The Deployment of a Long-Term Seafloor Seismic Network on the Juan de Fuca Ridge

W. S. D. Wilcock
School of Oceanography, University of Washington, Seattle, WA 98195 USA

P. R. McGill
Monterey Bay Aquarium Research Institute, 7700 Sandholdt Road, Moss Landing, CA 95039 USA

E. E. E. Hooft, D. R. Toomey, H. M. Patel
Department of Geological Sciences, University of Oregon, Eugene, OR 97403 USA

D. S. Stakes
Cuesta College, Division of Physical Sciences, San Luis Obispo, CA 93403 USA

A. H. Barclay
Lamont-Doherty Earth Observatory, 61 Route 9W, Palisades, NY 10963 USA

T. M. Ramirez
AOA Geophysics, 7532 Sandholdt Road #6, Moss Landing, CA 95039 USA

R. T. Weekly
Department of Earth and Space Sciences, University of Washington, Seattle, WA 98195 USA

***Abstract* – From 2003-2006, a novel seismic network comprising seven short-period corehole seismometers and a broadband Guralp CMG-1T OBS was deployed using remotely operated vehicles (ROVs) in a subseafloor configuration on the Endeavour Segment of the Juan de Fuca mid-ocean ridge as part of a multi-disciplinary prototype NEPTUNE experiment to investigate the linkages between seismic deformation, hydrothermal fluxes, and microbial productivity. The network recorded high quality data that illustrate the advantages of using an ROV to deploy seismometers in well-coupled configurations away from the effects of ocean currents. The data is presently being analyzed to understand the linkages between seismic deformation and hydrothermal circulation, and the nature of seismic swarms that are associated with ridge spreading events. A subset of the seismometers will be incorporated into the NEPTUNE Canada cabled observatory.**

I. INTRODUCTION

The W. M. Keck Foundation has supported a multidisciplinary prototype experiment for the NEPTUNE regional cabled observatory to study the linkages between geological deformation, fluid fluxes across the seafloor, and microbial productivity along oceanic plate boundaries. One component of this experiment was the deployment of small local and regional networks of high-quality seafloor seismometers on plate boundaries near the northern end of the Juan de Fuca plate in order to (1) characterize seismicity over a 1- to 3-year interval and understand the linkage between earthquake activity and temporal variations in hydrothermal fluxes and (2) gain experience with the seismometers that will become an integral part of cabled seafloor observatories.

Long-term monitoring of earthquakes is key to understanding the deformation of the earth and the role of tectonic, volcanic, and hydrologic processes along plate boundaries. In hydrothermally active regions, earthquakes provide information on the depth of hydrothermal cooling, the location and nature of thermally induced cracking, and the distribution of active faults that provide the likely conduits for fluid circulation. Tectonic earthquakes and volcanic intrusions and eruptions (which are themselves accompanied by earthquake swarms) have the potential to substantially change the patterns and intensity of hydrothermal flow. Thus, knowledge of seismicity is critical to interpreting hydrothermal time series and for assessing the role of geological events in modulating chemical and biological fluxes across the seafloor.

II. SEISMIC INSTRUMENTATION

Most marine seismic studies are conducted with free-fall autonomous ocean-bottom seismometers that are deployed from a ship and land haphazardly on the seafloor. The sensors are often poorly coupled to the seabed, particularly in rough, unsedimented environments such as mid-ocean ridges. The sensors also sit above the seafloor where ocean currents generate noise. To overcome these limitations, the Keck experiment utilized both short-period and broadband seismometers, developed by the Monterey Bay Aquarium

Research Institute (MBARI), that are carefully placed below the seafloor by a remotely operated vehicle.

A. Short-period Seismometer

The MBARI short-period corehole seismometer [1] was developed collaboratively with GEOSense to improve the signal to noise and fidelity of seismic records for local and regional earthquakes in the 1-90 Hz frequency band. The sensor comprises 3 orthogonal Mark Products L-28B geophones that are housed within the front portion of a titanium pressure vessel measuring 6.4 cm in diameter and 38 cm in length. Low power (< 1 mW) active electronics are integrated with the sensors in order to extend the natural 4.5 Hz corner frequency of the geophone below 1 Hz. In areas with basement outcrops, the sensor is deployed with an ROV by inserting it ~30 cm into a 7-cm-diameter horizontal corehole (Fig. 1); Tygon tubing wrapped around the sensor ensures a snug coupling with the corehole walls. In sedimented areas the sensor is placed into a 69 kg concrete block ("seismonument") that is buried by an ROV a few centimeters into the sediments. The sensor also incorporates a biaxial electronic tilt sensor that measures the tilt of the two horizontal channels during deployment; two LED lights mounted in the vertical handle of the sensor indicate when the instrument is leveled within the nominal 5° tolerance required for the horizontal geophones. For the Keck experiment, the three channels were sampled at 128 Hz and logged with an MBARI/GEOSense LP1 data logger that is housed together with the batteries required for a 1-year deployment in a 17" glass sphere. The instrument was designed to allow for underwater connections from the data logger to the sensor and from the data logger to the ROV in order to verify data acquisition after deployment and to permit the recovery and replacement of the data logger without disturbing the sensor. However, for the Keck experiment the logger and sensor were deployed as a single unit that was swapped out each year for multiyear deployments.

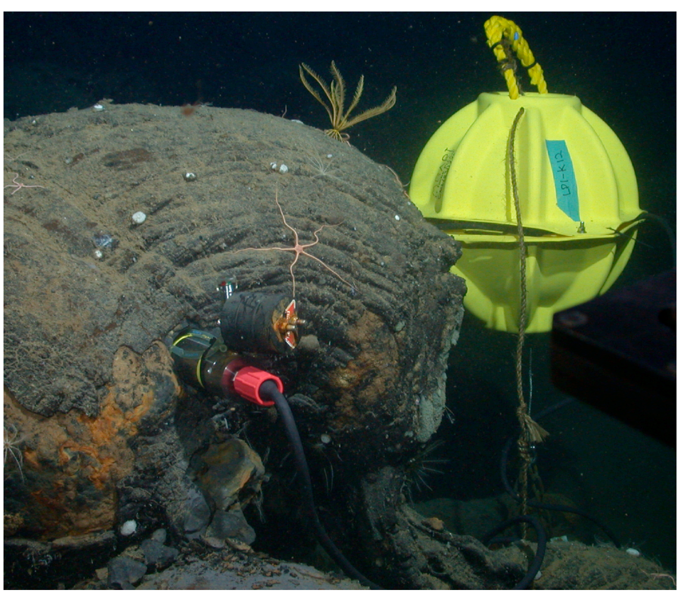

Figure 1. MBARI short-period corehole seismometer. The titanium sensor pressure housing is inserted into a horizontal corehole drilled into a basaltic pillow and is connected by a cable to the data logger inside the yellow hardhat.

B. Broadband Seismometer

The broadband seismometer is based on an instrument developed collaboratively by MBARI and the University of California at Berkeley for deployment in 1000 m of water in Monterey Bay [2-5]. The seismometer package comprises a 3-component Guralp CMG-1T seismometer that is sensitive over a frequency band from 2.8 mHz (360 s) to 50 Hz and is integrated with a 24-bit digitizer, a precise clock and a leveling system. For this experiment a spherical, cast titanium pressure housing was developed for the seismometer package to allow deployments in up to 4000 m of water. The seismometer is buried inside a PVC caisson measuring 60 cm in diameter by 60 cm depth (Fig. 2) that is infilled with 0.8-mm diameter glass beads. A 20-m cable with an underwater wet-mateable connector attaches the seismometer to a seafloor package that includes an MBARI/GEOSense LP1 data logger and a 30 kW-hr lithium battery. A wet-mateable connection between the data logger and the ROV is used to initiate the sensor recording and verify data acquisition. For multi-year deployments the data logger and battery pack unit is swapped without disturbing the seismometer.

III. NETWORK DESIGN AND INSTALLATON

We operated a local network on the central part of the Endeavour segment of the Juan de Fuca Ridge for three years from 2003-2006 (Fig. 3). The network extended about 10 km along the ridge axis and 6 km across with a typical instrument spacing of 3 km. It was designed to monitor microearthquakes associated with five high-temperature hydrothermal vent fields that are driven by heat loss from a crustal magma chamber. The network comprised one broadband seismometer, five short-period seismometers

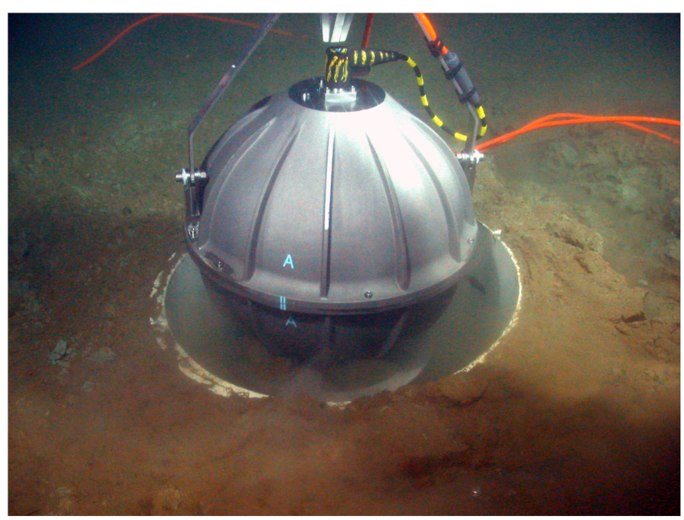

Figure 2. Deployment of the Guralp CMG-1T seismometer package into the caisson.

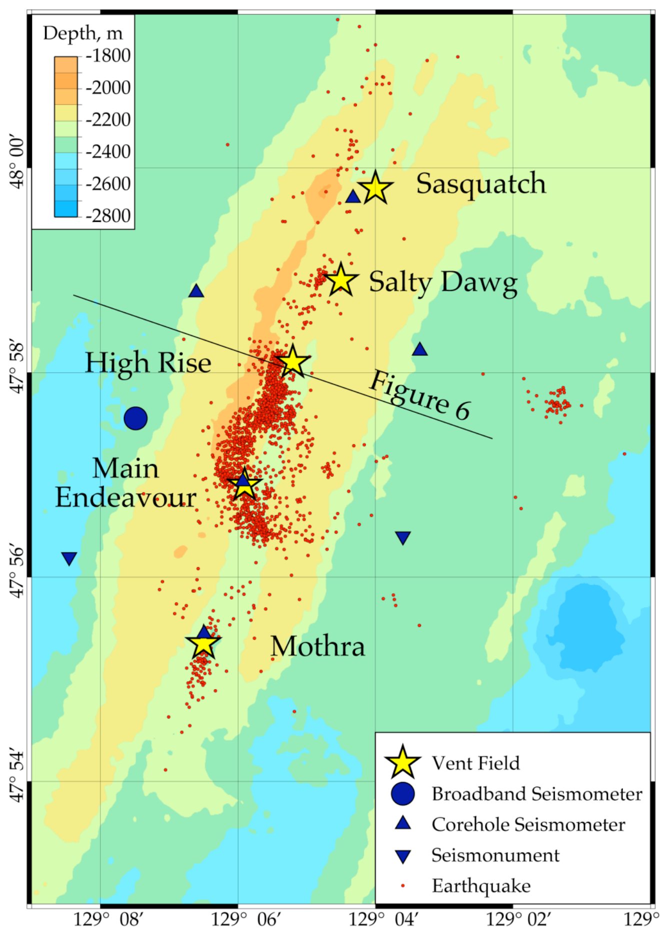

Figure 3. Bathymetry map of the central portion of the Endeavour segment showing the location of high-temperature vent fields (labeled with names), seismic stations, and earthquake epicenters for the first year of operation of the Keck seismic network.

deployed in coreholes drilled into basalt, and two short-period seismometers in concrete seismonuments.

From 2004-2005 we also operated a second smaller local network at the intersection of the Nootka Fault and the Cascadia subduction zone (49°15'N, 127°40'W) that comprised one broadband seismometer, three short-period seismometers in seismonuments, as well as a short-period seismometer that was part of a buoy-based acoustically-linked seafloor observatory developed at Woods Hole Oceanographic Institution (WHOI) [6, 7]. This network was designed to monitor earthquakes that might perturb a small cold seep.

A third broadband seismometer was also deployed from 2004-2005 on the Explorer plate (49°30'N, 129°W). The three broadband seismometers formed a regional seismic network that was designed to be contiguous with broadband stations on Vancouver Island that form part of the Canadian National Seismic Network

A. Short Period Seismometer Deployments

The coreholes for the short-period seismometers were drilled during cruises in 2002 on the R/V Western Flyer with ROV Tiburon and in 2003 on the R/V Thomas Thompson with the ROV Jason II, using an ROV rock drill that was developed by MBARI [8, 9] and which is now owned and operated by the National Deep Submergence Facility at WHOI. The process of drilling holes proved quite time consuming for two reasons. The rock drill is designed to recover 1.25" diameter cores with a 1.5" coring bit and so to drill holes of sufficient diameter for the corehole seismometers it was necessary to use a 2.85" reamer bit with a 1.25" core. This substantially increased the cross-sectional area of rock to be drilled over normal operations which, coupled with the limited power available on the electrically operated ROVs, resulted in penetration rates of ~2-3" per hour. Second, it proved difficult to drill holes whose pitches were within ±5° of horizontal, the nominal tolerance of the horizontal geophones. With the drill sled attached, the ROVs pitch forward at an angle of ~10° because their center of forward thrust is above the points where the sled contacts the rock. Because the rock drill is equipped with only two points of contact which are distributed horizontally, it proved difficult to adjust the natural pitch of the ROV without finding, by time consuming trial and error, sites at which the ROV could drill into a vertical rock face while sitting stably and horizontally on the seafloor. Nevertheless, despite these difficulties five of the six planned coreholes were successfully drilled.

The deployment and annual refurbishment of the short-period seismometers in coreholes (Fig. 1) and seismonuments has been undertaken with the ROVs ROPOS (2003), Tiburon (2004) and Jason II (2005) and proved to be an efficient operation typically requiring no more than an hour of bottom time at corehole sites and less than half an hour at seismonument sites.

B. Broadband Seismometer Deployments

The deployment of the broadband seismic sensor is a complex process that has been undertaken with the ROVs ROPOS (2003) and Tiburon (2004) and requires about 12 hours of bottom time. The sensor is carried down to the seafloor with the ROV while the other components are transported on a free-falling elevator. After locating the elevator and setting the sensor down, the first step is the emplacement of the caisson ~20 m from the elevator. The ROV alternates between 'jumping' on the caisson to insert it deeper into the sediments and excavating the sediments from within the caisson using a water-jet suction pump. This is a slow process and for the Keck deployments the excavation was often interrupted by the low visibility in the caisson resulting from suspended sediments and by the clayey sediments clogging the nozzle on the suction pump.

After preparing the caisson, the electronics module is placed ~15 m away, the Guralp seismometer package is centered in the caisson (Fig. 2), and the seismometer cable is then uncoiled and extended to the electronics module. The ROV is connected to the data logger to verify operation and the seismic sensor is then connected to verify boot-up.

After disconnecting the ROV, the next step is to fill the caisson around the seismometer with 300 lbs of glass beads. In 2003 the glass beads were transported from the elevator to caisson in 50 lbs bags made of sailcloth and were then emplaced in the hole either from a small nozzle or by ripping the bags. This process proved time consuming and so in 2004, MBARI developed a bead hopper to transport and dispense all of the beads in a single operation. A releasable flotation package on the bead hopper offsets the weight of the beads so that the ROV can remove it from the elevator and place it directly over the hole. The flotation is released, the beads are poured into the hole, and the empty hopper is then transported back to the elevator. After ensuring that the beads are flush with the surrounding seafloor, the ROV places U-shaped cable wickets where necessary to anchor the seismometer cable to the seafloor, thus preventing any water-current-induced cable motion from disturbing the seismic sensor.

The last step of the deployment before recovering the elevator and ROV is to reconnect the ROV to the electronics module in order to unlock and level the Guralp sensor, measure the sensor orientation with the sensor compass, get a GPS time sync measurement to establish the drift of the seismometer clock, start the data logger, and verify its operation.

IV. DATA ANALYSIS

The data quality from the Keck deployments is very high. Fig. 4 shows an example of a local earthquake recorded on a short-period seismometer deployed in a basal corehole in comparison to a typical record for a freefall OBS. The improved coupling obtained from the corehole configuration is clearly evident in the S-waves, which show no signs of the monochromatic resonance that is commonly observed for free-fall OBSs. Fig. 5 shows an example of a teleseismic record

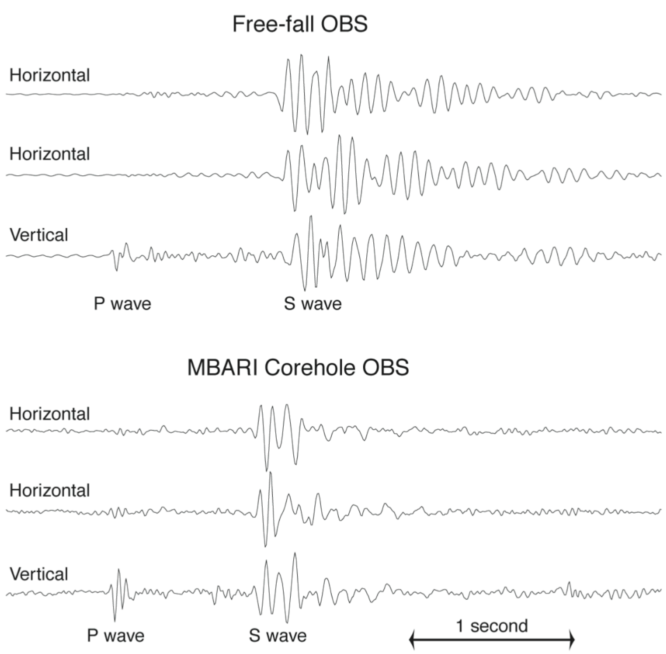

Figure 4. Examples of (top) typical microearthquake seismogram recorded by freefall OBS and (bottom) a corehole seismometer in the Keck Endeavour seismic network. The improved coupling of corehole OBS is apparent in the S-waves.

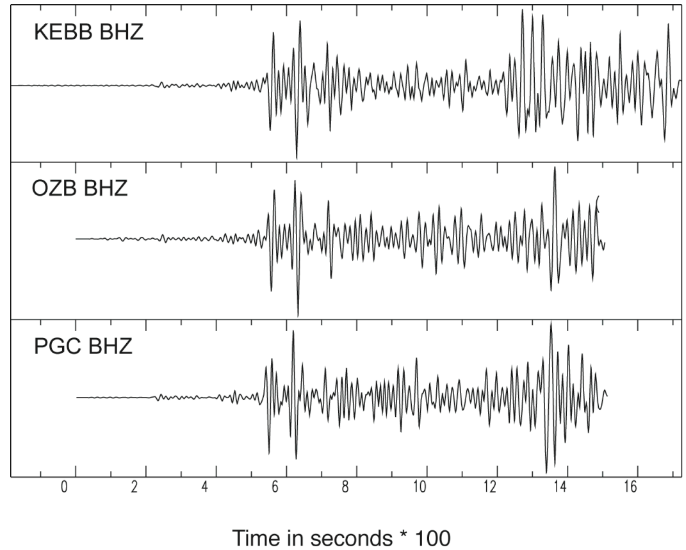

Figure 5. Comparison of vertical seismic records for the magnitude 7.5 Scotia Sea teleseism of August 4, 2003 bandpass filtered at 0.025-0.7 Hz (40-1.4 s) recorded by (top) the Keck Endeavour seafloor broadband seismometer and by broadband stations on land (middle) OZB and (bottom) PGC on Vancouver Island.

for the Endeavour broadband seismometer filtered between 0.025 and 0.07 Hz (40-14 s period). In this frequency band the signal to noise is comparable to nearby coastal stations.

The data from the regionally distributed broadband seismometers are being used by other investigators to understand the generation of microseismic noise [10] and to study the characteristics of regional earthquakes including the aftershocks of the November 2, 2004 magnitude 6.6 intraplate earthquake that occurred within 50 km of one of the broadband stations. Our own analysis, which we summarize briefly below, has focused on the Endeavour network.

A. Endeavour Network 2003-2004

The preliminary analysis of the first-year of Keck seismic data was undertaken during a research apprenticeship class taught in the fall of 2004 at the University of Washington's Friday Harbor Laboratories. Eight post-baccalaureate students obtained a preliminary catalog of over 12,000 earthquakes on the Endeavour segment [11, 12]. Two of the apprentices then worked to conduct a second-pass analysis to refine the locations of ~3000 earthquakes that are within or near the network. Further analysis of these proximal earthquakes has focused on the application of cross-correlation and relative relocation techniques [13], the determination of focal mechanisms [14], and improved estimates of earthquake magnitudes.

The results show that the whole Endeavour segment was seismically active during 2003-2004. Within the network, the earthquakes are located in tight clusters at ~2-2.5 km depth (Figs. 3 and 6) in the inferred location of the hydrothermal reaction zone immediately above a crustal magma chamber imaged by seismic reflection studies [15]. The number of earthquakes below each vent field correlates with the

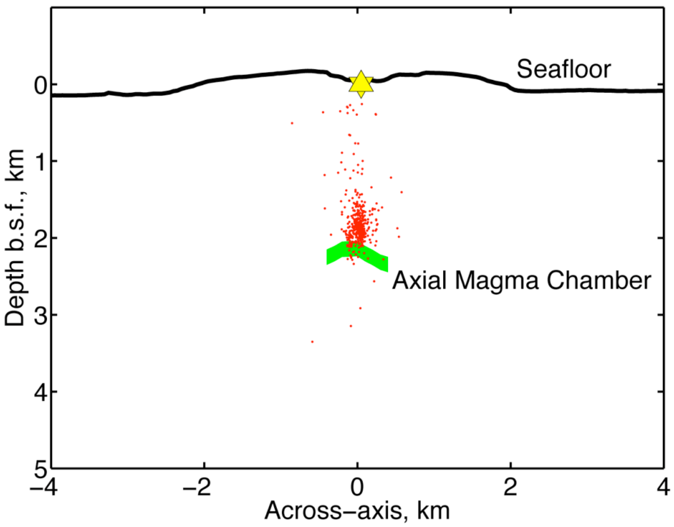

Figure 6. Cross section for a profile oriented perpendicular to the spreading ridge passing through the High Rise vent field (profile location shown in Fig. 3) showing location of the seafloor (black line), the vent field (yellow star), the axial magma chamber reflector (green line), and earthquakes lying within 0.5 km of the section (red dots).

hydrothermal heat flux [16]. Focal mechanisms suggest that the stress field may be locally influenced by either the injection of magma or the presence of over-pressured hydrothermal fluids.

B. *February/March 2005 Endeavour Swarm*

To date, our analysis of data from the second year of the operation of the Endeavour local network has focused on twelve days of data that coincides with a large swarm in February/March 2005 that was detected by the US Navy's Sound Surveillance System (SOSUS) [17] and may be the result of a volcanic intrusion. The epicenters of over 6000 earthquakes show that the earthquake swarm was much more complex than inferred from remote seismic observations and included clusters of earthquakes in four distinct regions [18]. The main activity was located well to the north of the Endeavour local seismic network but it appears that each cluster successively triggered seismicity further to the south. The onset of seismicity beneath the hydrothermal vent fields occurred at the same time as hydrothermal observations show that the temperature and chemistry of a low-temperature vent in the most southerly vent field were perturbed.

C. *Automatic Event Location*

Because of the large number of earthquakes recorded by the Keck Endeavour network, we are presently working to implement automatic techniques to locate them. Following a standard approach, we first apply a 5 Hz high-pass filter and consider the ratio of the root mean square (RMS) of the demeaned signal amplitude in short- ($\leq$1 s) and long-term ($\geq$10 s) running windows. We identify triggers where the ratio exceeds a threshold value and find events by searching for intervals in which the majority of stations trigger within a specified interval. We eliminate events that are likely fin or blue whale vocalizations by computing the spectra of the triggered signals; fin and blue whale vocalizations have a large proportion of their spectral power near 20 Hz [19].

To locate earthquakes, we first apply an autoregressive picking technique to short time windows centered upon the trigger times to determine P-wave arrival times on the vertical channels. We locate the earthquake with these P-wave arrival times and attempt to repick stations with large residuals by recentering the time window for the autoregressive picker on the predicted P-wave arrival time. P-wave picks that still have unacceptable residuals are discarded.

S-waves are harder to pick because they are secondary arrivals, but for most earthquake records we find that the S-waves are the highest-amplitude arrivals on the horizontal channels in the 5-12 Hz band. We make preliminary S-wave picks by finding the maximum of the RMS amplitude of a short-term running window and placing the pick where the RMS reaches 50% of its maximum value. The pick is refined by applying the autoregressive picker to a short time window centered on the preliminary pick. We locate the event with the P- and S-wave picks and, as for the P-waves, attempt to repick S-waves with large residuals.

To date we have tested the picker with data from 2003-2004 and the results are quite encouraging. The method appears to be quite robust and we expect to apply it to unanalyzed data from the Endeavour network for 2004-2006 and the Nootka network for 2004-2005.

V. CONCLUSION

Operationally the seismic component of the Keck experiment was very successful. It is one of the first deployments of a seafloor seismic network with sensor installations and data quality that are comparable to a good land network. The data from the Endeavour segment are presently being analyzed to understand the relationships between seismic activity and hydrothermal circulation and to investigate swarms that are associated with ridge spreading events. It is anticipated that four of the short-period instruments and the broadband site will be transitioned to the NEPTUNE Canada regional cabled observatory when it becomes operational in 2008.

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