the tiltmeter cable the armor of the cable is not used. The current loop is formed with the two conductors in the cable. The two conductors should be completely insulated from the armor.

The communication and data transfer to the instrument is done over optical fibers. The conductor has 4 separate fibers. Two of them are spares and 2 are used for a full duplex communication. The fiber dubbed “CMD is for the signals from the surface to the instruments and the fiber dubbed “DATA” is for the opposite direction.

Failure mode

The “reserve current” dropped over time – which could indicate that one or more instruments increase their current draw or that an additional load on the cable acts as a short in the current loop.

Results - Copper

The power supply was hooked up to the cable and the fibers were hooked up to the GeoRes data acquisition system. The voltage was slowly increased while observing the current. At several points during the transient attempts were made to communicate with the seismometers.

The current followed the voltage - linear like a resistor – or like an operating seismic tool string (The tool string has a U-I characteristic of a resistor due to the design of the instrument power supplies and the loopback terminator). Furthermore the characteristic not only shows no signs of failure – also the absolute values (e.g. 500mA at 140V) match those seen during regular operation.

So these measurements indicate no failure – however when the resistance between armor and each conductor (both lines should be insulated from armor) was measured with a multimeter

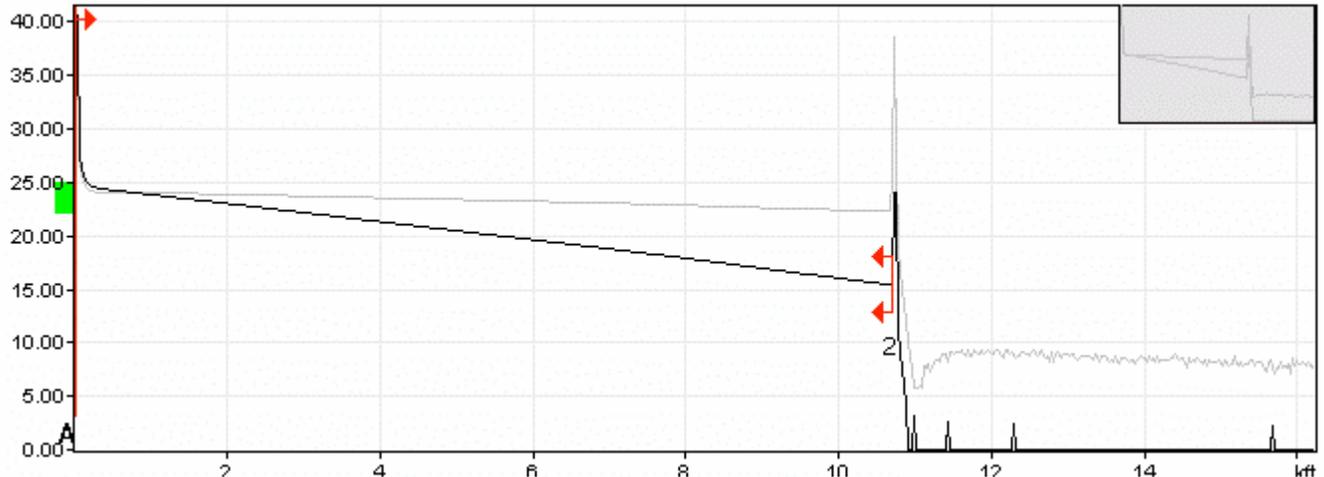
Summary of the cable test results

performed at SAFOD prior to pulling the toolstring on October 4th 2010.

extreme low values (500Ohm for the red conductor and 2.4kOhm for the blue conductor) were recorded. This could indicate that either the cable or the instrument has been flooded.

Results - Fiber

The characteristics of both active fibers ("DATA" and "CMD") were measured with an OTDR (Model FTB-7200D-12CD-EI) using light with several wavelengths (850, 1300, 1310, 1383, 1550, 1625nm).



The graph shows signal strength (in dB) vs. depth (in kft) for the DATA fiber at 850nm (dark line) and 1300nm (light line). After a very sharp drop over the first couple of 100ft (which corresponds to the part of the cable which was above ground) the attenuation is linear with depth. The reflection at ~10700ft is the result of the end of the fiber (or the F/O converter on top of the top seismometer)

A numerical analysis of the results is not made here since typical values of a fiber in good condition are not available at the time this report was written.

In a qualitative analysis the graphs show no signs of failure of the fibers:

- All measurements put the end of the fiber between 10630 and 10785 ft.
- For the downhole part the attenuation of both fibers is linear with depth for all wavelengths However the "DATA" fiber when tested with 1383nm shows a higher attenuation below 8000ft. 1.6dB of the 4.5dB loss happens below 8000ft. This result could be interpreted as a fiber damaged by prolonged exposure to high temperatures.

Wavelength [nm]	Attenuation [dB] over the downhole part of the fiber	
	CMD	DATA
850	7.7	9.97
1300	2.1	2.5
1310	2.8	2.44
1383	5.08	4.5
1550	3.65	1.96
1625	4.63	2.04

Someone who is more familiar with interpreting OTDR data should revisit the data.

Summary of the test results

performed at SAFOD after the tool string was pulled on October 8th 2010.

Please refer to the sketch at the end of this document for the location of the different items mentioned in this report.

Overview

Between October 4th and 8th 2010 the tool string deployed at the SAFOD borehole was removed from the well.

Observations during the polling of the tool string

The polypropylene coating of both control lines which was in the inclined section of the well was damaged and showed abrasion and cuts – especially right above the Canon clamps. Well fluid got between the coating and the stainless steel tube and was bubbling out at the damaged locations. Fluid samples were taken. The coating was removed at several locations where the coating got damaged to check if the stainless steel tube was damaged. No damage to the stainless steel tube was observed.

Instrument removal

On October 8th the 5 PODs came to the surface.

1. The fiber optic line above POD1 was cut. The line seemed to be intact.
2. The fittings of splice S1 were loosened. The splice was not pressurized excessively, fluid appeared, which was sampled.
3. POD1 was removed. It is still attached to the EUE tubing since the hinges appeared to be corroded.
4. The line between POD1 and POD3 was cut in pieces while removing the EUE tubing to reach POD2. At each cut small amount of fluid appeared at the cuts.
5. Splice T1 was opened. The splice was not pressurized and seemed to be dry.
6. The lower of the two splices T2 was opened to disconnect the cable. A drop of fluid emerged, corrosion to the coax cable was visible.
7. POD2 was removed
8. The line above POD3 was cut. Small amounts of fluid appeared
9. The fittings of splice S2 were loosened. The splice was not pressurized excessively, fluid appeared
10. The line was cut below splice S2. Small amounts of fluid appeared at the cut.
11. POD3 was removed
12. The line was cut above POD4. It was dry
13. POD4 was removed
14. The line was cut above POD5. Small amounts of fluid appeared at the cut.
15. POD5 was removed

Summary of the test results
performed at SAFOD after the tool string was pulled on October 8th 2010.

PODS

Once the instruments were on the surface they were brought to the computer hut for testing. All tests were done by hooking the PODs directly to the power supply / modem without connecting through the 10,000ft cable(s).

POD2

The tiltmeter modem was connected to the top of POD2 at splice T1. The shield of the coax line was brittle and corroded.

When the POD was powered up, the POD never drew more than 20mA (a good tiltmeter draws ~75mA). U-I characteristic: 2V: 10mA, 4V to 33V: 20mA. The voltage was not increased above 33V to prevent damaging the tiltmeter.

Communication was attempted but failed.

The power (@ 33V) was left connected for about 20 min. Current draw did not change. After disconnecting the power, a small voltage was measured (~10mV), which was decreasing fast like when a big capacitor is been discharged.

The "battery-like" characteristic of the cable as seen prior to the removal of the tools string could not be reproduced.

Conclusion: POD2 acts like an "open" with some parasitic load

POD4

The tiltmeter modem was connected to the top of POD4 at the cut above POD4. The cut was clean and dry.

When the POD was powered up, the current jumped immediately to the pre-set max of the power supply (150mA) at a voltage of 5V. When the test was repeated, the POD acted like an POD2 for brief moment (20mA @ 26V), but after a couple of seconds showed signs of a short again.

Conclusion: POD4 acts like a "short"

POD1

The power supply for the seismic tool string was attached to the cut cable above POD1. The cut was clean and dry.

In order to close the current loop the splice below POD1 was opened. The splice was completely flooded with a fluid which smelled and felt like motor oil. Most likely it was the oil which was used to fill the PODs since there are no pressure seals between the inside of the PODs and the inside of the stainless steel tube.

The heat shrink and the kapton tape which was used to insulate the solder points inside the splice seemed to be dissolved by the oil and disintegrated at the first touch.

However a small layer of heat shrink remained around the solder and at least by a visual inspection the solder points did not touch each other.

The black and the brown wire below POD1 were connected together to form the current loop.

Summary of the test results

performed at SAFOD after the tool string was pulled on October 8th 2010.

When the power supply was turned on and the voltage was slowly increased, at no point more than 20mA was flowing through the line. The voltage was not increased above 50V to prevent the cable head / DS150s from been damaged.

The voltage between the top and the bottom of POD1 was measured while the power supply was set to 50V. 10V / 40V were measured between the red line (+) / blue (-) and the bottom.

The fibers were spliced to an connector and attached to the data acquisition system. Communication was attempted but failed.

POD 3, POD 5

Since no equipment was on site to test the DS150s inside the PODs without the fiber optic converter, a working POD1 was required to test PODs 3 and 5. So no assessment of the state of PODs 3 and 5 could be made on site.

When splice S2 was opened, the same situation as in splice S1 was observed: The oil dissolved the Kapton tape and the heat shrink. The brown wire broke above the solder joint, most likely at the location where the insulation was stripped.

Cables

The cables (rolled on the spools) were tested for continuity (Multimeter) and insulation (1G Ω Megaohm-Meter)

Fiber-Optic Cable

End – to – End:

- Red: 99 Ω
- Blue: 99 Ω
Fiber optic tube: 5k Ω
- Stainless steel tube: 155 Ω

Insulation:

- Red to Stainless steel tube: ∞
- Blue to Stainless steel tube: ∞
- Red to Blue: ∞

Coax Cable

End – to – End:

- Center: 64 Ω
- Shield: 66 Ω
- Stainless steel tube: 185 Ω

Insulation:

- Center to Stainless steel tube: ∞
- Shield to Stainless steel tube: ∞
- Center to Shield: ∞

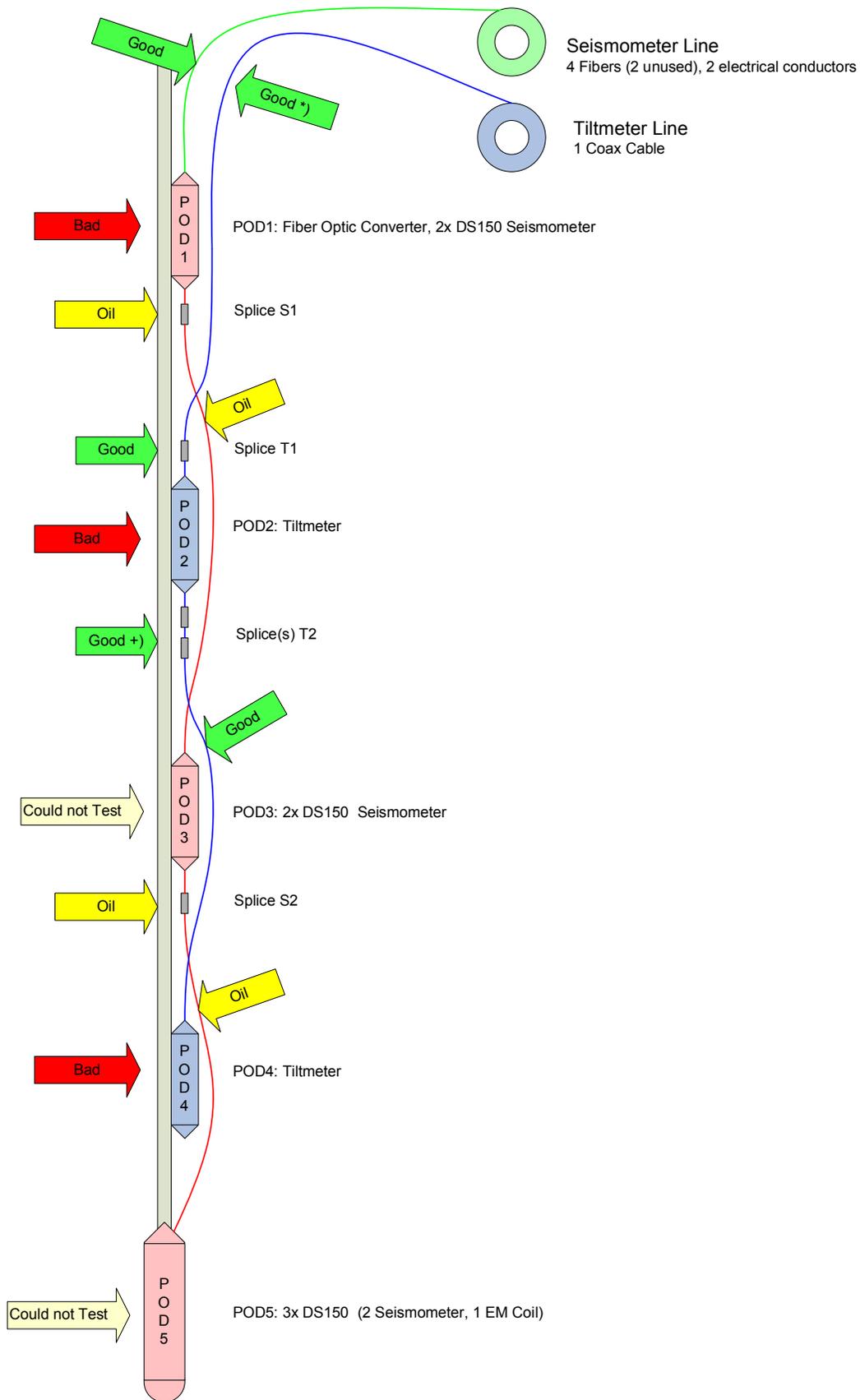
Summary of the test results
performed at SAFOD after the tool string was pulled on October 8th 2010.

In contrast to the uphole end of the cable the downhole end was corroded: The center cable was black, the shield was brittle and no shiny.

Recommendations for further tests

1. Test POD3 and POD5 directly (not going through the fiber optic converter) connected to the GeoRes data acquisition system
2. Do the test of POD1 again
3. Open the PODs, remove DS150s and tiltmeters from the PODs and connect them directly to the data acquisition system / tiltmeter modem.

Summary of the test results performed at SAFOD after the tool string was pulled on October 8th 2010.





**Characterization of Aqueous and Non-Aqueous
Samples from the San Andreas Fault Observatory at
Depth (SAFOD) POD Strings**

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February, 2011

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List of Acronyms

DCM	Dichloromethane
FID	Flame ionization detector
GC	Gas chromatography
MS	Mass spectrometer
SAFOD	San Andreas Fault Observatory at Depth
UNEP	United Nations Environmental Program

Introduction

Between October 4th and 8th 2010, instruments (PODs) deployed at the San Andreas Fault Observatory at Depth (SAFOD) borehole were removed from the well. The PODs were deployed as two lines or “strings.” Several instruments were found to be damaged and did not function on standard tests. Signs of cuts and abrasions were found on the polypropylene coatings of lines for the two Pod strings. Fluid was found between the stainless steel instrument housing and the coating, but the stainless steel housing was not damaged. The shield of the coax line was brittle and corroded in some locations. The lines were found to contain fluid when opened at splice points and samples of fluid were collected. Individual PODS were opened and fluids were collected.

The individual PODs were filled with synthetic motor oil (Mobile 1, 10w-40) when assembled, but fluids were not expected to be found in the lines or the stainless steel housing. Fluid samples from the two SAFOD POD assemblies were sent to the Ecological Engineering Research Program (EERP) laboratories at the University of the Pacific (Stockton, CA) for analysis. The objective of the analysis was to provide a qualitative characterization of the fluids to assist in determining the source of the fluids in the assemblies.

Fluid samples collected from the damaged instruments included a mixture of oil, water, emulsion, mud, and proppent (aka proppent, proppant). The hypothesis tested was that the source of the oil in the lines was due to internal leakage from the PODs, with the alternative hypothesis being that hydrocarbons were entering the equipment string from external sources in the formation. The source of aqueous fluid in the instrument string was hypothesized to be from the formation, with the alternative hypothesis that the aqueous fluid entered the string from the surface. Various analysis were conducted to test the two hypotheses.

Materials and Methods

Samples were received on January 7th, 2011, checked in, and stored at 4 °C prior to analysis. All glassware used was muffled at 550 °C to remove all organic contaminants prior to use. All dilutions are recorded on weight to weight (w/w) basis.

For extractable hydrocarbon analysis, oil, mud, and proppent samples were weighed into clean glassware and dissolved in dichloromethane. Typically, 0.5 mL of oil, emulsion, mud, and proppent samples were dissolved or extracted with 10 mL of high purity (99.96%) dichloromethane (EDM Chemicals Inc, Darmstadt, Germany). Aqueous samples and aqueous

phases of multiphase samples were extracted with dichloromethane for analysis. Typically, ten mL of aqueous samples were mixed with 10 mL of dichloromethane and sonicated for 45 minutes. After sonication, samples rested for at least 45 minutes to allow separation of the solvent and aqueous phases. A portion of the dichloromethane extract was collected and treated with a sodium sulfate (J.T. Baker, Phillipsbury, N.J.) in a packed column, to remove any remaining moisture before analysis.

Extractable hydrocarbons were measured on an Agilent 6890N Gas Chromatograph (GC) System equipped with a flame ionization detector (FID) and a 5973 mass spectrometer (MS) detector (Agilent Technologies, Santa Clara, CA). Hydrocarbons were analyzed according to a modified UNEP protocol (Burns et al., 1992). Both the GC/FID and GC/MS analysis were conducted under the same conditions. The column used was a 30 m HP-5MS with a 0.25 mm diameter and 0.25 μ m film thickness. All gasses were ultra-high purity grade. Helium was the carrier gas and nitrogen was the makeup gas on the FID analysis. Separation was achieved with an initial oven temperature of 50 °C, held for 1 minute, followed by an increase of 5 °C /min to 290 °C, a hold of 290 °C for 20 minutes, then the temperature is increased by 5 °C /min to a final temperature of 300 °C. The inlet temperature was 290 °C, with a constant carrier gas velocity of 40 cm/s. Injection volumes were 1 μ L with a split ratio of 1:100. Tentative compound identifications were made using the NIST library of standard mass spectra. Identification using authentic standards was not included in the project scope of work.

Volatile hydrocarbons in oil were measured using a headspace analysis. Ten mL of oil was placed in a 20 mm x 125 mm culture tube fitted with a Teflon Mininert cap. Sample tubes were sonicated, and were then heated for 20 minutes in a boiling water bath. Headspace samples were manually injected on the GC/MS. Injection volume was 100 μ L and was run in splitless mode. Duplicate samples had identical peak retention times, and very similar peak heights. For volatile hydrocarbon analysis, a cryogenic kit was installed on the GC/MS and the initial oven temperature was lowered to 10 °C, held for 2 minutes, increased by 5 °C/minute to 35 °C and held for 20 minutes. The same instrument, column, and gases were used as described above. The inlet temperature was 290 °C for this analysis. Other attempts to collect and concentrate volatile oil degradation products by distillation and condensation were not immediately successful and were abandoned.

Aqueous and non-aqueous samples were optically characterized. A portable refractometer NDX-1 (VEE GEE Scientific Inc, Kirkland, WA) was used to measure the optical density of aqueous, oil and mud samples.

The salinity and pH of aqueous samples were measured using standard methods. Electrical conductivity (EC) measurements were made on aqueous samples using a multi-parameter PCSTestr 35 (Oakton Instruments, Vernon Hills, IL) modified to measure 1 mL volumes.

Aqueous samples including SF-1, SF-2, SF-12L, SF-13L, and SF-15L were examined under a Leica DM IL inverted microscope (Leica Microsystems, Wetzlar, Germany) at 400x to determine if microorganisms were present. SF-15L was also examined under a scanning electron microscope at approximately 1000x.

Results & Discussion

Samples received by EERP were assigned sample identification numbers upon receipt (Table 1). Table 1 summarizes the sample ID's used for this analysis, sample description, and whether or

not samples were analyzed. The volume of SF-5 (SAFOD Splice S2) was too small to measure. SF-8 (small zip lock bag of an oily substance) was not measured due to sample size and type. SF-9 and SF-10 (dirty Q-tips and dirty rags) were not measured. All other samples were analyzed by GC/FID, GC/MS and if possible by one or more of the other methods described above depending on the sample properties. Samples with more than one phase were identified by both the whole sample characteristic and the individual phase characteristics; each phase of a sample was given a unique sample id.

Samples with multiple phases were given “U”, “M”, and “L” designations, depending on the number of phases. U-phases were later determined to be non-aqueous. L- and M-phases were either aqueous, solids or emulsions. Descriptive documents provided by Wade Johnson (UNAVCO, Inc, Boulder, CO) and others concerning the POD failure and the collection of fluid samples from the POD strings are attached as Appendix A and B. The sample chain of custody is provided in Appendix C. Based on this information, the samples were given an ordinal, relative depth assignment (“1” being most shallow and “9” being most deep) to aid in data interpretation.

Oil-Phase Analysis

Extractable hydrocarbons were analyzed to determine if the non-aqueous samples from the POD line were similar to the reference oil, Mobil-1, which is added to the PODs as part of their manufacturing process. In addition, aqueous samples were analyzed to look for evidence of hydrocarbons from sources other than the Mobil-1 synthetic oil. All analysis indicated the synthetic motor oil as the only significant source of hydrocarbons in the POD string. Figure 1 shows a representative analysis of Mobil-1 reference oil and the oil from the PODs by GC/FID. The samples show a distinctive pattern that agree with the reference oil. The majority of observed peaks and “hump” of unresolved hydrocarbons eluted between 36 min and 60 min, which corresponds to a column temperature of 230 °C to 290 °C. In comparison, this pattern is significantly different from the patterns typically observed in crude oil (Figure 2), which includes a broader array of compounds, with distinct peaks and a higher range of boiling points.

The samples did contain early eluting components or compounds that were not found in the reference oil (Figure 3). Analysis by GC/MS was used to demonstrate that the early eluting compounds were not alkanes or other hydrocarbons, which would be indicative of contamination from geologic hydrocarbons. The peaks were identified as components of silicon grease (Figures 3, 4, 5, and 6). The samples that contained silicon grease are listed in Table 2. The presence of silicon grease in the POD oil could be an indication of seal failure.

The oil content of whole samples, a measure of sample purity, was determined by two methods. In the first method, the total FID signal area between 36 and 60 minutes was determined for each sample extract and compared to the signal observed for pure Mobil 1 reference oil. The FID signal is proportional the hydrocarbon content of each sample and the fraction of oil (w/w) in each sample could be determined. The results from this analysis (Table 2) suggest that most of the oil phase samples contained contaminants, most likely water. Two of the samples, SF-11 and SF-14, from PODs 4 and 5 are within the range of error for this type of analysis (~20 %) and do not appear different from the reference oil or show significant dilution or contamination. These results were confirmed by an analysis of five major hydrocarbon peaks found in the Mobil 1 oil (Table 2). The retention times of these peaks were 36.30, 42.29, 43.07, 43.68, and 43.90 minutes. The peaks were hydrocarbons and nitrogen containing organic compounds, but the peaks could

not be identified without the use of authentic standards, which was beyond the scope of this effort. These five peaks were found in all of the samples except the aqueous samples and SF-6 (hot mud).

Several of the samples had strong odors, reminiscent of crude oil or produced water. Since the samples were not shown to be contaminated with hydrocarbons from the geologic formation, the samples were examined for indications of oil degradation. Chromatograms from the reference oil were compared to chromatograms of oil from the POD strings to identify peaks that were present in the reference oil, but not in the field samples. Two peaks were identified as being present in the Mobil 1 sample, present in SF-17 and SF-14, but absent from all other oil samples (Figure 7). These compounds could not be identified by a library search, but the mass spectra corresponding to the peaks are characteristic of nitrogen containing organic compounds (Figures 8 and 9). The disappearance of high molecular weight nitrogen compounds may be indicative of thermal degradation or oxidation. The only oil sample that contained detectable amounts of these compounds were from PODs 1 and 4 (Table 2).

Oil degradation was examined further by measuring volatile compounds using head-space analysis. Sample SF-11 (from POD 5) had sufficient samples for replicate analysis and had a characteristic odor, similar to the other oil and water samples. Twenty-two peaks were observed in the SF-11 sample which were not present in the reference oil or were at much greater concentrations than the reference oil (Table 3). Four peaks were either higher in the Mobil-1 sample or were similarly present in both samples. The likely compound identifications for each peak, as determined by a database search of a NIST library, are listed in Table 3, along with the probability of identification. The total volatile compounds observed, as a sum of peak areas, is more than 80 times greater in the SF-11 sample compared to unused Mobil 1. The presence of alcohols and ketones in SF-11 that are absent or very small in Mobil 1 indicate degradation of the oil is occurring. The types of compounds observed are consistent with oxidation products formed during thermal and mechanical breakdown of oil (Levermore et al. 2001).

Aqueous-Phase Analysis

Results for analysis of the aqueous phase samples are presented in Table 4. Results for specific conductance, pH, and refractive index indicate two sources of water in the sample set. Water samples from the SAFOD well head are low in total dissolved solids and are of neutral pH (Table 4). In contrast, water samples from the PODs have high concentrations of salts (approximately three-times saltier than sea water) and are acidic. These results indicate the water in the PODs came from the geologic formation and that there is no evidence of more than one source of saltwater intrusion into the POD strings.

Aqueous samples were also examined microscopically for the presence of debris and bacteria. Microscopic analysis of the samples suggest that there are bacteria present in the samples, as indicated by the presence of uniform bodies in the appropriate size range (Figure 10). Since the samples were not collected or handled using sterile techniques, it is not possible to determine if the bacteria were present *in-situ* or if they grew in the water samples after the samples were removed from the subsurface. However, the low pH of the water samples, the reported high temperatures of the geologic deposit, the apparent degradation of high molecular weight components (peak at 52.5 and 56.5 minutes), and the presence of volatile oxidation products consistent with thermal degradation, would suggest that the observed change in oil composition need not be biologically driven.

Analysis of other phases

Three of the samples received were emulsions or slurries. Results for these samples are presented in Table 5. All of these samples contained oil that was consistent in character to thermally degraded Mobil 1 synthetic motor oil.

Conclusions

- All oil samples were consistent with Mobile-1, 10W-40 synthetic motor oil.
- No evidence of geologic sources of hydrocarbons, or hydrocarbons from any source other than Mobile 1 oil, were found in any sample
- The oil from the PODs demonstrated evidence of thermal degradation, including a pungent odor, loss of high molecular weight components in samples from deeper depths, and the presence of volatile hydrocarbon oxidation products.
- Oil samples from the PODs also contained silicon grease. This may be an indication of seal failure.
- Water samples from the POD string have low pH and high salt content, consistent with corrosive waters from the geologic formation.
- Water found in the PODs was distinct from near-surface water samples, indicating that the water did not enter the lines from the surface.
- Bacteria were present in water samples, but the role of bacteria activity as a driver for observed oil degradation indicators is unlikely.

References

Burns, K., Farrington, J., Ehrhardt, M., Palmork, K., 1992. Determination of Petroleum Hydrocarbons in Sediments. Regional Seas: Reference Methods For Marine Pollution Studies No. 20. United Nations Environment Programme prepared in co-operation with IOC and IAEA, p. 75.

Levermore, D. M., Josowics, M., Rees, W. S., and Janata, J., 2001. Headspace analysis of engine oil by gas chromatography/mass spectrometry. *Anal. Chem.* 73, 1361 - 1365.

McLafferty, F.W., Turecek, F., 1993. Interpretation of Mass Spectra. University Science Books, Sausalito, CA.

Table 1. List of samples received for analysis and sample designations.

Sample ID	Description	Sample Collection Date	Enough sample to measure?
SF-1	H ₂ O from SAFOD well head container 1	9/20/2010	Y
SF-2	H ₂ O from SAFOD well head container 2	9/20/2010	Y
SF-3	SAFOD bottom joint ISO, looking for cut in cable jacket		Y
SF-4	SAFOD Splice S1		Y
SF-5	SAFOD Splice S2		N
SF-6	External Hot Mud Collection off of EUE tube below joint 2		Y
SF-7	SAFOD fluid from cable cut above pod 5		Y
SF-8	1 small ziplock bag of an oily substance		N
SF-9	Dirty Q-tips		N
SF-10	Dirty rags		N
SF-11	POD 5 EUE CAP Top Sample 1	12/2/2010	Y
SF-12L	POD 5 Sample 4 collected after Bull plug removed (lower aqueous portion)	12/1/2010	Y
SF-12U	POD 5 Sample 4 collected after Bull plug removed (upper oil portion)	12/1/2010	Y
SF-13L	POD 3 Sample 2 removed from Bottom after well cap removed (lower aqueous portion)	11/30/2010	Y
SF-13M	POD 3 Sample 2 removed from Bottom after well cap removed (mid mousse portion)	11/30/2010	Y
SF-13U	POD 3 Sample 2 removed from Bottom after well cap removed (upper oil portion)	11/30/2010	Y
SF-14	POD 4 Sample 2 Top of POD after cap removed	11/30/2010	Y
SF-15L	POD 5 Sample 6 collected near EM x-over when milling (lower aqueous portion)	12/2/2010	Y
SF-15U	POD 5 Sample 6 collected near EM x-over when milling (upper oil portion)	12/2/2010	Y
SF-16	POD 3 Sample 1 Top POD after screw end removed, Propent, large void at top	11/30/2010	Y
SF-17	POD 1 Sample 3 drained from the bottom of POD while tilted at 20 degrees	11/30/2010	Y
SF-18	POD 2 Sample 2 bottom of POD AAØ/ Cap removed drained after POD tilted to ~20 degrees	11/30/2010	Y
SF-19	Unopened Mobile 1 synthetic 10W40, may not be the same used in SAFOD instruments		Y

Table 2. Summary of results for liquid, non-aqueous phase samples

EERP ID	Relative Depth	Sample Discription	POD number	Average Refractive Index at 20 +/- 2 °C (nD)	Oil Content Compared to Mobil 1 (%)	Major Hydrocarbon Peaks Compared to Mobil 1 (%)	Peak at 52.5 Minutes Compared to Mobil 1 (%)	Peak at 56.5 Minutes Compared to Mobil 1 (%)	Silicon Grease Present
SF-17	2	POD 1 Sample 3 drained from the bottom of POD while tilted at 20 degrees	1	1.4730	62.8	57.9	35.7	33.7	yes
SF-4	3	SAFOD Splice S1		1.4725	38.1	31.0	0.0	0.0	yes*
SF-18	4	POD 2 Sample 2 bottom of POD AAØ/ Cap removed drained after POD tilted to ~20 degrees	2	1.4740	55.0	52.2	0.0	0.0	yes*
SF-13U	5	POD 3 Sample 2 removed from Bottom after well cap removed	3	1.4705	39.2	38.4	0.0	0.0	yes
SF-14	7	POD 4 Sample 2 Top of POD after cap removed	4	1.4733	106.4	98.6	3.5	2.8	yes
SF-7	8	SAFOD fluid from cable cut above pod 5		1.4718	50.6	43.0	0.0	0.0	yes*
SF-11	9	POD 5 EUE CAP Top Sample 1	5	1.4700	89.8	85.9	0.0	0.0	yes
SF-12U	9	POD 5 Sample 4 collected after Bull plug removed	5	1.4750	20.9	20.3	0.0	0.0	yes
SF-15U	9	POD 5 Sample 6 collected near EM x-over when milling	5	1.4745	59.2	68.4	0.0	0.0	yes

* Determined by FID only, not confirmed by MS analysis. N/A, not analyzed.

Table 3. GC/MS analysis of volatile compounds in the headspace of SF-11 and Mobil 1. Presence of volatile compounds in POD samples is consistent with thermal oxidation of motor oil.

Retention Time	POD5 EUE CAP (SF-11) Area Count	Mobil 1 Area Count	Probable Compound(s)	Chemical Formula	% Probability
1.85	517,204	<i>No Peak</i>	Butane, 2-methyl	C5H12	83.1
2.02	65,909,134	64,073	Acetone	C3H6O	70.7
2.046	7,172,654	<i>No Peak</i>	Isopropyl Alcohol	C3H8O	82.7
2.08	<i>No Peak</i>	579,672	Dimethylamine	C2H7N	42.5
2.38	1,197,866	13,937	Methylene Chloride	CH2Cl2	98.4
2.633	4,782,861	<i>No Peak</i>	1-pentane, 4 methyl	C6H12	57.5
2.8	180,362	<i>No Peak</i>	No match	C6H14O	<40
2.855	11,966,242	<i>No Peak</i>	No match	C6H14O	<40
3.33	958,532	75,588	Hexane	C6H14	78.1
3.382	1,768,122	<i>No Peak</i>	2-Butanone	C4H7N	85.3
3.53	638,031	<i>No Peak</i>	No match	C6H14O	<40
4.13	1,186,523	<i>No Peak</i>	1-propanol, 2-methyl	C4H10O	90.1
4.74	2,869,966	614,411	Benzene	C6H12	73.3
4.93	193,340	21,929	Hexane, 2-methyl	C7H16	48.4
5.1	350,101	55,014	Acetic Acid, 1 methylethylester	C5H10O2	86.5
5.15	137,255	<i>No Peak</i>	Hexane, 3-methyl	C7H16	58.7
5.7	187,041	<i>No Peak</i>	2-pentanone	C5H10O	80.0
5.92	457,741	11,896	Heptane	C7H16	66.3
6.23	<i>No Peak</i>	67,066	No match	C2H4FNO	<40
6.52	309,304	56,738	cyclohexane, methyl	C7H14	80.9
7.35	1,555,639	13,266	Methyl Isobutyl Ketone	C7H12O	73.7
7.61	489,190	<i>No Peak</i>	Propane 2-ethylthio	C5H12S	98.1
8.09	111,642,226	32,627	2-pentanol, 4 methyl	C6H14O	60.6
9.9	449,642	11,726	heptane, 2,4 dimethyl	C9H20	40.6
14.62	392,008	504,306	No match	C8H10	<40
18.62	567,522	489,191	No match	C9H20	<40
Total	215,824,526	2,611,440			

Table 4. Summary results for aqueous phase samples.

EERP ID	Relative Depth	Sample Name	POD number	Average Refractive Index at 20 +/- 2 °C (nD)	Specific Conductance (mS/cm)	pH	Total Dissolved Solids (mg/L)	Total Dissolved Solids (% of seawater)
SF-1	1	H2O from SAFOD well head		1.3350	10.62	7.0	6,903	22
SF-2	1	H2O from SAFOD well head		1.3350	10.56	7.0	6,864	22
SF-13L	5	POD 3 Sample 2 removed from Bottom after well cap removed	3	1.3690	174.3	5.3	113,295	360
SF-12L	9	POD 5 Sample 4 collected after Bull plug removed	5	1.3610	146.9	5.5	95,485	304
SF-15L	9	POD 5 Sample 6 collected near EM x-over when milling	5	1.3620	145.1	5.5	94,315	300
SF-3	Unknown	SAFOD bottom joint ISO, looking for cut in cable jacket		1.3353	12.34		8,021	25

Table 5. Summary data for emulsions and slurry samples.

Internal Sample ID	Relative Depth	Phase character individual sample	Sample Name	POD number	pH	Oil Content Compared to Mobil 1 (%)	Major Hydrocarbon Peaks Compared to Mobil 1 (%)	Peak at 52.5 Minutes Compared to Mobil 1 (%)	Peak at 56.5 Minutes Compared to Mobil 1 (%)
SF-13M	5	Emulsion	POD 3 Sample 2 removed from Bottom after well cap removed	3		10.1	9.2	0.0	0.0
SF-16	5	Propent	POD 3 Sample 1 Top POD after screw end removed, Propent, large void at top	3		6.1	3.6	0.0	0.0
SF-6	Unknown	Mud	External Hot Mud Collection off of EUE tube below joint 2		7.0	2.2	0.0	0.0	0.0

Figure 1: Extractable hydrocarbon analysis of Mobil-1 synthetic oil (black line) and sample SF-11 (POD 5 EUE CAP top sample 1, blue line). Hydrocarbon analysis is consistent between samples and does not indicate contamination by geologic sources of oil. Refer to Figure 2 for comparative analysis of crude oil using the same method.

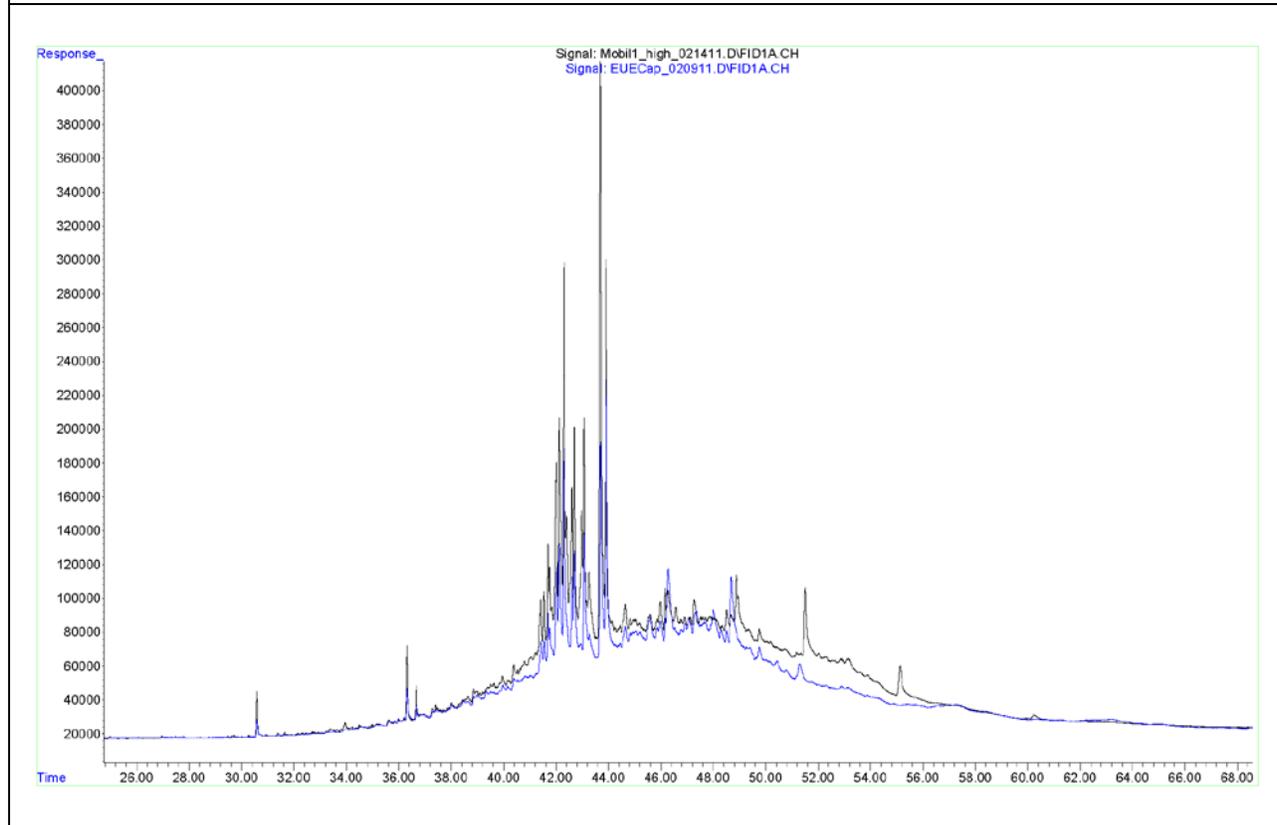


Figure 2: Analysis of crude oil using UNEP protocol as described in methods section. Geologic sources of natural hydrocarbons are more complex mixtures than synthetic oils (Figure 1) and contain more low-boiling point hydrocarbons (note alkane series eluting before 26 minutes) .

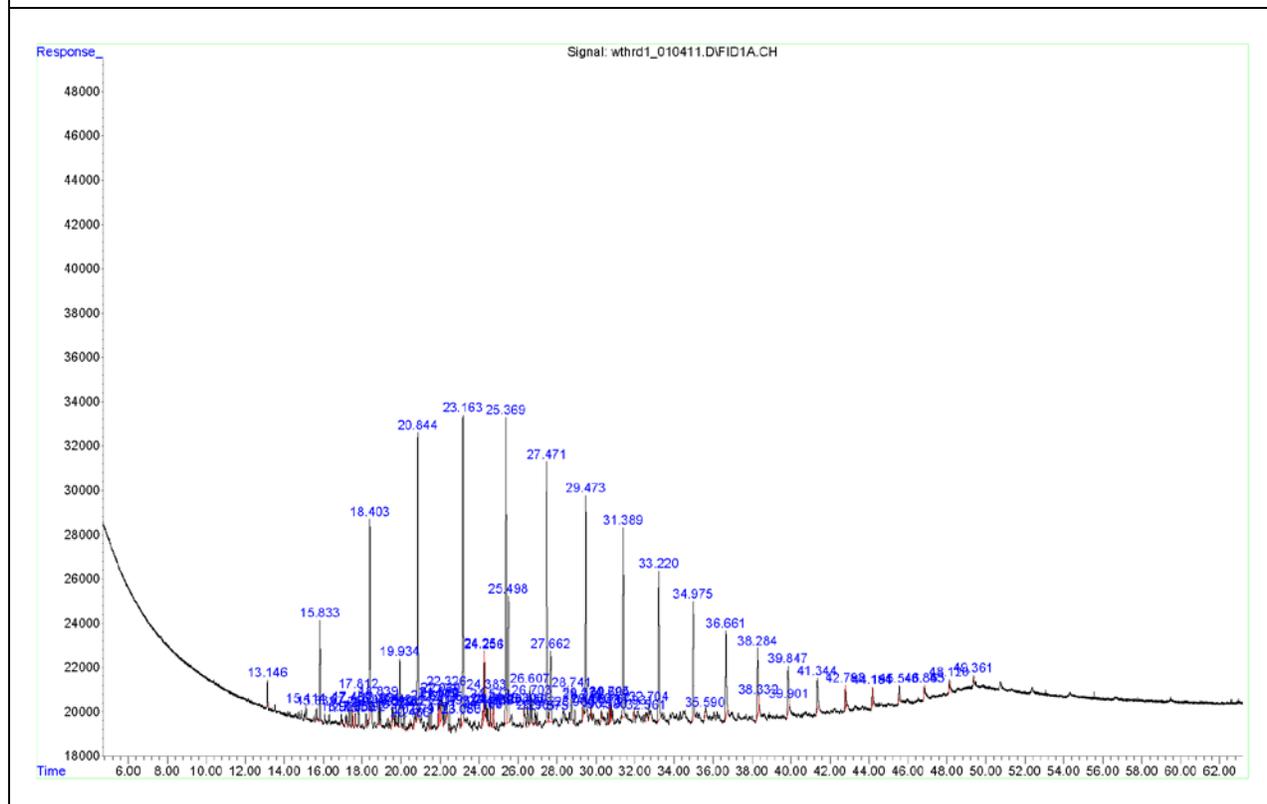


Figure 3: (A) Chromatogram of sample SF-13U (POD 3 Sample 2 removed from bottom after well cap removed, upper oil portion) showing early eluting peaks. (B) Chromatogram of Dow Corning III lubricant. Peaks identified by mass spectral analysis (Figures 4, 5, and 6 below).

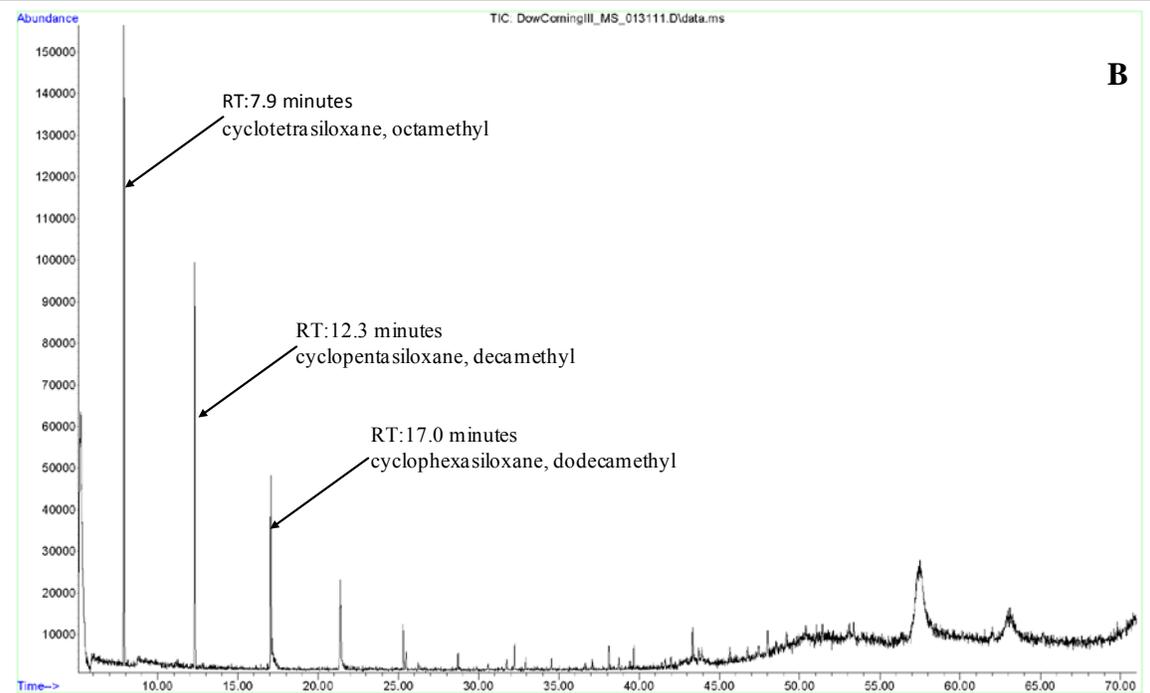
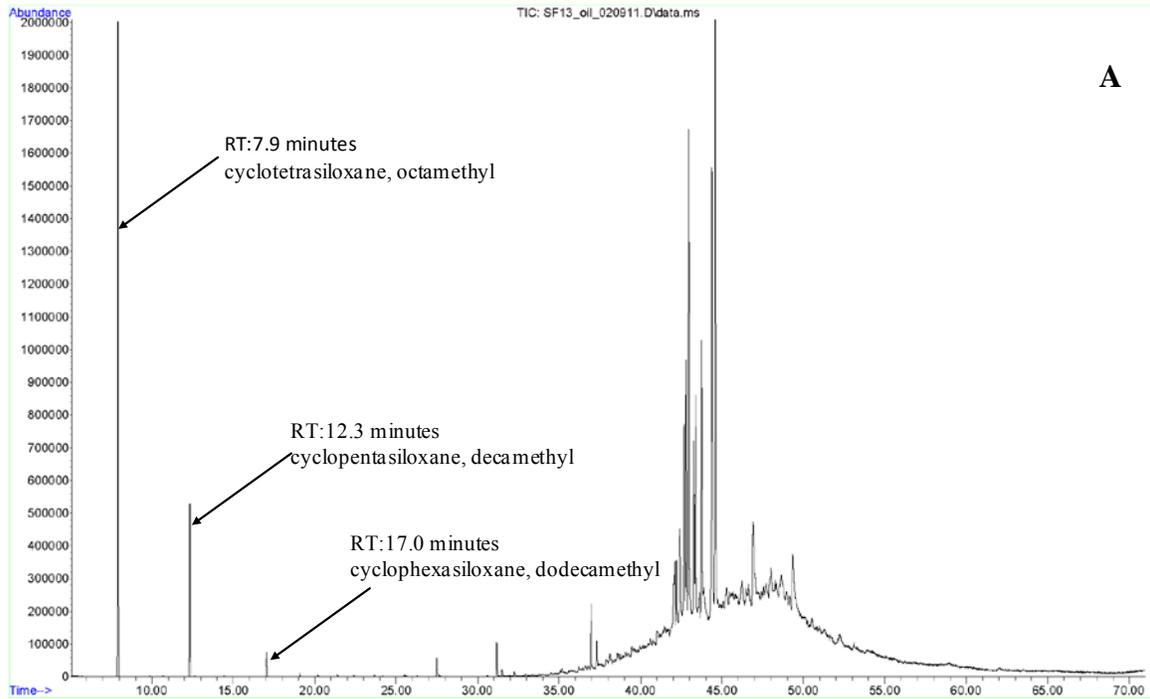
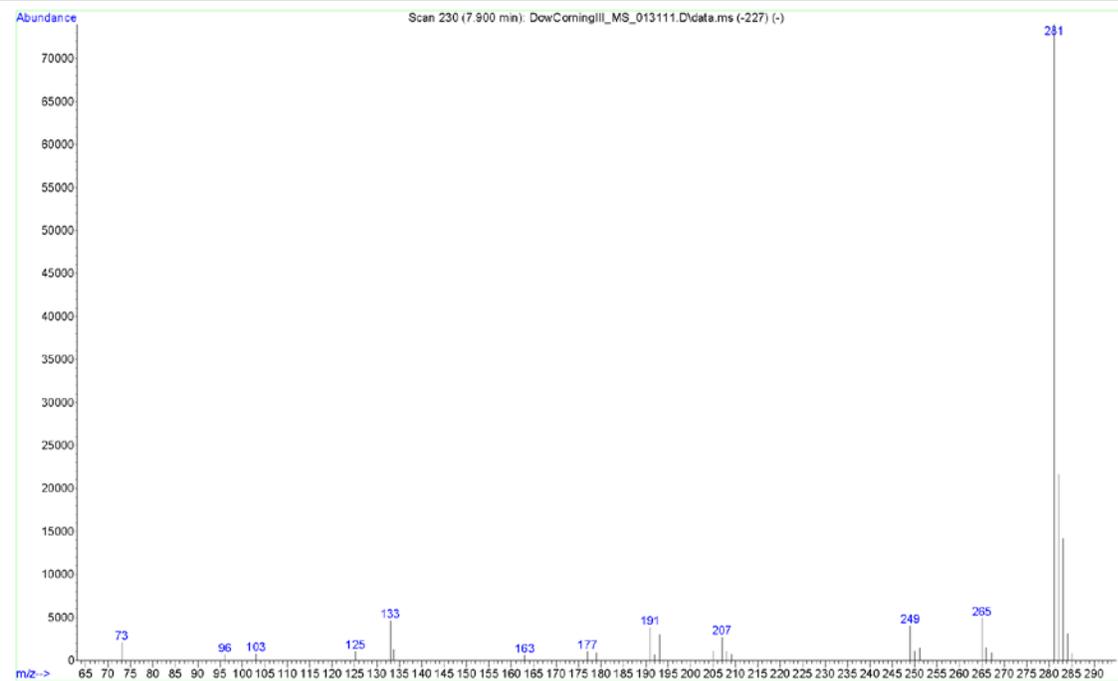
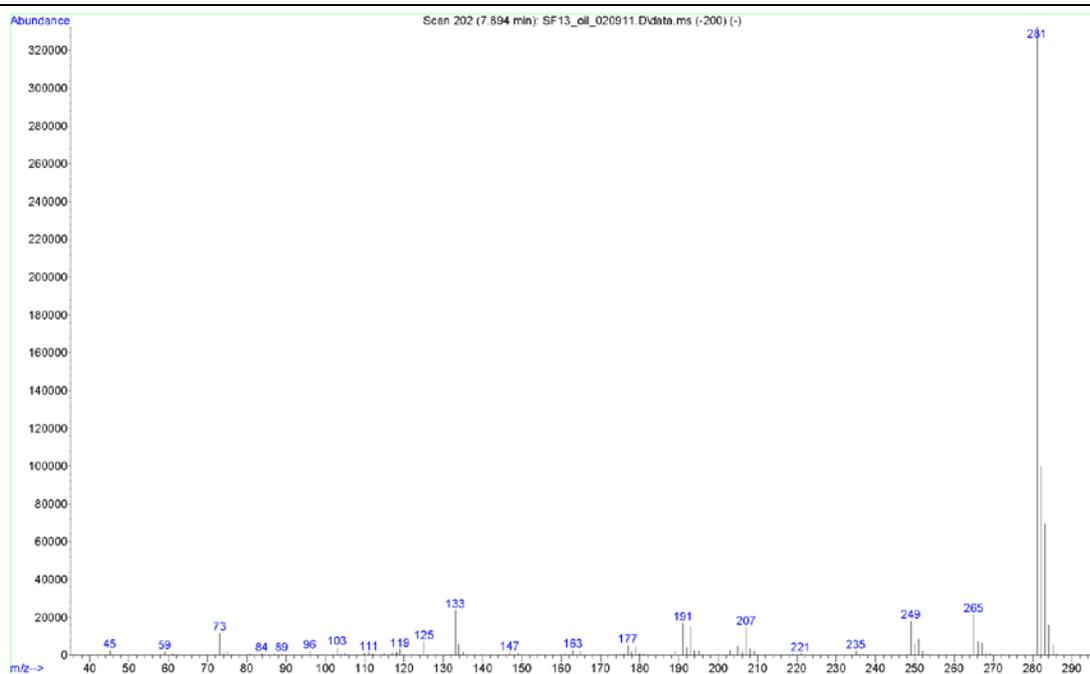


Figure 4. (A) Dow Corning III lubricant. Spectra at peak retention time of 7.9 minutes. Likely compound: cyclotetrasiloxane, octamethyl (93.9 % probability). (B) SF-13U (POD 3 Sample 2 removed from bottom after well cap removed, upper oil portion). Spectra at peak retention time of 7.9 minutes. Likely compound: cyclotetrasiloxane, octamethyl (96.4 % probability).



A



B

Figure 5. (A) Dow Corning III lubricant. Spectra at peak retention time of 12.3 minutes. Likely compound: cyclopentasiloxane, decamethyl (89.5 % probability). (B) SF-13U (POD 3 Sample 2 removed from Bottom after well cap removed, upper oil portion). Spectra at peak retention time of 12.3 minutes. Likely compound: cyclopentasiloxane, decamethyl (93.3 % probability).

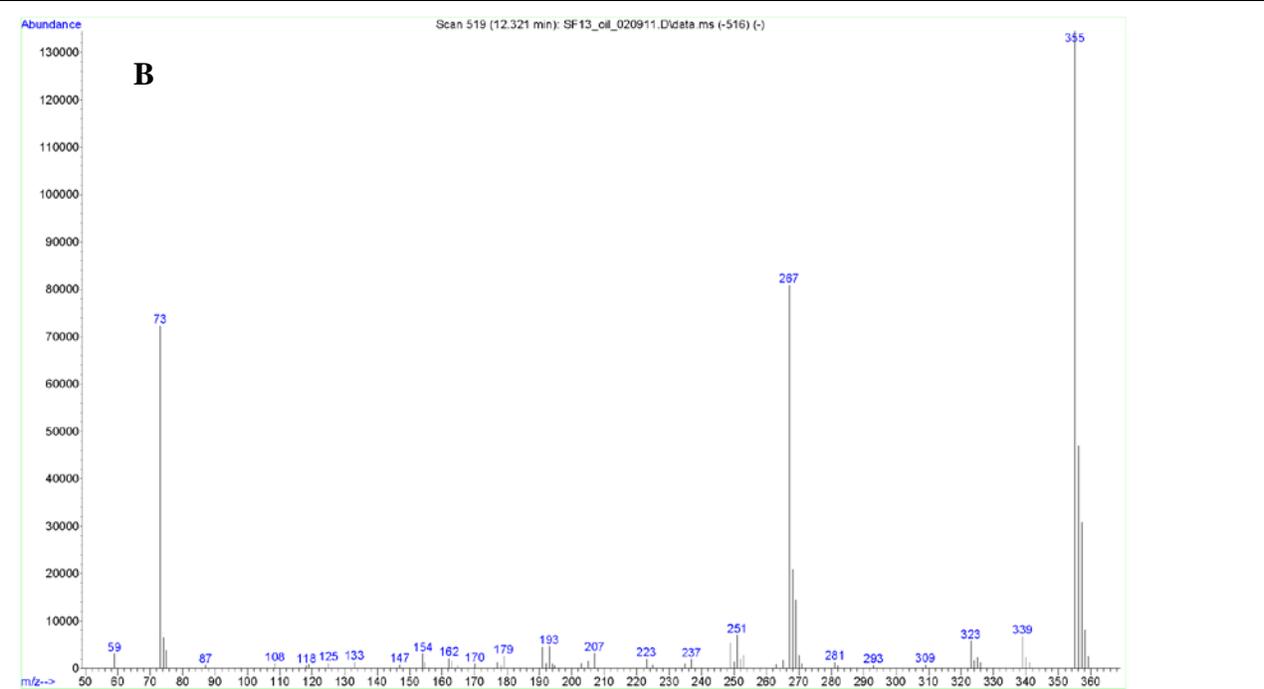
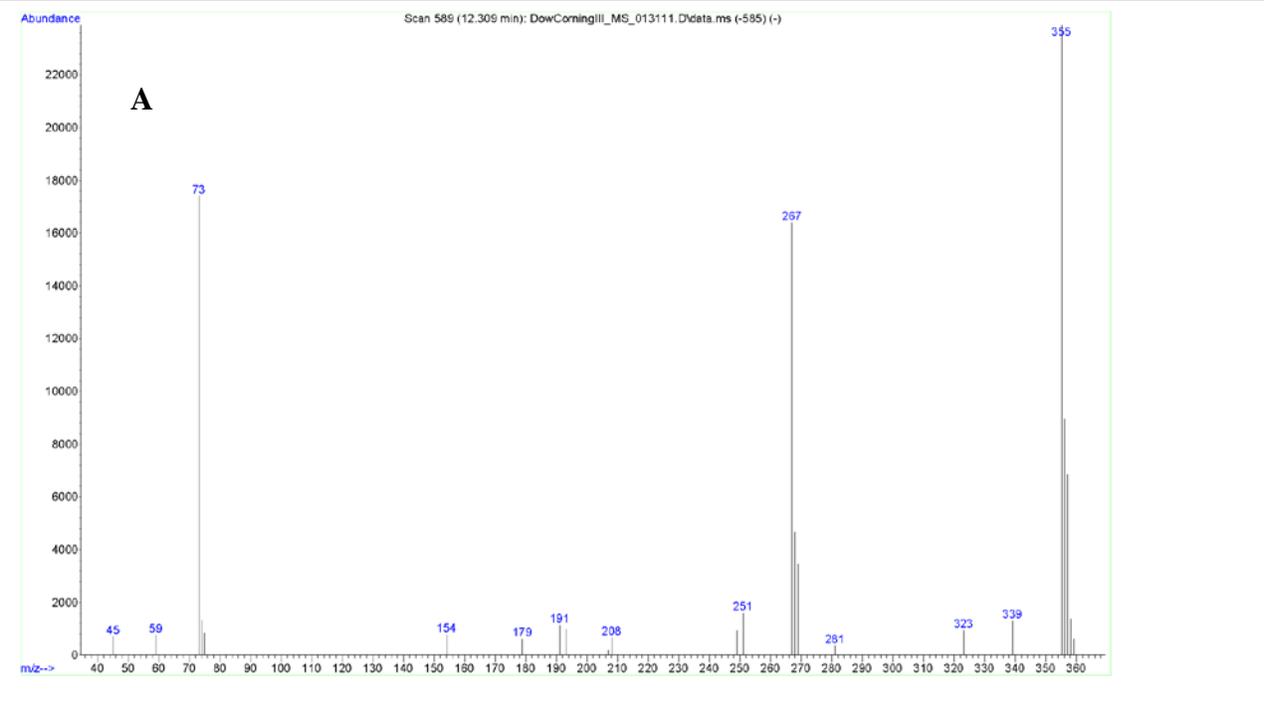


Figure 6. (A) Dow Corning III lubricant. Spectra at peak retention time of 17.0 minutes. Likely compound: cyclohexasiloxane, dodecamethyl (98.2 % probability). (B) SF-13U (POD 3 Sample 2 removed from Bottom after well cap removed, upper oil portion). Spectra at peak retention time of 17.0 minutes. Likely compound: cyclohexasiloxane, dodecamethyl (95.9 % probability).

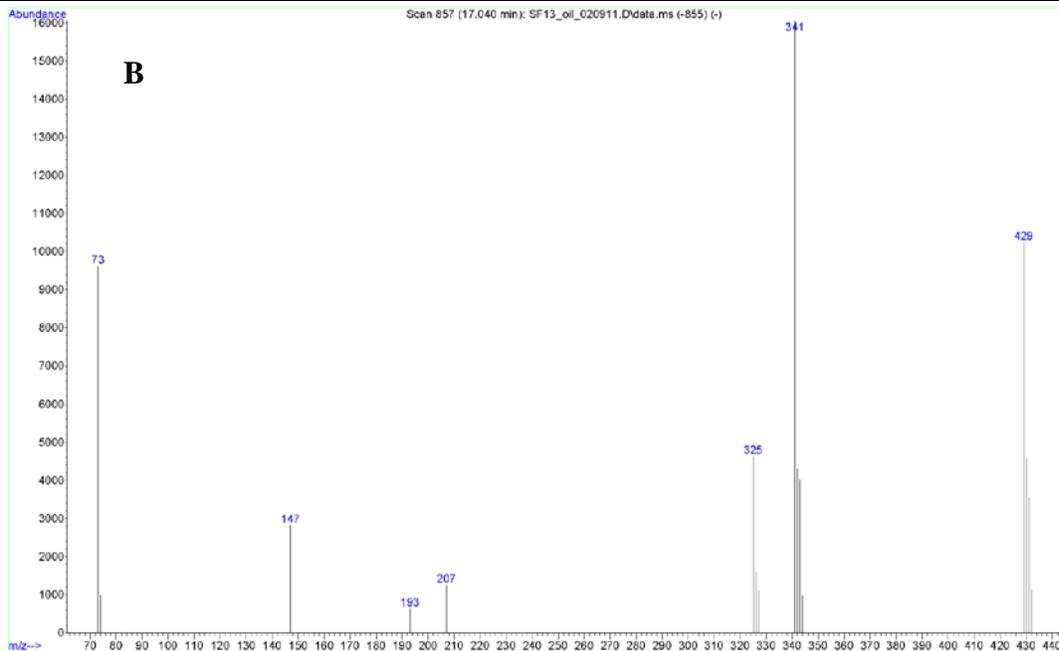
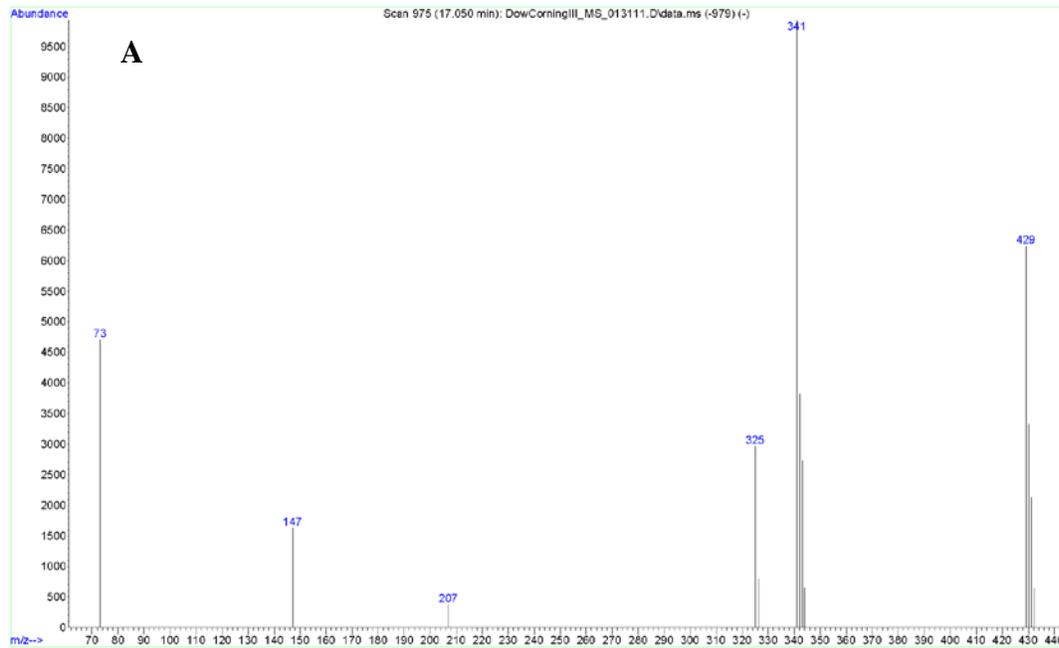


Figure 7: (A) Chromatogram of Mobil 1 synthetic oil showing peaks at 52.5 and 56.5 minutes. (B) Two samples of oil from PODs contained these peaks (SF-17 shown). (C) All other oil samples from PODs did not contain these peaks (SF-12U shown). Loss of peaks are indicative of motor oil degradation.

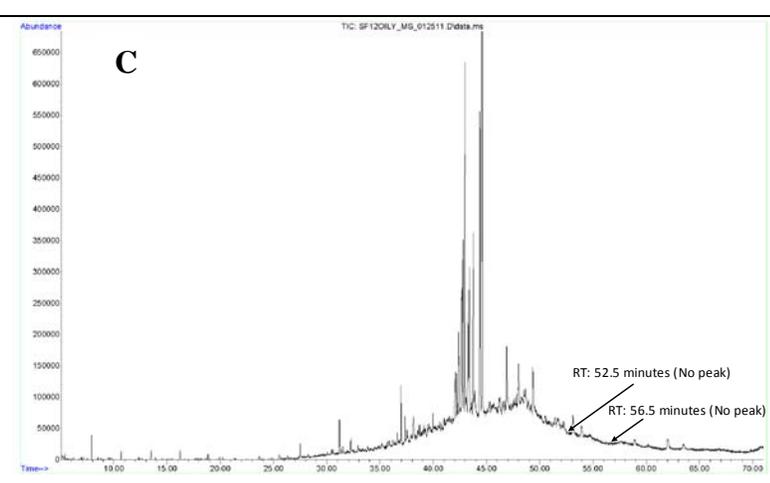
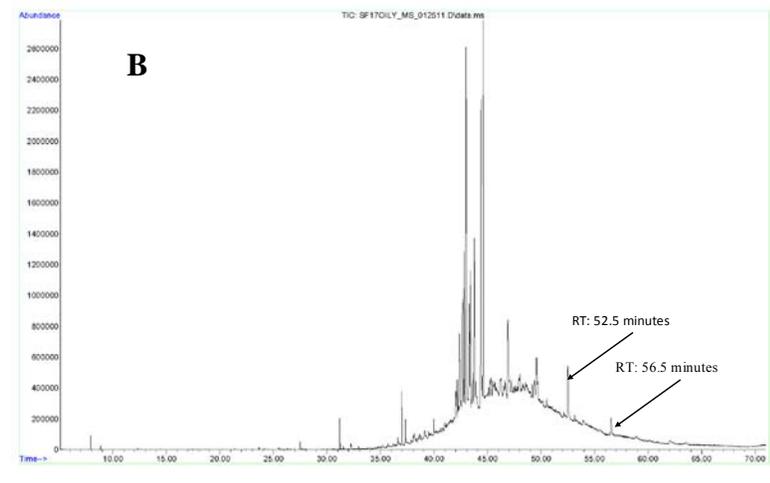
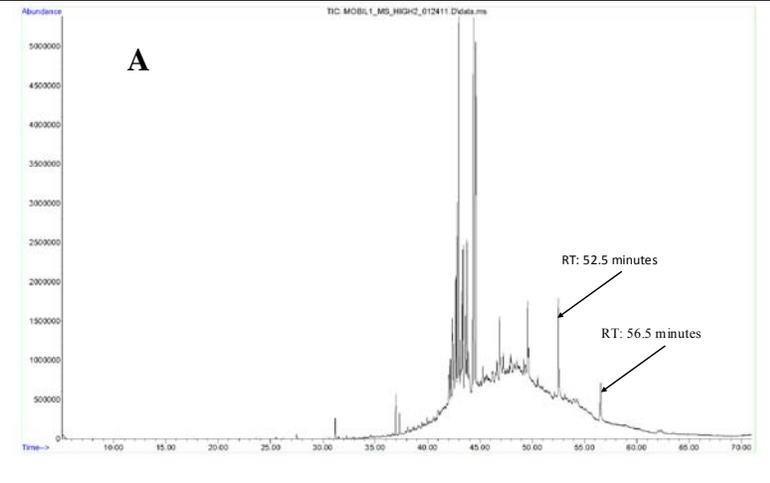


Figure 8. Spectra of oil components with a peak retention time of 52.5 minutes. (A) Mobile-1 synthetic 10W-40 motor oil. (B) Sample SF-17, POD 1 Sample 3 drained from the bottom of POD while tilted at 20 degrees. Mass spectra are consistent with nitrogen containing organic compounds, but were not identified using a library search.

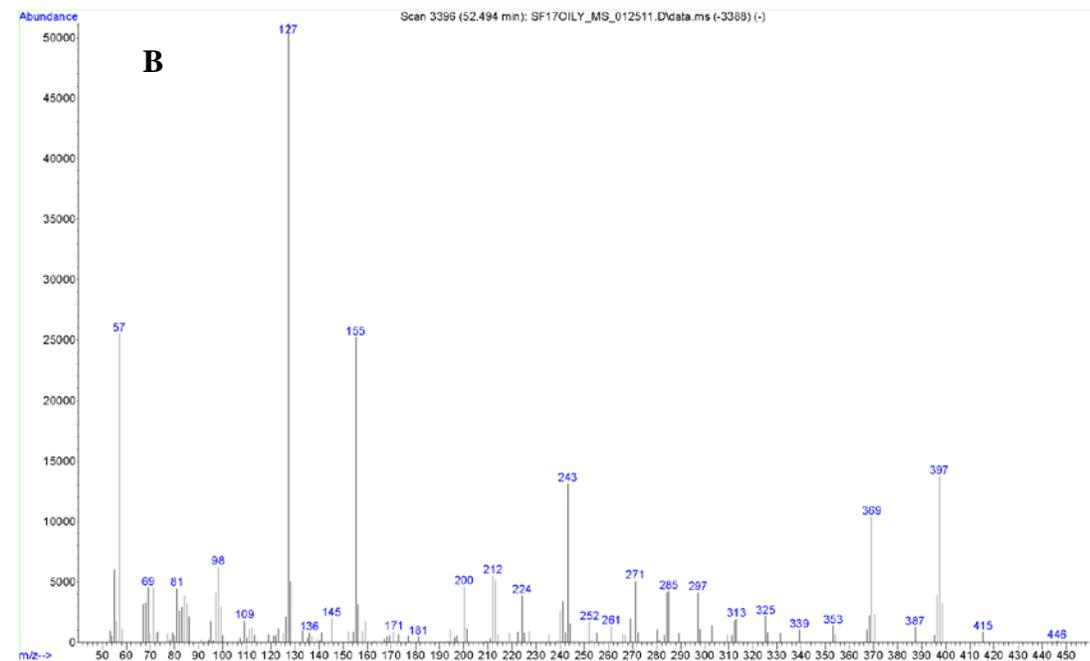
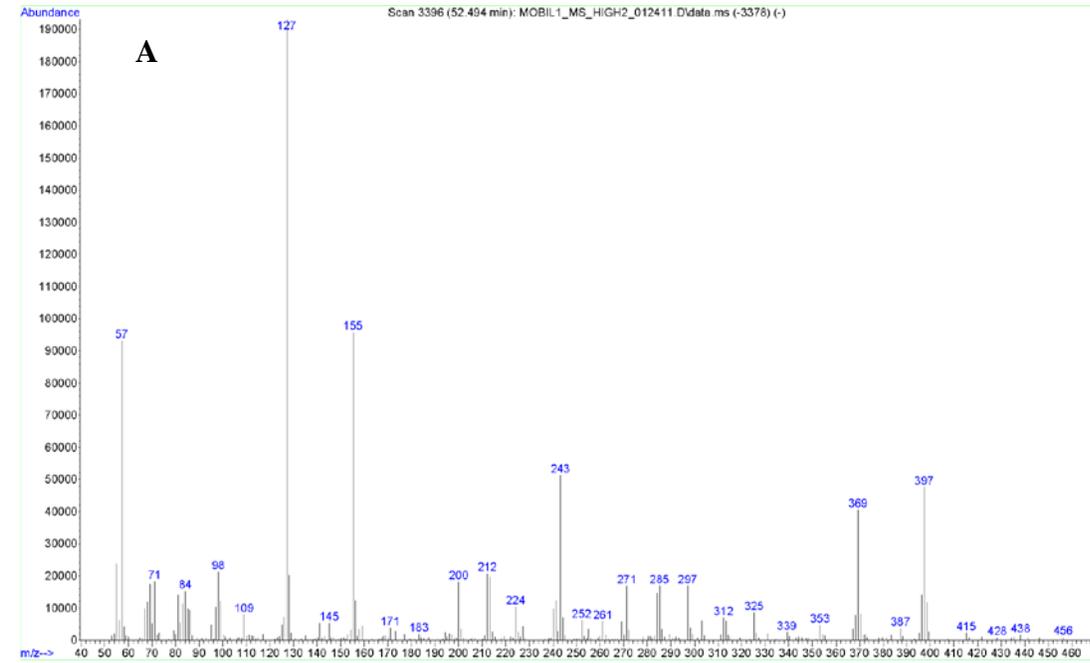


Figure 9. Spectra of oil components with a peak retention time of 56.5 minutes. (A) Mobile-1 synthetic 10W-40 motor oil. (B) Sample SF-17, POD 1 Sample 3 drained from the bottom of POD while tilted at 20 degrees. Mass spectra are consistent with nitrogen containing organic compounds, but were not identified using a library search.

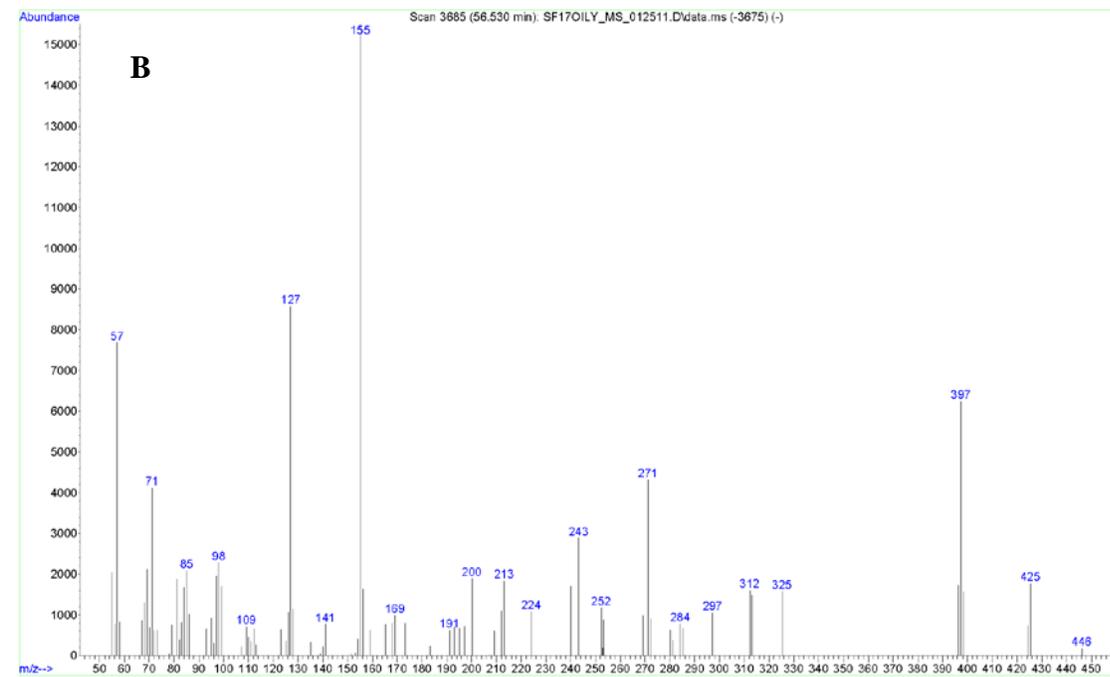
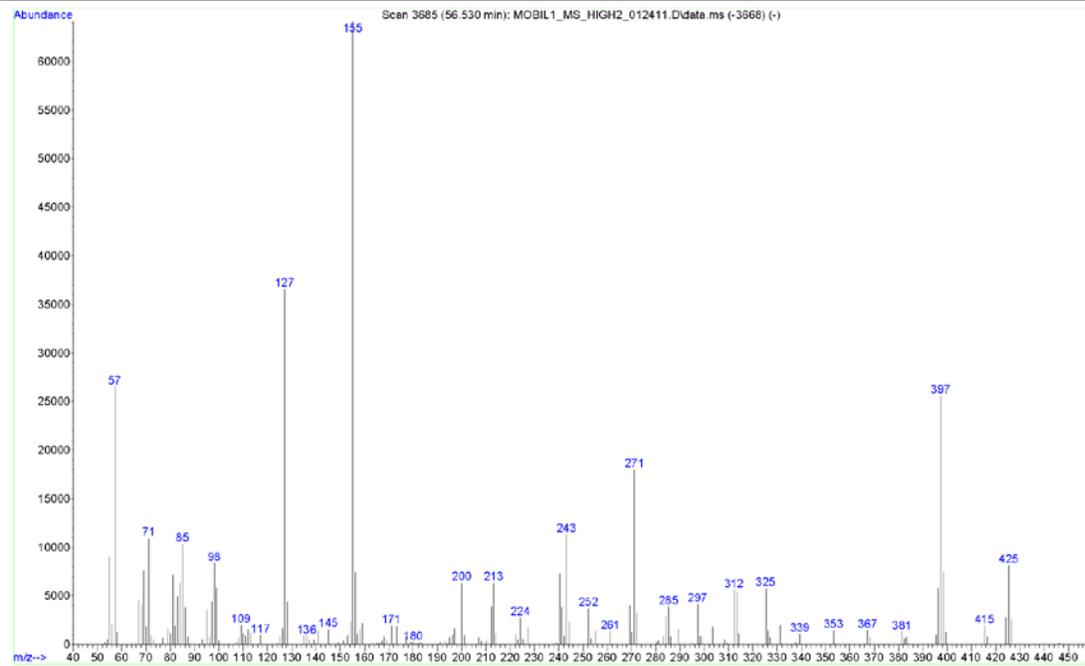
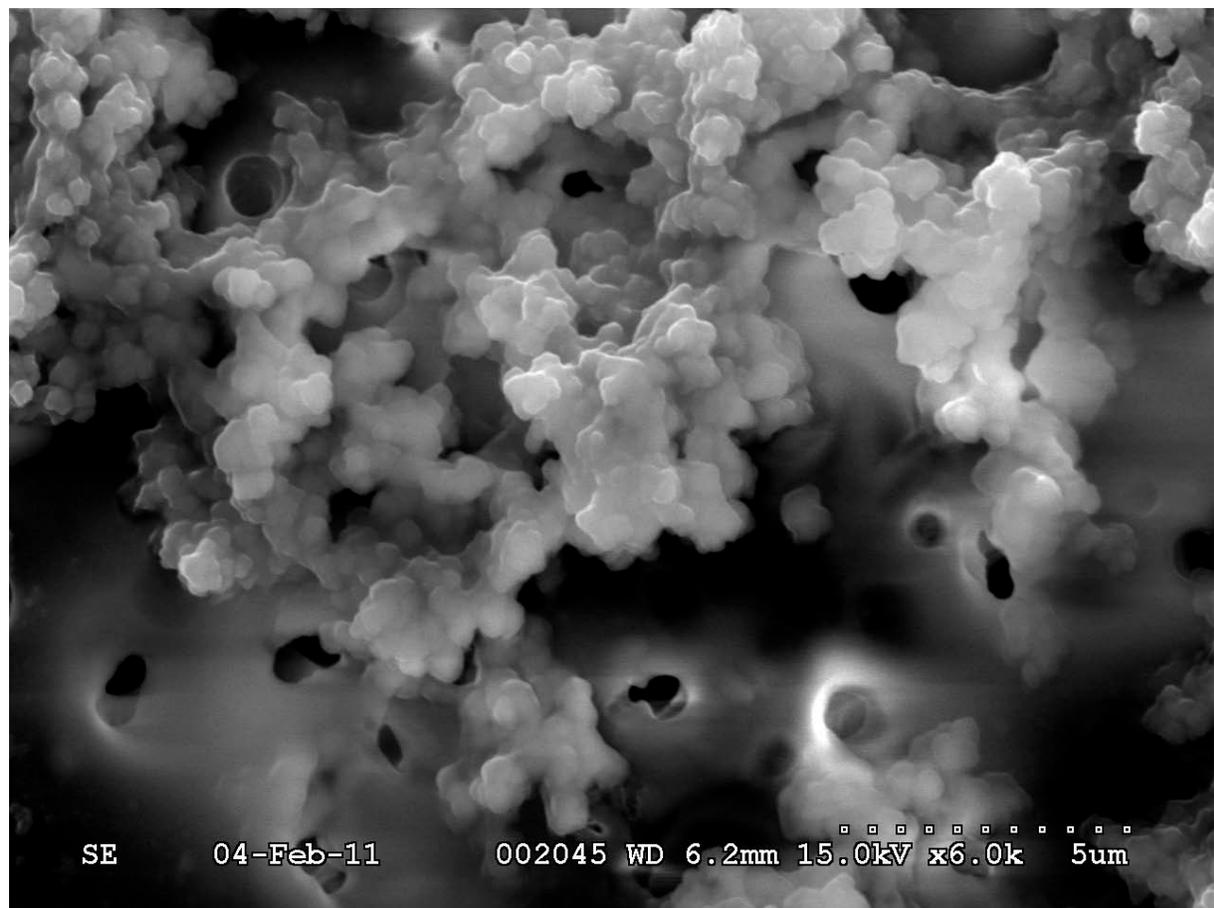


Figure 10. Scanning electron microscope image of SF-15L. The space between each square (lower right corner) is 5 μm (approximately 1000x magnification).



Appendix A

Summary of the test results

performed at SAFOD after the tool string was pulled on October 8th 2010.

Please refer to the sketch at the end of this document for the location of the different items mentioned in this report.

Overview

Between October 4th and 8th 2010 the tool string deployed at the SAFOD borehole was removed from the well.

Observations during the polling of the tool string

The polypropylene coating of both control lines which was in the inclined section of the well was damaged and showed abrasion and cuts – especially right above the Canon clamps. Well fluid got between the coating and the stainless steel tube and was bubbling out at the damaged locations. Fluid samples were taken. The coating was removed at several locations where the coating got damaged to check if the stainless steel tube was damaged. No damage to the stainless steel tube was observed.

Instrument removal

On October 8th the 5 PODs came to the surface.

1. The fiber optic line above POD1 was cut. The line seemed to be intact.
2. The fittings of splice S1 were loosened. The splice was not pressurized excessively, fluid appeared, which was sampled.
3. POD1 was removed. It is still attached to the EUE tubing since the hinges appeared to be corroded.
4. The line between POD1 and POD3 was cut in pieces while removing the EUE tubing to reach POD2. At each cut small amount of fluid appeared at the cuts.
5. Splice T1 was opened. The splice was not pressurized and seemed to be dry.
6. The lower of the two splices T2 was opened to disconnect the cable. A drop of fluid emerged, corrosion to the coax cable was visible.
7. POD2 was removed
8. The line above POD3 was cut. Small amounts of fluid appeared
9. The fittings of splice S2 were loosened. The splice was not pressurized excessively, fluid appeared
10. The line was cut below splice S2. Small amounts of fluid appeared at the cut.
11. POD3 was removed
12. The line was cut above POD4. It was dry
13. POD4 was removed
14. The line was cut above POD5. Small amounts of fluid appeared at the cut.
15. POD5 was removed

Summary of the test results
performed at SAFOD after the tool string was pulled on October 8th 2010.

PODS

Once the instruments were on the surface they were brought to the computer hut for testing. All tests were done by hooking the PODs directly to the power supply / modem without connecting through the 10,000ft cable(s).

POD2

The tiltmeter modem was connected to the top of POD2 at splice T1. The shield of the coax line was brittle and corroded.

When the POD was powered up, the POD never drew more than 20mA (a good tiltmeter draws ~75mA). U-I characteristic: 2V: 10mA, 4V to 33V: 20mA. The voltage was not increased above 33V to prevent damaging the tiltmeter.

Communication was attempted but failed.

The power (@ 33V) was left connected for about 20 min. Current draw did not change. After disconnecting the power, a small voltage was measured (~10mV), which was decreasing fast like when a big capacitor is been discharged.

The “battery-like” characteristic of the cable as seen prior to the removal of the tools string could not be reproduced.

Conclusion: POD2 acts like an “open” with some parasitic load

POD4

The tiltmeter modem was connected to the top of POD4 at the cut above POD4. The cut was clean and dry.

When the POD was powered up, the current jumped immediately to the pre-set max of the power supply (150mA) at a voltage of 5V. When the test was repeated, the POD acted like an POD2 for brief moment (20mA @ 26V), but after a couple of seconds showed signs of a short again.

Conclusion: POD4 acts like a “short”

POD1

The power supply for the seismic tool string was attached to the cut cable above POD1. The cut was clean and dry.

In order to close the current loop the splice below POD1 was opened. The splice was completely flooded with a fluid which smelled and felt like motor oil. Most likely it was the oil which was used to fill the PODs since there are no pressure seals between the inside of the PODs and the inside of the stainless steel tube.

The heat shrink and the kapton tape which was used to insulate the solder points inside the splice seemed to be dissolved by the oil and disintegrated at the first touch.

However a small layer of heat shrink remained around the solder and at least by a visual inspection the solder points did not touch each other.

The black and the brown wire below POD1 were connected together to form the current loop.

Summary of the test results

performed at SAFOD after the tool string was pulled on October 8th 2010.

When the power supply was turned on and the voltage was slowly increased, at no point more than 20mA was flowing through the line. The voltage was not increased above 50V to prevent the cable head / DS150s from been damaged.

The voltage between the top and the bottom of POD1 was measured while the power supply was set to 50V. 10V / 40V were measured between the red line (+) / blue (-) and the bottom.

The fibers were spliced to an connector and attached to the data acquisition system. Communication was attempted but failed.

POD 3, POD 5

Since no equipment was on site to test the DS150s inside the PODs without the fiber optic converter, a working POD1 was required to test PODs 3 and 5. So no assessment of the state of PODs 3 and 5 could be made on site.

When splice S2 was opened, the same situation as in splice S1 was observed: The oil dissolved the Kapton tape and the heat shrink. The brown wire broke above the solder joint, most likely at the location where the insulation was stripped.

Cables

The cables (rolled on the spools) were tested for continuity (Multimeter) and insulation (1G Ω Megaohm-Meter)

Fiber-Optic Cable

End – to – End:

- Red: 99 Ω
- Blue: 99 Ω
Fiber optic tube: 5k Ω
- Stainless steel tube: 155 Ω

Insulation:

- Red to Stainless steel tube: ∞
- Blue to Stainless steel tube: ∞
- Red to Blue: ∞

Coax Cable

End – to – End:

- Center: 64 Ω
- Shield: 66 Ω
- Stainless steel tube: 185 Ω

Insulation:

- Center to Stainless steel tube: ∞
- Shield to Stainless steel tube: ∞
- Center to Shield: ∞

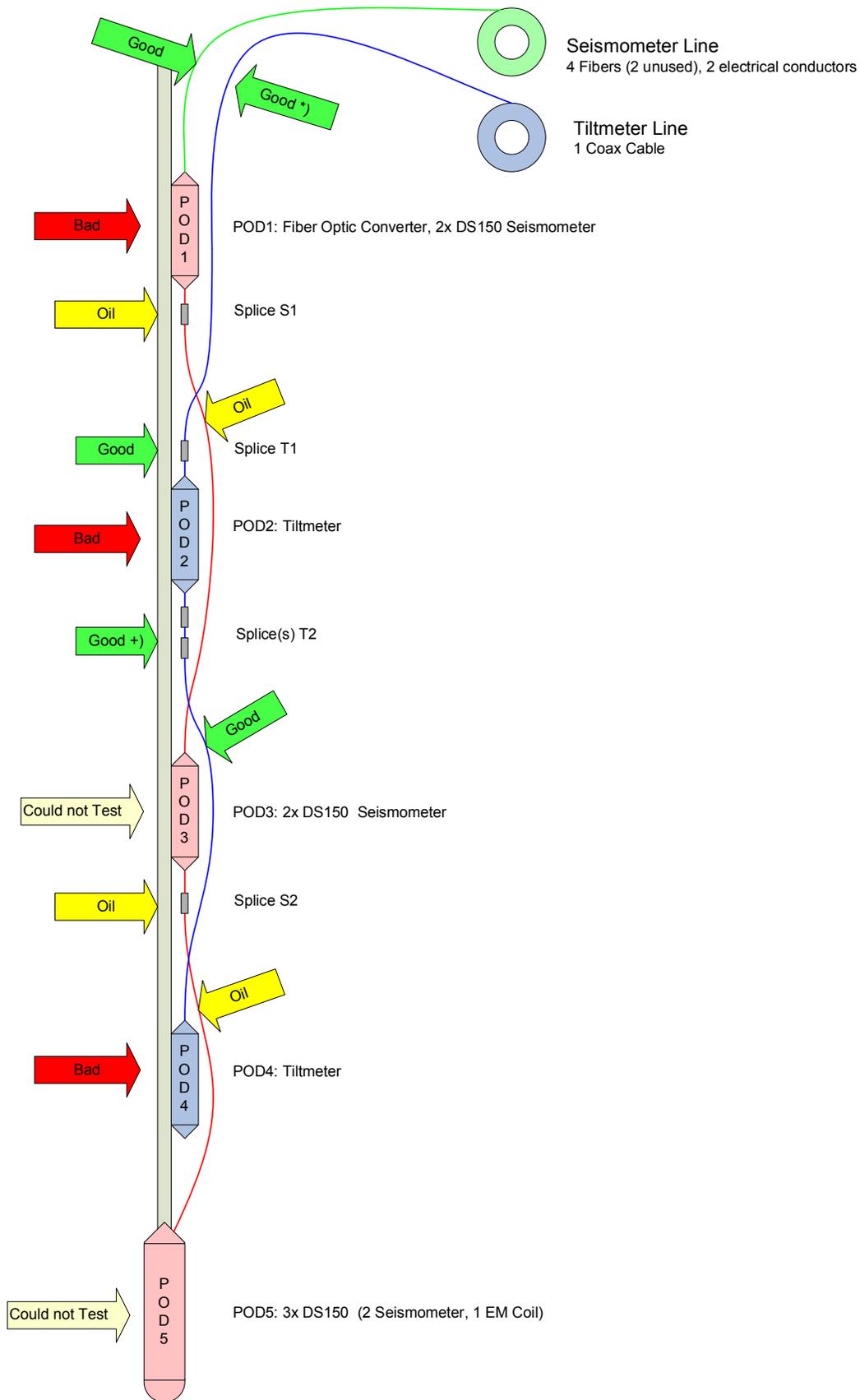
Summary of the test results
performed at SAFOD after the tool string was pulled on October 8th 2010.

In contrast to the uphole end of the cable the downhole end was corroded: The center cable was black, the shield was brittle and no shiny.

Recommendations for further tests

1. Test POD3 and POD5 directly (not going through the fiber optic converter) connected to the GeoRes data acquisition system
2. Do the test of POD1 again
3. Open the PODs, remove DS150s and tiltmeters from the PODs and connect them directly to the data acquisition system / tiltmeter modem.

Summary of the test results performed at SAFOD after the tool string was pulled on October 8th 2010.



Appendix B

SAFOD fluid and propant samples from inside of instrument Pods.

Collected Nov 29th to Dec 2nd.

Pod 1: Three samples collected. 11/30/10

Sample 1: Fluids collected after top cap removed

Sample 2: Fluids collected when bottom cap was cut off of pod

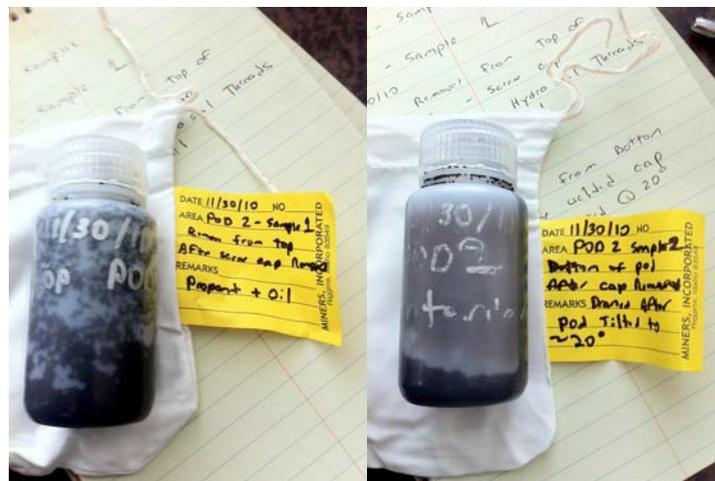
Sample 3: Fluids and some propant. Collected from bottom of Pod1 while it was at ~20degree angle.



Pod 2 : Two samples. 11/30/10

Sample 1: Propant and fluid removed from top of pod 2 after cap was removed.

Sample 2: Fluid removed from bottom of Pod 2 after cap cut off. Pod was at ~20 degree angle.



Pod 3: Three Samples. 11/30/10

Sample 1: Propent and some fluid. Large voids at top. Had to dig out propent with rod.

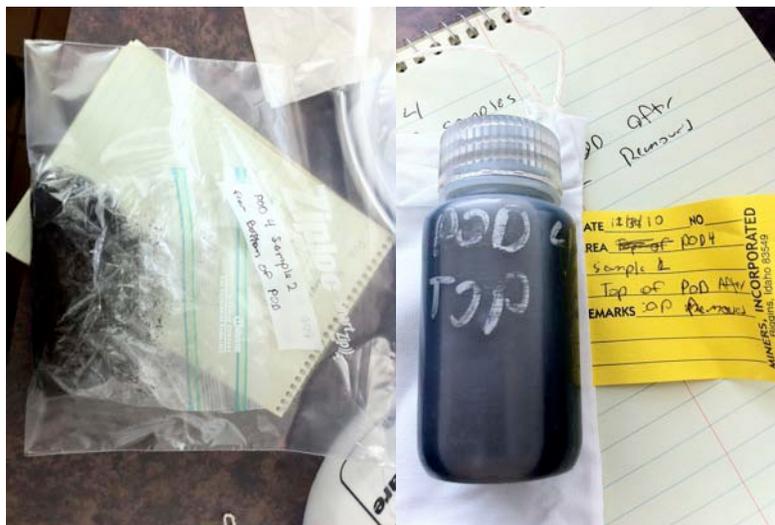
Sample 2 and 3: Fluid collected when bottom cap was cut off. Milky grey fluid with gel like material.



Pod 4: Two samples 12/1/10

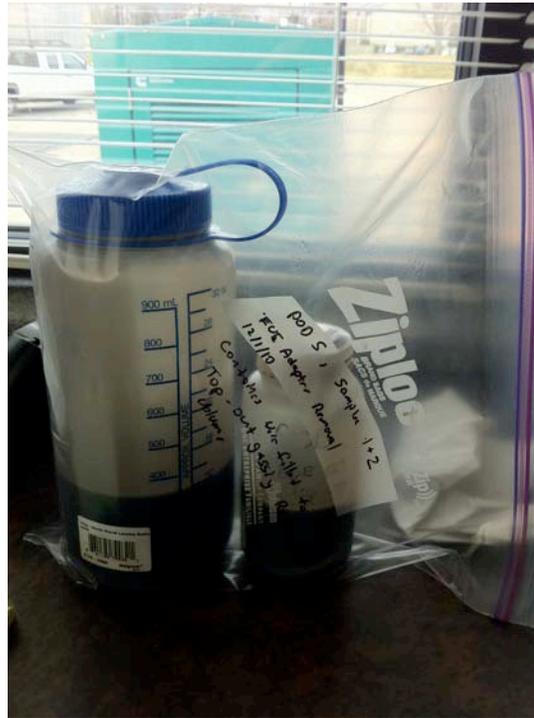
Sample 1. Fluid from top of pod after cap was removed

Sample 2. Propent from bottom of pod after cap cut off

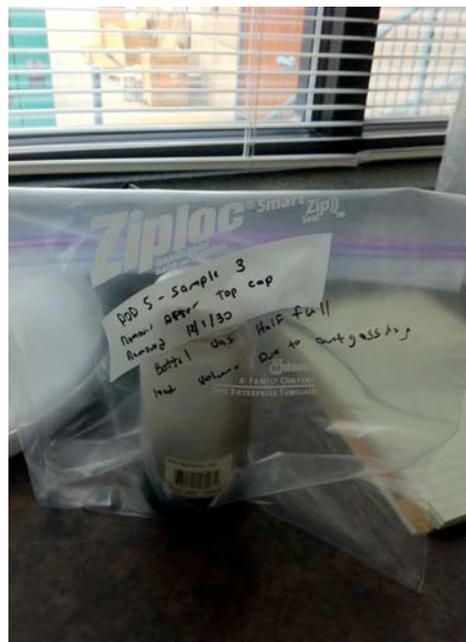


Pod 5: Seven Samples. 12/1/10 to 12/2/10

Samples 1 and 2: Fluid captured when EUE adapter was removed from top of Pod. Bottles were filled to top with fluid. After degassing fluid has lost 2/3rds of its volume.



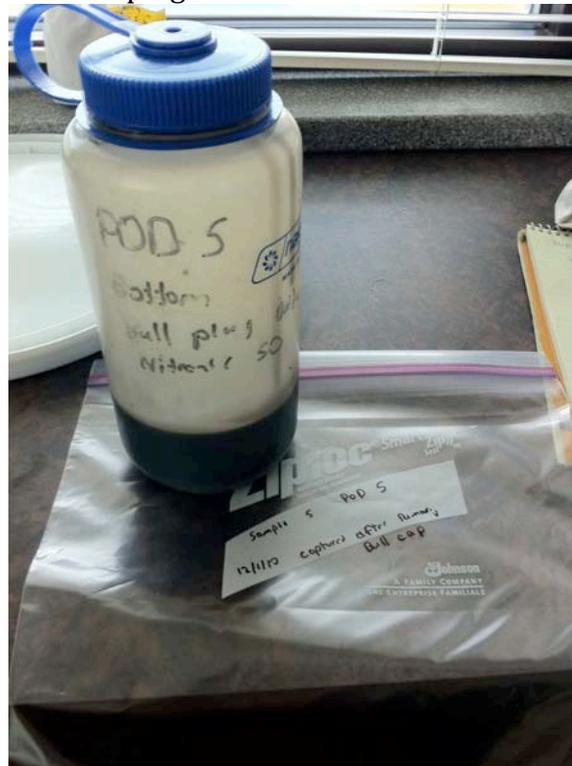
Sample 3: Fluid captured when top cap was removed. Sample has also lost 2/3rds of its volume.



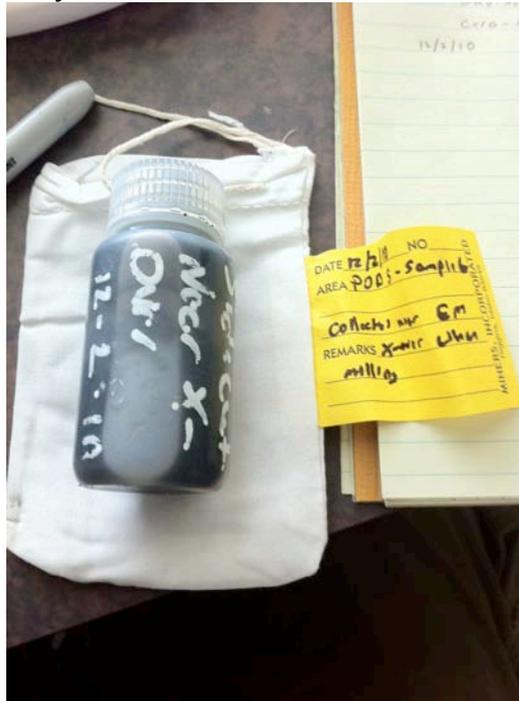
Sample 4: Captured when bull plug was removed. (bottom cap under Nitronic 50 section)



Sample 5: Captured after bull plug was removed.



Sample 6: Captured when milling Pod 5's carbon steel section on 12/2/10. Broke through wall near EM tool cross over. This section was a pressurized filled with fluids. Cavity was sealed by Cerro-Tru.



Sample 7: 12/2/10 . Propant recovered from interior of POD 5 after splitting carbon steel section.

Cerro-Tru samples:

Pod1. One sample from interior of pod

Pod 4: Two samples

Pod 5: Two samples.

Internal samples.

Pod 2 Tiltmeter. Two Samples:

Sample 1: Swabs from inside tiltmeter housing

Sample 2: Fluid from Bottom interconnect.



Appendix C

Samples shipped to Will Stringfellow.

Pod 1: Fluid from bottom of Pod.

Pod 2: Fluid from bottom of Pod.

Pod 3: Propent and some fluid from top(LArge airspace at top of this pod when we opened it.)

Fluid from bottom of pod. Fluid may have out gassed into bottle.

Pod 4: Fluid sample from top of pod.

Pod 5: Fluid captured when EUE plug removed. (degassed. Gas trapped in bottle)

Fluid captured when bull plug removed from bottom of pod

Fluid captured while milling. Was in pressurized cavity near EM tool X-over.

Swabs and oil from tiltmeter in Pod 2

Samples from removal:

H2O sample taken from well head before removal. (2 60ml bottles)

Fluid from Splice S1

Fluid from Splice S2

Fluid from cable cut 1 m above pod 5

Mud and fluid collected from exterior of EUE joint bellow Pod 2

Mobil 1 synthetic "High Milage" 10w-40 motor oil. This is the only 10w-40 motor oil they produce at this date. Unknown if this is the same as the oil used for SAFOD.

Please return unused samples. Thanks!

Wade Johnson
Strainmeter Engineer
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Joe Henfling's Houston Meeting Notes

11/28 Questions prior to meeting

Questions for Pinnacle –

- 1) Mixture of oil, propend and cerro metal alloy: Preheat and “pour” into annularus of pods and tool housing? (except Pod5 where metal poured after oil and propant)
Note: Cerrotru metal alloy was Carboprop 20/40 with Mobil 1 motor oil
- 2) Assembly procedures
- 3) Details on wires entering electronics
- 4) Ability to “turn off” bottom tilt meter?
- 5) Electronics testing?
- 6) Electronics monitored during welding?
- 7) Thermal expansion issues

11/29 - Meeting at Pinnacle:

Background of project, points discussed during meeting

- Pilot hole has no gas production
 - o Main difference between pilot and main hole
- DS150 (with no locking arm) and DS250 used in pilot well
- 6 week (3 weeks) in main hole because of gas related issues
 - o Mainly shorts in cablehead
- No previous data to indicate if tools would last approximately 3 years
- Requirement for good sensor coupling lead to “POD” design approach to isolate tools from gas environment
- Pod 5 has termination for both power and telemetry for current loop
- Pods have multiple DS150 to able required functions
- Pod 5 has 3 DS150s
- Pods 1 and 3 have at least 2 DS150s
- Tilt 4 shorted when installed
 - o “switchable” to enable isolation from tilt 2
- Top DS150 in Pod 5 failed first
- After tilt tools failed, indication from surface was one tool “shorted” and one “opened – no current draw”
- DS150s are 1.625” OD; ID of Pod was 1.995”; wall thickness was approximately .217” (range of .190 to .217)
- Intentional air pocket at top of Pods to allow for expansion of oil
 - o Approximately 5/8” air pocket
- Standard hardware used inside Pods – standard cablehead but modified to allow Swagelok fittings; uses elastimer seals throughout standard units
- Before shipping failed instruments after they were pulled:
 - o Test of Pod 3 and 5
 - o Pod 1 was already tested as much as possible until fiber converter is separated from DS150 (Pod1 is disassembled)

- Lincoln machine shops disassembly plans (based on dimensions given):
 - o Remove Pod from EWE tubing at weld
 - o Cut end caps off
 - o For Pod 1; 2.992" ID and 3.5" OD and 10.8 feet long
 - o Split using Horizontal mill (2 cuts 180 degrees)
 - o Open top end and pour out oil/sand and take sample
 - o Remove as much of tubing up to top of electronics to eliminate horizontal cut length
 - o Cut bottom sub off and pour as much as possible (take sample)

- After meeting, went to shop area to power up Pods
 - o Tried to power Pod 3 and 5 with no response; current ok
 - o Tried to power Pod 1; spliced fiber, current ok, transmitter ok, no response from downhole electronics

Evening meeting with Bill and Steve (USGS); questions/topics

- History of MH007 to MH20
- Tilt failure
 - o Package is basically "off the shelf" 50+ units out in industry
 - o Resolution 100 u radians; sample rate 1 second
- Data when failed and characteristics of failure
- Talk over Pod disassembly procedure
- Chemical analysis prior to installation
- Details of analog tool
- Fluid taken when tools were pulled from well
 - o 500 ml at wellhead – September 20, 2010
 - o Collected "drops" to few ml at various locations
- Tour of FTP site

Notes from meeting with Bill and Steve:

- completed main well has gas issues that effected cablehead and cable
- DS150 (1.5" OD) and DS250 (2.5" OD)
- 15 Hz geophones, 3 axis
 - o Electronics include digitizer, telemetry
- Most USGS testing was with DS250
- Pinnacle would have preferred running tools into pipe that was oil filled, but not enough funding
- DS150 was "reversed engineered" to enable geophones to be replaced with MEMS accelerometer
- Kalrez V95 was first line of defense; backup was Viton 90 orings
- Splices did not use staggered joints (all splices at same location, then heat shrink wrap and taped)
- USGS does have analysis of downhole both liquid and gas phase
- High pressure (1000 psi) at surface when drilling complete, now not present (acts like a large accumulator)

- Most likely not as much of a gas issue compared to earlier days (end of Phase 2)
- Tools failed like a short
 - Failed sequentially; starting at bottom
- Tilt tool was monitored when deployed, as such know depth of failure
- Data was ok; then spikes, followed by complete failure
- Does have module status but not monitored until problems were encountered
- Question: failure of individual DS150 – Did Pods fail as a unit or individual DS150s failed before complete Pod failed
- Accelerometer used for MEMS was Colibrys SF1500
- Geophone rated to 100C (GS20)

11/30 At Lincoln Machine shop to witness the disassembly of Pods

- Disassembly of Pod2 (top tiltmeter) Start time 8:30am
 - Removed bow springs with portable saw
 - Cut off top Swagelok fittings
 - Removed top cap; unscrewed without a problem (hydraulic pipe threading unit used)
 - Took sample at top; looked like sand/oil mix, no water
 - Cut lower Swagelok fitting
 - Tried to lift Pod vertically to see if tool would slide out; no luck
 - Cut around welded end with portable bandsaw
 - Took sample; looked like top sample
 - Tried to use forklift to push tool out; no luck
 - Hydril thread connections looked good; evidence of seal (clean metal- photos taken by Bill)
 - Note – electronics housing in Pod was not centered; top touching one side of Pod ID and the bottom electronics housing touching opposite (electronics was at an angle)
 - Set up to cut slots using horizontal mill
 - Will try and not cut all the way through
 - Tool was only a few inches from bottom end of Pod
 - Bottom Swagelok fitting was removed and it looked ok

- Disassembly of Pod 1 (10:30am)
 - Cut hinge pins and removed CS tubing
 - Cut Swagelok fittings
 - Removed top cap using hydraulic pipe threading unit
 - Sample taken; looked better than Pod 2, cleaner oil, less “sand”; no evidence of water
 - Electronics housing was located near top of Pod
 - Cut bottom welded connection using portable bandsaw
 - Top seal looked ok; evidence of working seal (clean metal)
 - Sample taken when bottom sub was cut off (tool was horizontal);
 - Looks like oil/sand mix; no evidence of water
 - Cerrotru in bottom sub (end piece that was cut off) came out in “strips” and looking into Pod looks like “blobs” and “strands” of Cerrotru; some oil and propant, but mostly Cerrotru
 - Top sample was mostly oil, with a bit of propant
 - Considerably more oil evident at bottom end compared to Pod 2
 - Bottom of sub had Cerrotru at the bottom 4”; up from the Cerrotru to bottom of DS150 was approximately 4” (total of 8” from bottom of sub where it was cut off to bottom of DS150);
 - As it turns out the Cerrotru was basically in pieces that was loosely held together; it could be easily broken up
 - After looking at it in more detail, the Cerrotru was more solid than originally thought; one side looked melted together and was left in the

Pod; the part that was cut off had a lot of “strings” but also had solid chunks

- Removed chunk from Pod; the top part was melted together

START of milling of Pod 2 – 1:30pm

It is being cut dry; the slot width is 3/8” mill slot

- Disassembly of Pod 3 (top end) – approximately 1:30pm
 - Swagelok was cut off both top and bottom of Pod
 - Using hydraulic unit, unscrewed top cap
 - When opened, no oil was present
 - Had propant/oil mix
 - No evidence of water
 - Seal looked ok, but possible signs of contamination (not as polished looking as Pod 1 and 2)
 - Looks like gas seal (bottom seal in connection) was compromised
 - Jake from Lincoln Machine shop indicated the threads were over torqued and as such, compromised the thin seal
 - The liquid seals are probably ok
 - Gas seal shows signs of pitting
 - Top of tool is approximately 9” from top of Pod
 - Note: copper thread lube is recommended on Hydril threads
- Disassembly of Pod 4
 - Using hydraulic unit, unscrewed top sub
 - Had considerable smell
 - More oil than previous Pods; no propant or Cerrotru
 - Oil looked like oil of top sub of Pod1
 - Pod 4 tool top was very close to top of Pod; maybe 2” from top of Swagelok fitting
 - Seal looks similar to Pod 4; evidence of over torque condition and the seal had pits
 - First sign of pipe dope on threads (other Pods had no indication)
 - Cerrotru is mainly on one side of the electronics package
 - Bottom plug was cut off with portable band saw
 - The plug was full of propant and oil mix; more mix in Pod
 - Smell was strong (H₂S?)
 - Oil looks ok
 - Removed considerable propant from Pod bore
 - Bottom of tool is 27” from where the Pod end was cut off
- Disassembly of Pod 3 (bottom end)
 - Cut off weld joint using portable band saw
 - Water looking liquid dripped out of saw cut
 - Later it looked like a gell-like liquid

- Liquid/sand mixture
- As the cut was complete, the water like substance “squirted” out at times (liquid under pressure)
- Probably at least a quart of substance came out
- Chunks of “ice” consistency blobs came out as well
- Bottom of DS150 was 12” from cut end

At approximately 3:30 pm the first mill slot penetrated Pod 2 in two places. The slot exposed the tool and indicated the tool was approximately .040” from Pod wall. Note: while machining the Pod got hot enough to melt Cerrotru; The cutting of the first slot took about 2 hours from start.

At 4:10 pm the slot broke through and the Pod was rotated 180. Oil came out, but not a lot (probably a few tablespoons of oil). It appears the Cerrotru was concentrated in 2 or 3 areas along the length. Not evenly spaced; some stringers; no propant was observed; oil looked clean

Evening meeting with Bill and Steve 11/30

- History
 - 2008/09/23 Deployment of system
 - Short in splice between Pod 3 and Pod 5
 - Repaired
 - Issue developed between Pod 2 and Pod4 during deployment
 - Repaired?
 - 2008/09/26
 - Right after tool string passed deviation in well, Pod 4 stopped working
 - When tools recovered earlier this year, the splice was ok; no short
 - Powered down on 10/04 to replace power supply; powered back up on 10/09; Pod 5 did not respond
 - After 2 hours, Pod 3 stopped working and one of the DS150s in Pod 1 stopped responding
 - Note: tilt meter string was powered using an improper power supply and possible damage to string; the Y accel failed and shortly after the tool stopped working
 - Probably a coincidence, normally over voltage would fail the regulator
 - Usually a single accel failure is an indication of temperature related issues
 - Seismic tool working ok at this point in time, could use 42db of gain and obtain great results
 - After 4 days, status errors started to develop
 - Got worse, then better for 2 hours, then bad; now temperature is up to 135C (internal) up from 123C at start

- Powered down to let cool; no life after that 10/14
- Checked impedance of power line and looked ok
- Converter has no processor (no diagnostics); just takes RS485 and converts to fiber; hence no tools, no data
- December 2, 2008 sample at surface from wellhead and appeared to be Mobil 1 possibly lost from the Pods; at that time, the well was pressured up and when vented, received this oilish mixture out of the vent
- In Pod 3 the bottom had approximately 1 quart of water/oil and the tool was started horizontal; one would think the water would have been seen at top

12/01 at ~ 7:30 AM

Pod 2 is now ready to have the “lid” cut off.

- Small amounts of propant is concentrated around the mid section

Note: talked to shop foreman about the “over torqued” threads. Yesterday when the top subs were being unscrewed, no torque was indicated by gauge. If the connections were over torqued, then it torque would have been shown on the gauge of the hydraulic unit.

- After discussing it farther, the foreman pointed out the hydraulic gauge may only indicate torque when the joints are threaded together and may not indicate the reverse torque when the pipe is unscrewed. He will check.
- Note: 1500 – 1900 ft/lbs of torque is the range for the type of threads on the Pods. About 1700 ft/lb is optimum.
- Ralf (Pinnacle) was present during the removal of the Pod caps and did not hear resistance in the hydraulic motor
- 8:20 The upper piece from Pod 2 was lifted off of Pod 2
 - Very small amounts of propant
 - The Cerrotu was more prevalent on one side of the Pod; some was found at various places around the electronics housing
 - Top end has solidified Cerrotu along the edge of the ID of the Pod
 - After the electronics housing was removed, small amounts of oil was observed
 - Had meeting to discuss plans
 - Determined to open Pod 1 next, then Pod 4; in parallel open end of Pod 5; note – Pod 5 may have “hook” type thread and should not be removed, Pinnacle will check
 - Area of Pod that is made from Nitronic will not be disturbed; contains coil
 - Discussion of torque in hydraulic unit
 - The gauge was working after all
 - No connections appeared to be over torque
 - Highest indication was 200 ft/lbs of torque; some did not register torque; indicating under torque condition
- 9:25 Pod 3 ready to be cut open

- Looking into Pod 3 slot looks like the Cerrotru solidified in the top ½ of the Pod; little propant observed throughout the length of Pod
- 9:30 the upper piece of Pod 3 was removed
 - The Cerrotru looks like it made a “seal” circumferentially around the top of the tool; It looks like the “gel” mixture observed earlier came from the bottom 2/3 of the Pod area and an empty cavity in bottom area
 - Second look – it looks like the gel was present up to near the top of the Pod
 - Probably oil only in upper 8” of Pod; the rest has evidence of the “gel”
- 9:45 Pod 1 being prepared for placement in horizontal mill
- 10:00 Pod 5 was investigated for type of thread; uses FJL thread that has 3 tapered threads; to make a seal thread and face seal; the torque needed is 3000 ft/lbs and the connection details are stamped in for later reference; the torque profile is also recorded along with the person performing the work
- The drips from the tube located on the upper cap of Pod 5 appears to be oily
- Cut off the Swagelok and a mixture of oil/water (under pressure) and slowly came out; sample collected
- Appears mixture came from inside Pod 5, not inside tubing
- Setting up hydraulic unit to remove fittings of Pod 5;
 - It is not observed the torque reading was NOT operational yesterday; only an indication of backlash
 - Today the hydraulic unit was changed to enable reading the reverse torque
 - 10:45 removed top portion of Pod 5 (crossover)
 - No torque was detected
 - Liquid came out and was slightly pressurized
 - Crossover looks like it has standard pipe threads; need to check
 - Top of pipe connection is open to Pod 5
 - No torque was observed when EUE pipe was removed; no evidence of pipe tape or pipe sealant on threads (wellbore fluid contamination very likely in observed setup)
 - Looking at collected sample, considerable gas in sample; in a quart container, the liquid was down to bottom ¼ or so of container (approximately 1 ½ inches in bottom of container)
 - Approximately 1 gallon of liquid/gas mixture was collected
 - Looks like a “frothy” mixture
 - Quart bottle now approximately 300 ml of liquid and 300 ml of “frothy” mixture
 - Recap of above sequence:
 - Cut off Swagelok; some liquid came out and was collected
 - Set up to remove EWE pipe
 - Unscrewed EWE pipe and a large flow started followed by times of gas release
 - Total volume of gas/liquid was approximately 1 gallon
 - Considerable propant in top of Pod 5
 - 11:20 removed remaining Swagelok by drilling out tube inside Swagelok
 - 11:23 removed top sub from Pod 5

- 11:24 start of removal
 - Took 3000 ft/lbs of torque
 - Bumped twice
 - Jake (Lincoln Machine Shop) said this is correct for thread size
- 11:30 removal of top sub
 - Propant/oil/sludge/gas mixture (approximately 16 oz)
 - Thread at cap is same as middle and bottom section (FJL thread)
 - As flowing out of end of Pod; water-like blobs exited Pod (appeared “ice-like”)
 - Blobs of water every once in a while
 - Toward end of release, Cerrotru came through in chunks
 - Note: pipe dope was evident in FJL thread
 - Propant is evident; several oz of propant was collected
- Note: talked to Jake (Lincoln) about FJL thread; any precision thread such as FJL is not made for many make/breaks; must be gauged prior to makeup
 - Jake checked EWE thread and it was within specs (API thread)
 - 8 round EUE pipe 2 3/8”
 - Nicely made, but not a seal connection (not appropriate for this application)
- 11:52 removed end sub from Pod 5
 - Reverse torque required was 1500 - 2000 ft/lbs (difficult to accurately measure with gauge)
 - Minimum recommended torque is 2500 ft/lbs
 - Fluid out the end of the Pod started as mostly water (fairly clear); small amount of oil/gas mixture
 - As flow continued, more oil-like but with water
 - Approximately 600 ml of fluid
 - Pipe dope was evident on threads

NOTE:

- 1) In general, it appeared the Cerrotru may have acted like a “seal” preventing the oil from getting to the bottom of the Pod
- 2) For shipment, the Cerrotru will be removed from Pod 2 and Pod 3; will not come off easily – well bonded

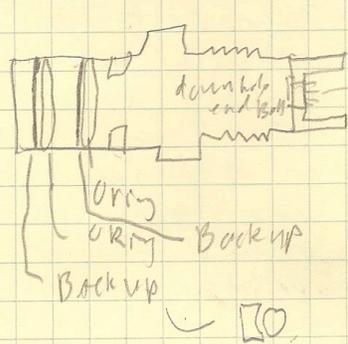
At Pinnacle (with Jamie) to disassemble electronics housings from Pod3

- 2:40 - Starting to disassemble at uphole end at set of screws above connector; should be where fluid would be if tubing bulkhead leaked
- Some water-looking substance leaked when the four screws were removed (oil/water mixture)
- Difficult to separate sub from pressure housing; using brass pin to help separate
- Next, separated at the connector and unplugged
 - o The uphole end is the male connector was dry; only sign of any moisture is outside of sealed area where fluid is expected and would not harm electronics
- 2:55 – now working on bottom end
 - o Started at Swagelok; removed, no fluid
 - o Removed all 8 screws located near the Swagelok; NPT connection has Teflon tape
 - o Removed recessed washers that are below screws
 - o Removed parker oring plug; nut was appropriately tight
 - o Removed outer sleeve to expose inner bulkhead
 - Packed with gel-like substance; probably DC111 (Dow Corning valve lubricant); when DC111 is exposed to heat/moisture likely to change to gel-like substance
 - o Orings are flat
 - o No fluid observed inside electronics area
 - o Removed scrw connection at bulkhead and separated connector halves; no moisture observed
- 3:15 – Trying to power up electronics
 - o No wake up of either DS150
 - Plugged DS150s into jumper to enable communication to computer
 - o Disassembled lower DS150 (MEMS unit)
 - Removed parker plug; slight pressure buildup was released
 - Removed four set screws
 - Pulled uphole-end bell out of DS150; looks dry; the connector looks ok as well
 - Orings are flat
 - Inside DS150 pressure housing is desiccant and no moisture evident (but the desiccant bag was in pieces)
 - Removed set screws on opposite end and removed downhole-end bell
 - The electronics look ok
 - Checked resistance form primary to secondary side of both transformers and they look ok
 - o 3:35 Disassembly of upper DS150 (geophone)
 - Removed Parker plug; slight pressure buildup was released
 - Removed four set screws on connector end of DS150
 - Removed uphole-end bell; orings are flat but ok
 - Looks dry

- Cracked capacitor observed on DS150 preamp/AD board (referenced as C55)
- Capacitors C6 and C16 of power supply board cracked (measured to ground and they were not shorted)
- Desiccant pack was ok
- Checked transformer, primary to secondary; ok for in-circuit measurements
 - 104 kohm T4
 - 125 kohm T1
 - Open T2
 - Open T5
- Geophone package still in pressure housing; only electronics removed
- Talking to Kyle (Pinnacle) the most likely problem based on observed failures on other tools would be the transformer; the transformers have failed in past due to temperature issues; now use their own transformer
- Testing bulkhead assembly for upper end; stripped back insulation and the outer copper is oxidized on all conductors
- Continuity check performed
 - Conductors to tube are all isolated (ok)
 - Conductors are all isolated from each other (ok)
 - End-to-end continuity check (all wires checked ok)
- See sketch shown below for reference

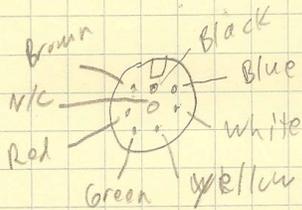
→ check down hole end Bell of DS150 #10576

mems unit O-Rings



O Ring Grooves looks OK
Backup Rings look OK

NO PITS

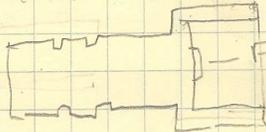


Bottom is Mem

10576 mems

10542 Graphen

uphole end Bell mems unit

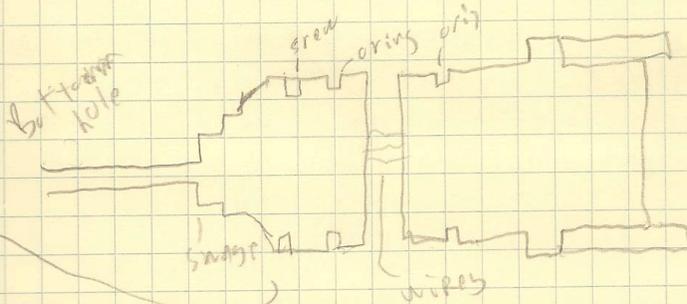


O Rings look FLAT But OK, no cracks

Backup Rings OK

Groove looks OK

NO PITS



Rings Flat But OK

complan to DS150

- 4:40 pm preliminary evaluation of tilt meter electronics from Pod 2
 - Powered up electronics – should be 70 ma of current if electronics are ok
 - At 20 volts (proper voltage), the current was only 20 ma; too low for correct operation
 - Electronics did not power up; no response
 - This is the same as observed when removed from well

12/02 At Pinnacle to continue with electronics evaluation with Jamie

- Summary from yesterday's attempt to power up the DS150s from Pod3; the voltage and current were ok to indicate proper operation, but no communication was possible; each were tried independently
- Disassembly of Pod 2 (tilt meter)
 - Removed bulkhead assembly-to-banana plug connector
 - No water; looks good
 - Measured leakage using megger
 - 1000 volt – 4 gigohm (no leakage, looks ok)
 - Removed top (uphole-end) bulkhead
 - No fluid
 - Checked with megger
 - 1000 volts – 4 gigohm (no leakage, looks ok)
 - Powered up tilt meter electronics; same result as last night; 20 volts – 20 ma
 - Removed upper electronics enclosure end; held in place with four plugs inside of the outer pressure housing
 - Pressure had built up in housing
 - The electronics enclosure end shot out and landed on the floor; (gas pressure); this is the spring-end of the connector assembly
 - Removed lower tool enclosure end; held in place by 4 plugs inside the pressure housing; this end is connected to the electronics carrier
 - Pulled out the electronics; they were covered with oil-like substance;
 - The power supply board had signs of corrosion on the power device tabs; the smell was similar to what Sandia observes when the HT electronics polyimide boards come out when deployed long-term well tests
 - Disassembled top cablehead
 - No leaks; looks good
 - Same smell as the electronics
 - Some DC111, not much
 - Corroded metal piece on ground connection
 - Disassembled lower cablehead
 - Evidence of a leak

- The fluid looks like DC111 and the oil mix
 - The same metal piece is not corroded in this end
 - The cablehead has a 10-32 thread screw for a grease fitting (not a pressure seal); as such, the oil could have worked into this thread over time and filled/mixed with DC111
 - Note: upper assembly probably did not have oil on outside and as such no oil “leaked” into this thread
- Looking at the electronics power supply board, the electrolytic capacitors had corrosion across positive leads (many capacitors; mainly power supply board but other boards (to a lesser degree))
- Looking at upper tool enclosure
 - Removed orings and backup rings
 - Backup rings are split Teflon type
 - Orings are stiffer and larger, but came off without breaking
 - Oring grooves look ok
 - Looks like melted epoxy (or something similar) at pin end of tool enclosure sub
- 8:45 Pod 3 - looked at oring on DS150s (disassembled yesterday) for the uphole-end bell – geo unit DS150 #10542
 - The orings are flat but ok
 - The oring grooves are ok
- Pod 2 – looking at bottom end of tool enclosure
 - Removed end of tool carrier that has the orings
 - Note: the electrical spade insulation for the ground connection was not intact; must have broken into pieces; the positive spade connection was brittle but intact
 - The orings and backup rings were intact
 - Orings were very flat
 - The backup rings were not Teflon; they were rubber-style
 - The backup rings came out in pieces
 - The orings were stiff; one had to be cut to enable removal from sub
 - Pictures taken at 10:14
- 10:30 - Pod 3 – geo unit DS150 opening up upper Swagelok cablehead end of DS150
 - Has foul smell
 - Very little DC111; some oil and possibly a little bit of water
 - Removed orings
 - Orings were flat but more flexible than Pod 2
 - Oring slightly damaged during removal
- Pod 3 geo unit DS 150 (#10542) bottom sub
 - Orings are flat, but ok
 - Oring grooves are ok
- Pod 2 tilt meter - Looking at bottom end Swagelok cablehead
 - Orings exposed to pressure side are swollen and nicked
 - Low pressure side orings are flat, but ok

- Oring grooves are ok
 - Pod 2 tilt meter – looking at top end Swagelok cablehead
 - Looks very similar to upper end
 - The high pressure side orings are swollen
 - Low pressure side orings are flat and appear flatter than high pressure side
 - Oring grooves are ok
 - Measuring oring gland
 - Bottom end (one that appeared to have leaked)
 - Inner gland - 1.027” low pressure side
 - Outer gland - 1.029” high pressure side
 - Upper end
 - Inner gland – 1.026”
 - Outer gland – 1.026”
- 11:30 am Start of disassembly of Pod1
 - Removed of top cablehead Swagelok fitting
 - No fluid, looks good
 - Removed bottom DS150 # 6122; no fluid when disconnected from upper DS150
 - Powered up DS150 #6122; voltage ok, 4 volt drop across electronics, .55 amps
 - Communication was established
 - Some errors
 - Temperature reading not correct
 - No analog channel response
 - Just digital part of electronics are responding
 - Software indication of no 5 volt power
 - All diagnostic tests failed
 - Powered up upper DS150 # 6010
 - Did not respond
 - Voltage and current was correct (4 volt drop, .5amp)
 - No fluid, looks ok
 - Removed DS250 to DS150 crossover
 - No leaks observed
 - Tested function of DS250 by using working DS150
 - Works ok
 - crossover does not have any active components; just transformer and passives
 - Opening fiber optics converter on downhole side
 - No pressure buildup observed when Parker plugs were removed
 - Removed all six plugs
 - Removed sub and unplugged
 - Connector is brittle
 - Kyle (Pinnacle) indicated the connector is electrical leak prone
 - Foul odor, but no fluid

- Removed upper six plugs to enable removal of sleeve
 - Removed sleeve
 - No fluid
 - Considerable corrosion on metal connector for send/receive fiber optic driver
 - Board connections looked ok
 - Orings were flat
 - Kyle (Pinnacle) is looking into testing fiber optic board by itself
- 1:00 pm – Meeting with Ken Smith and Angus regarding SAFOD deployment and issues experienced
 - Error codes received when electronics started to fail does not help
 - Receiving control bias errors; no detailed diagnostics are available
 - DS150s are not good for long deployments
 - DS150s tested for 4 to 5 days
 - DS250s tested for 3 to 4 weeks at 120C
 - Common failures include
 - Connectors throughout
 - Transformers; wires used are not high temperature, now use polyimide coated wires
 - In general, DS250s may be better for long term at higher temperature, but in reality, many same components used for both; not as experience using DS150s at higher temperatures
 - Data drop out when failures began, looked like leakage spikes
 - Need to check if MEMS are on the top or bottom in Pod 1
 - In long term deployments, Pinnacle recommends to use two current loops and 2 fiber optic links (for redundancy)
- 2:37 – Looking back at the fiber optics board (Pod 1)
 - Kyle looked at fiber optics board and the fiber optics ceramic insert stayed in the connector; not allowing the board to be tested
 - Bottom DS150 is MEMS #6122
 - Meaning MEMS failure did not raise temperature
- Pod 4 tilt meter
 - Looking at cablehead with Swagelok end
 - Opened up single conductor spring end, connected to electronics sub
 - Had fluid contamination
 - Looked like oil with DC111 by the pin
 - Connected power to tilt meter Pod 4; 20 volts, no current draw, indicating something has opened
 - Orings were flat; the backup rings are not Teflon, but rubber
 - Removed electronics sub board carrier; downhole end
 - Electronics were removed with the sub
 - No oil or moisture
 - Considerable corrosion on capacitors
- Pod 1; Kyle looked at the DS150 with MEMS from Pod 1 (this is the same DS150 that came to live in previous test, but did not have 5 volt power)

- Removed wires for MEMS (3 wires that power the MEMS, orange, yellow and red)
- Repowered the DS150 and now the DS150 indicates the 5 volts is present; the 3 channels did not go through the channel check; the 5 volt reading came back;
 - The current reading, voltage reading for the 5 volt and the temperature measurement came back
 - This indicates the A/D converter is not function, at least for the low resolution measurements
- 3:25 Start of disassembly of Pod5
 - Removed Swagelok fitting for the cablehead
 - No inner face seal between pins
 - Connected computer to top DS150 unit using shorting plug on bottom of electronics (return of current loop)
 - No response
 - Connected computer to bottom two DS150s
 - #6118 responded but 5 volt is reading 2.5 volts and the temperature measurement was not right
 - Disconnected DS150# 6118 from DS 150 #10622
 - Oil was observed between the units
 - Connected computer to DS150 #10622 by itself
 - No response
 - Connected computer to DS150 #6118 by itself
 - Same as before; 5 volts is reading 2.5 volts, current was .322 amps, temperature reading was not correct (reading -272.878F)
- Note: only the DS150s with the MEMS from Pod 1 and 5 responded; The DS150 MEMS unit from pod 3 did not respond