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Short and long baseline tiltmeter measurements on axial seamount, Juan de Fuca Ridge

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Abstract

Long-term observations of seismic activity and ground deformation at mid-ocean ridges and submarine volcanoes are required for an understanding of the spatial and temporal characteristics of magma transport and intrusion. To make precise records of tilt on the seafloor we have installed short baseline tiltmeters in six ocean bottom seismometers (TILT-OBS) and developed a long baseline (100–500 m) two-fluid tiltmeter (LBT). In the TILT-OBS, the seismometer platform is levelled to better than 1° after deployment. The tiltmeter consists of a pair of electrolytic bubble sensors mounted on a secondary levelling stage on the seismometer platform. The levelling stage uses two motor-driven micrometers on a triangular mounting plate to bring the sensors to null. The sensitivity of these tiltmeters is 0.05 μrad, at a dynamic range of 0.2 mrad. A long baseline instrument was developed to achieve a better spatial average of deformation. Most approaches used on land to measure stable long baseline tilt cannot be applied to a submarine instrument, but tiltmeters in which the pressure of a fluid in tubes is measured are amenable to installation on the seafloor. The development resulted in a device that is essentially a center-pressure instrument folded back on itself, with fluids of different densities in the two tubes. During July to September 1994, these instruments were deployed on Axial Seamount, on the Juan de Fuca Ridge off Washington state, for a test of their relative performance on volcanic terrain, yielding 9 weeks of continuous data (seismic, tilt, and temperature) from five TILT-OBS and one long baseline instrument. Drift on all instruments was of the order of 1 μrad/day, with higher frequency variations of order 5–10 μrad. Initial drift on the TILT-OBS is shown to be associated with platform settling rather than with the sensor or its mounting. High frequency noise is coherent across instruments and tidal in character, and we conclude that tidal currents moving the sensors are responsible. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: Short and long baseline tiltmeters; Axial seamount

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1. Introduction

Mid-Ocean Ridge (MOR) volcanoes are volumetrically the most important type of volcano on earth, yet our understanding of MOR volcanoes is still in its infancy when compared to the extent of knowledge acquired on sub-aerially exposed active volca-

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noes like Kilauea/Hawaii, or Krafla/Iceland. Most of what we have learned about the dynamics and intrusive geometries of sub-aerial volcanoes comes from detailed monitoring programs carried out continuously over decades of diverse volcanic and intrusive activity (e.g., Decker, 1987). The most successful observatory programs on sub-aerial volcanoes involve seismic monitoring and deformation, neither of which has been systematically applied to MOR volcanoes over significant time periods. We need similar long-term monitoring of MOR volcanoes before we can understand fully their emplacement and chemical fractionation behavior, or the mechanisms of chemical ridge segmentation.

Experience from sub-aerial volcanoes shows that detailed monitoring programs provide independent constraints on the geometry, sizes, and dynamics of diverse magma reservoirs and feeders. At Kilauea volcano, for example, interpretation of petrological data was effectively guided by knowledge of the geometry and interconnectedness of feeder systems (e.g., Wolfe et al., 1987). At MORs, however, few monitoring data are available, and the chemical and petrological data themselves have to be used to infer the physics of the magma supply systems (e.g., Langmuir et al., 1986). The latter approach is typically non-unique and necessarily results in highly speculative models. Even though studies of ophiolites do provide important structural constraints, in particular, the dominance of intrusive rocks, so far they fail to provide unique interpretations of magma chamber geometries, and they are not suited for studies of intrusive dynamics.

In Fig. 1 (from Decker, 1987), we show the tilt record of the Uwekahuna vault at the Hawaii Volcano Observatory (HVO) located on the Kilauea caldera rim. This 30-year record typically displays steady rises over several months with sudden drops. This behavior is interpreted as slow inflation of a shallow magma chamber and catastrophic deflation, usually by eruption. The apparent increase in 'noise' in the January 1984 to July 1985 record is caused by approximately monthly 10–20 μrad cycles with steady tilt increases and sudden drops, perfectly mimicking the 21 eruption cycles observed in this time period at Puu Oo on the Kilauea East Rift, 20 km SE of Uwekahuna vault. These observations clearly show that the timing of eruptive and intrusive events is well reflected in the measurement of tilt.

The intrusive geometry of sheeted dikes and the dynamics of their emplacement at MORs is probably one of the major open structural problems in marine geology. Currently, there is no consensus about the direction of sheeted dike emplacement. Sheeted dikes are traditionally thought to intrude vertically (e.g., Cann, 1970; Kidd and Cann, 1974; Kidd, 1977), reflecting the passive upwelling of magma as a direct consequence of ocean floor spreading. However, there are several arguments which may be advanced in favor of lateral dike emplacement at mid-ocean

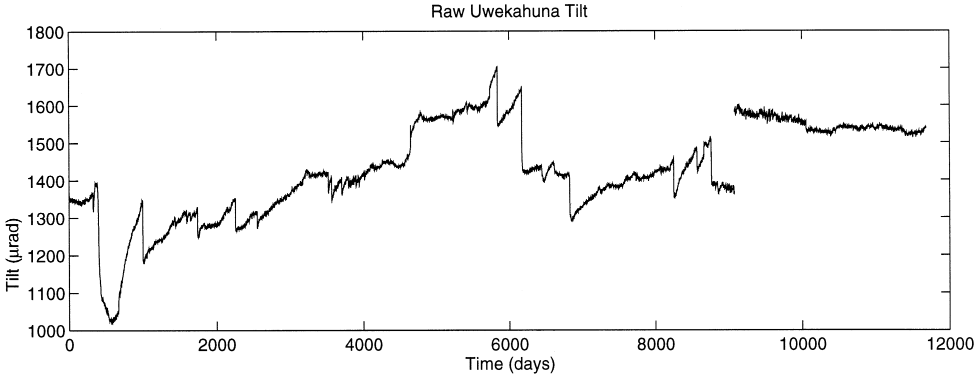

Fig. 1. Radial tilt at the Uwekahuna vault near the Hawaii Volcanic Observatory situated on Kilauea. Rapid deflation events are associated with a pressure drop in the magma chamber associated in turn with eruptions. Slow replenishment from depth produces the steady tilt (Decker, 1987).

ridges. In particular, theoretical considerations and in situ observations on sub-aerial volcanoes in Iceland and Hawaii (e.g., Sigurdsson and Sparks, 1978; Sigurdsson, 1987; Rubin and Pollard, 1987; Okamura et al., 1988) suggest that lateral propagation of sheeted dikes may occur in at least some MOR settings. Subsequent to predictions by Baragar et al. (1987) and Sigurdsson (1987), recent studies of sheeted dike emplacement processes in the Troodos ophiolite (Varga et al., 1991; Staudigel et al., 1992) showed that dike intrusive directions are certainly not exclusively vertically upward, and horizontal directions are common. Radial outward intrusion of sheeted dikes into the merging rift zones of MOR volcanoes cannot be distinguished from vertically upward intrusion any other way than through monitoring of the intrusive behavior of submarine volcanoes.

The deformation of the host rock in response to magma intrusion may be brittle or elastic, with or without the release of significant seismic energy. The recent ability to use military hydrophone arrays (SOSUS) has already proven extremely valuable for our understanding of MOR tectonic behavior (e.g., Fox et al., 1993; Fox, 1995). However, this only provides information on deformation associated with a high level of seismicity. It is still not known how important aseismic deformation and magma transport are in MOR processes.

2. Ocean bottom tiltmeters for submarine volcano monitoring

Among the instruments used for surface deformation measurements, only a few can be adapted to underwater operation. Several types are under development; absolute pressure gauges for vertical displacements (e.g., Cox/SIO; Fox/NOAA [Fox, 1990b, 1993]), acoustic extensiometers (e.g., Spiess/SIO; Normark/Morton USGS; Embley/Chadwick/NOAA) and several tiltmeters (Constable/Wyatt/Orcutt/Staudigel SIO; Chave/WHOI; Duennebier/HIG; Fox/NOAA; Stakes/MBARI). In addition to this list, Zumberge at SIO has new programs for both vertical displacements through absolute gravity measurements and a fiber-optic extensiometer.

Several approaches have been used in the development of submarine short baseline tiltmeters (SBT). Sakata and Shimada (1984) and Shimamura and Kanazawa (1988) developed tools that were emplaced as fixtures in relatively shallow water. A number of other parallel efforts to develop re-deployable SBTs are underway. Duennebier and Harris (Duennebier and Harris, 1990) of HIG reported a shallow water deployment of a tiltmeter in an OBS and Fox (Fox, 1990a) of NOAA reported that he is developing tiltmeters for a volcanic event identification system. Stakes (personal communication) of MBARI is developing a borehole tiltmeter, and Chave (personal communication) of WHOI is developing a short-baseline instrument. Our efforts in SBT development are discussed by Staudigel et al. (1991), Willoughby et al. (1993) and Wyatt et al. (1996), and LBT development is summarized by Anderson et al. (1997). While it is relatively simple to equip any seafloor instrument, such as a magnetometer or ocean bottom seismometer (OBS), with some form of inclinometer, our efforts have been to develop a tiltmeter with drift rates which are small compared with the expected volcanic signals. Volcanic deflation events, seen prior to and during eruptions and during re-distribution of magma between reservoirs, have tilt rates which exceed tens of microradians per day, but inflation events can be as low as a few microradians per month. Our goal, therefore, is to attain this level (μrad/month) of stability, appropriate for volcanic monitoring, and we are very close to this. While these values are still orders of magnitude larger than non-volcanic tectonic tilt observed by long baseline tiltmeters on land, they are orders of magnitude smaller than have so far been observed on the seafloor.

3. Short baseline tiltmeter

Our initial objective was to develop a portable submarine tiltmeter and to provide benchmark measurements of submarine tilt at a number of sites. Tiltmeters were added to the six existing Scripps ocean bottom seismographs (OBS) (Willoughby et al., 1993) to provide an instrument package that essentially has all the benefits of an OBS, with the added advantage of tilt measurement (TILT-OBS).

Fig. 2 shows a cross-section of a TILT-OBS and illustrates the location of the tiltmeters and inclinometers. The TILT-OBS is probably best compared to the portable tiltmeters and seismometers as they are commonly used to monitor sub-aerial volcanoes. These instruments have an obvious application for reconnaissance and as rapidly deployed first-order research tools during, or subsequent to, major eruptive phases or intrusive events. However, the lack of precipitation and isothermal seafloor environment, (the presence and variations of which are significant sources of noise on land tiltmeters), will probably allow observatory quality measurements to be made on decadal time scales using such a short-baseline instrument.

The TILT-OBS is designed to monitor ground tilt which may vary in volcanic terrain anywhere from sub-microradian to several milliradian and to cope with deployment angles which may vary by tens of degrees as a result of the free-fall emplacement procedure. Several tilt sensors are set to different gains to assure coverage of the full dynamic range with adequate sensitivity. Two orthogonally mounted inclinometers (Shaevitz/02338-03) are run at very low gain (538 μrad sensitivity, ± 1 rad dynamic range) and are attached to the equatorial ring of the OBS to monitor capsule inclination and gross tilts; these operate independently of the levelling mechanisms. Two other orthogonal inclinometers are run at higher gain, set at 10.8 μrad sensitivity with 44 mrad dynamic range and are mounted on the seismometer block to measure platform tilt, and to provide some redundancy for the tiltmeters. The dynamic range of these inclinometers is set to accommodate the range of inclinations provided by the seismometer levelling (better than 9 mrad). Finally, a pair of high sensitivity tiltmeters using electrolytic bubble sensors (distributed by Fredericks) are mounted on a secondary levelling stage. This levelling stage uses two motor-driven micrometers on a triangular mounting plate to bring the sensors to null once the package is on the seafloor. The present sensitivity of these tiltmeters is 0.05 μrad, at a dynamic range of 0.2 mrad, although an auto relevelling routine expands this further: The tiltmeters can be preset to relevel for any desired time during an

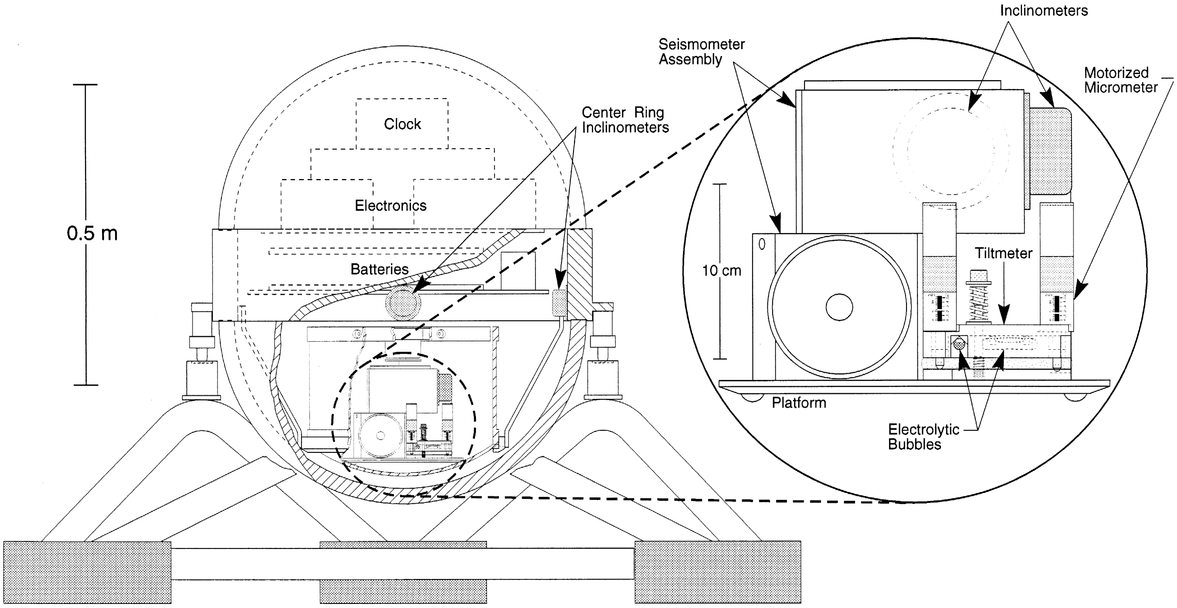

Fig. 2. Idealized, cutaway section through a TILT-OBS; expanded view illustrates the high sensitivity tiltmeter. Two orthogonally mounted low gain inclinometers are mounted on the center ring, and the high gain inclinometers and the high sensitivity tiltmeter are fixed to the seismometer block. The tiltmeter is mounted on a triangular plate that is independently levelled with motor-driven micrometers. The dynamic range of the high gain inclinometers is matched to the tolerance of the OBS levelling mechanism.

experiment. This ensures that they do not go, or remain, off-scale due to either drift, instrument settling or tilt signal. This relevelling scheme is very unlikely to result in an event being missed altogether, because with multiple instruments, the relevelling would be staggered. Since the time at which the relevels are performed is predetermined and carefully recorded, we can remove these intervals from the final data, thereby eliminating the risk that they would be mistaken for a tilt event. All inclinometer and tiltmeter functions, the levelling, and the data recording, are controlled by the OBSs' Central Processing Unit. To reduce power consumption, the inclinometers and tiltmeters are turned on and off for each measurement. A total of 15 min is allowed for warm-up, to avoid problems with sensor drift/noise that can be associated with switching sensors on and off. The sample interval can be varied to fit the experiment objectives, depending on whether short or long-term signals or both are of interest.

When 'deployed' on a concrete pier inside a test vault the tilt sensors comfortably track the same 3 μrad peak-to-peak earth-tide tilt signal as measured by a reference instrument (Fig. 3). (These tides are some 30 times larger than normal owing to ocean loading near the vault.) The first successful wet test of the first two of these TILT-OBSs was conducted on sediments on the eastern North American continental shelf. After an initial settling period of about 10 days characterized by rates of 20 μrad/day, the combined instrument settling and drift amounted to less than 0.7 μrad/day and is nearly linear for the final 12 days. These data show that unconsolidated sediment provides a satisfactory medium for submarine tilt measurement of volcanic signals. Hard rock deployments during a cruise on the East Pacific Rise exhibited similar drift rates.

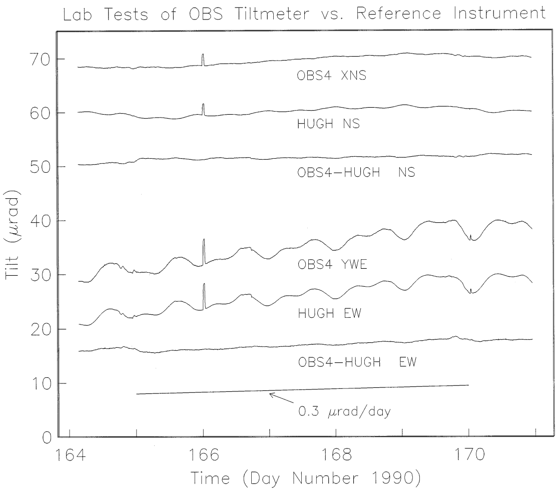

Fig. 3. Test of OBS tiltmeter system (OBS4, axes X and Y) against a reference standard instrument, a Hughes Research 'TM-3'. The spike at day 166 is a calibration pulse. For this experiment the sensors were mounted directly on a surface-plate in the IGPP basement vault. A reference line corresponding to a drift/signal of 0.3 μrad/day is plotted. The solid earth tides, evident in the OBS4 and TM-3 record, are primarily those caused by the ocean loading (and tilting) of the crust under our coastal test site, and look much like the local ocean tide record.

4. Long baseline tiltmeter

Long-baseline tiltmeters (LBTs) are typically permanently emplaced instruments that are prized for their high stability and accuracy, but while LBTs have been used successfully on sub-aerial volcanoes, development of a seafloor equivalent has proven quite difficult. Most LBT designs and techniques used to install high-quality land instruments (Agnew, 1986) are impractical for submarine tiltmeters. For example, almost all high-quality long-baseline instruments require a level installation, which is essentially impossible to achieve without remotely-operated vehicles or manned submersibles. However, center-pressure long-baseline tiltmeters, in which the differential pressure in two fluid-filled tubes is measured (e.g., Beavan and Bilham, 1977; Agnew, 1986), are feasible on the seafloor; we have chosen such a design.

A detailed description of the design and operation of the long-baseline instrument is given by Anderson et al. (1997); here, we give a brief summary. The tiltmeter, shown in Fig. 4, is essentially a center-pressure design folded so that the two tubes are side-by-side, with the differential pressure sensor at one end and fluid reservoirs sealed with compliant membranes at the other. This configuration has several advantages for seafloor work. First, because the fluid reservoirs (which are open to environmental pressure) are side-by-side, potentially significant pressure gradients need neither be compensated for nor measured. Also, only one pressure sensor is required, which makes both assembly and deploy-

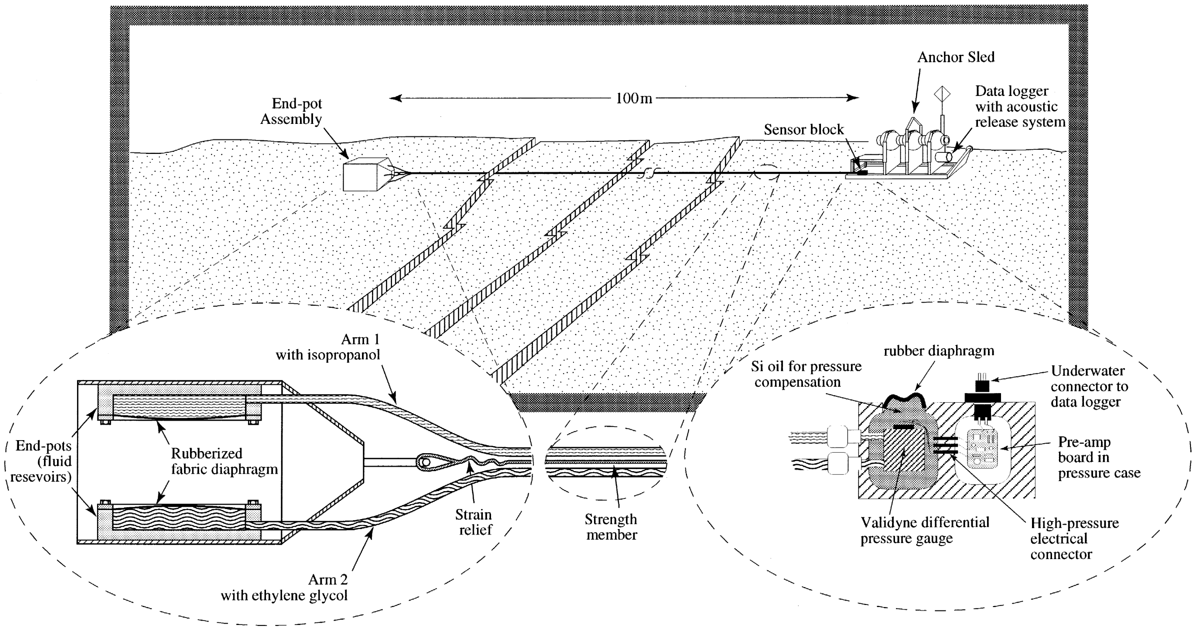

Fig. 4. Concept diagram for the temperature compensating long baseline tiltmeter. Pressure is measured between two tiltmeter arms containing fluids of different densities but similar products of density and thermal expansion coefficient.

ment of the tiltmeter simpler. Finally, by choosing fluids whose products of density and thermal expansivity are nearly identical, we can make our instrument temperature compensating to first order.

Measuring submarine volcanic tilt using this type of instrument is complicated by high confining pressures and rugged seafloor topography. For a typical MOR deployment, hydrostatic pressure is 10^7–10^8 times larger than the tilt-driven signals we wish to record, and since we wish the instrument to record tilt while deployed on sloping terrain, we require both a high dynamic range and low component creep. One commercial pressure sensor which fulfills these requirements is a variable reluctance gauge manufactured by Validyne Engineering, which we operate in a pressure-compensated oil bath to further reduce stress-driven creep of the sensor components.

5. Juan de Fuca experiment

During July to September 1994, we deployed both long and short baseline tiltmeters on Axial Seamount, on the Juan de Fuca ridge off Washington state, for a test of their relative performance on volcanic terrain. In all, six TILT-OBS, four long-baseline instruments (LBT) and three electromagnetic instruments were deployed for 9 weeks (Fig. 5). We reasoned that if the tiltmeters functioned well, our test might actually begin to contribute to our understanding of some important questions of the deformation behavior of MORs and possibly the intrusive dynamics and geometry. If the ground did not show any motion, we would be able to make an estimate of the upper limit of ground tilt, which had not been established, so far. Correlation of any surface deformation data (even no motion) with seismic data would allow us to speculate on the existence of aseismic magma transport, and/or the correlation of release of seismic energy and surface strain. The thin oceanic crust has virtually no buffering capability for the nearly continuous magma delivery from the mantle, in particular when compared to the thick crust at Iceland and Hawaii which quite successfully modulates the magma delivery. Tilt data or lack thereof, in particular in the context of well located seismic swarms, could have important implications for the magma migration from the mantle into the Axial Magma Chamber (AMC).

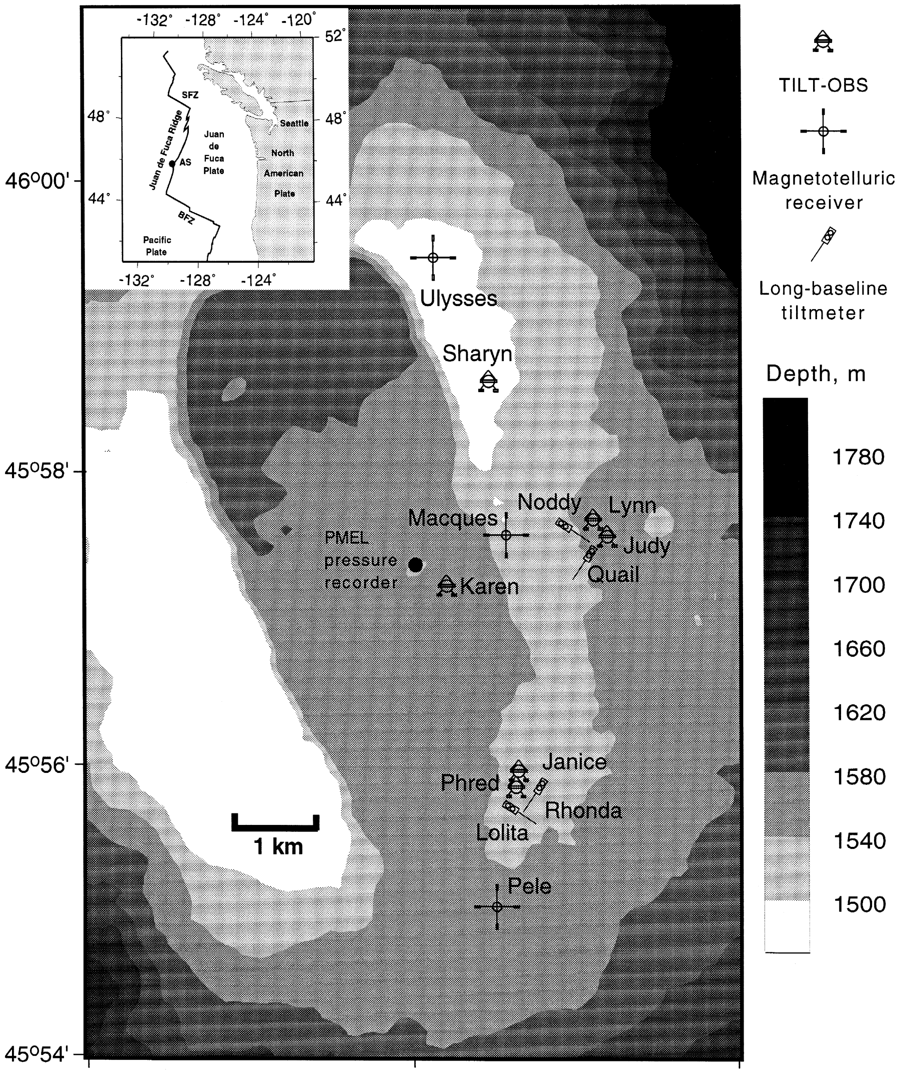

Fig. 5. Map of Axial Seamount showing instrument locations. Karen, Sharyn, Lynn, Judy, Janice and Phred are TILT-OBSs. Lolita, Rhonda, Quail and Noddy are long baseline instruments, although because of technical problems only Rhonda recovered data. Pele, Macques and Ulysses are electromagnetic recorders. The gravitationally inferred magma chamber and the earthquake swarm detected on the SOSUS array are centered beneath Macques. Inset map shows the location of Axial Seamount.

During the week prior to our deployment in late June 1994, a significant earthquake swarm associated with Axial Seamount was detected by the SOSUS array. C. Fox of NOAA suggested that we relocate our experiment to the seamount, which would provide us with the opportunity to monitor a volcano either during further eruptions or in a post-crisis mode. This location had the added advantage that Fox (Fox, 1990b, 1993) had two deformation instruments currently recording at that site. During the deployment cruise, the RV Atlantis-II was diverted to the area to conduct CTD measurements, following the events detected on the SOSUS array. At that time (July 3, 1994) an attenuation anomaly was measured at the site of TILT-OBS Janice and Phred (Fig. 5) characteristic of a bacteria bloom associated with recent volcanic activity (Embley, personal communication). The SOSUS observed seismic swarms did not continue following our deployment.

Five TILT-OBS recorded data for the entire time as did one LBT; the faults which prevented the other three long-baseline instruments recording were isolated and are preventable in future operations. A comprehensive data set has been obtained, with 30 channels of short baseline tilt exhibiting typical drift rates of less than 1 μrad/day, one channel of long baseline tilt with a drift rate of 1–3 μrad/day, a temperature record precise to a fraction of a millidegree, nine channels of magnetic field, six channels of electric field, fifteen channels of continuous seismic data and five hydrophone records. The magnetic and electric field data are discussed by Heinson et al. (1996). Analysis of the seismic data is currently underway and will be published separately (Tolstoy et al., 1997).

6. Short baseline tiltmeter results

Comparison of the inclinometer on the equatorial ring (lowest gain), the inclinometer on the seismometer platform (intermediate gain) and the precision tiltmeter (highest gain) demonstrates that all channels provide consistent records and are indeed measuring sensible tilt. This shows that the initial drift is associated with platform settling rather than with the sensor or its mounting, and therefore that sensor drift is not a serious problem (Fig. 6). Figs. 7 and 8 show tilt data (high gain sensor) from four instruments. Fig. 7 shows the raw data which illustrate the initial equilibration and long-term trend of the instruments. Platform settling is the most significant signal for at least the first month of the deployment, which suggests that long-term 'drift' rates will improve when the instrument is deployed for longer time periods. Fig. 8 shows the data with a spline fit drift removed to enable the shorter term variations to be compared. Note that there are periods of higher 'noise' (variations at tidal frequencies), which are consistent from instrument to instrument, further indicating that they are measuring a true signal. One instrument (Janice, not shown) exhibited a dramatic increase in noise during the second half of the deployment, associated with instrument stability and perhaps indicating opening of an active venting system near the instru-

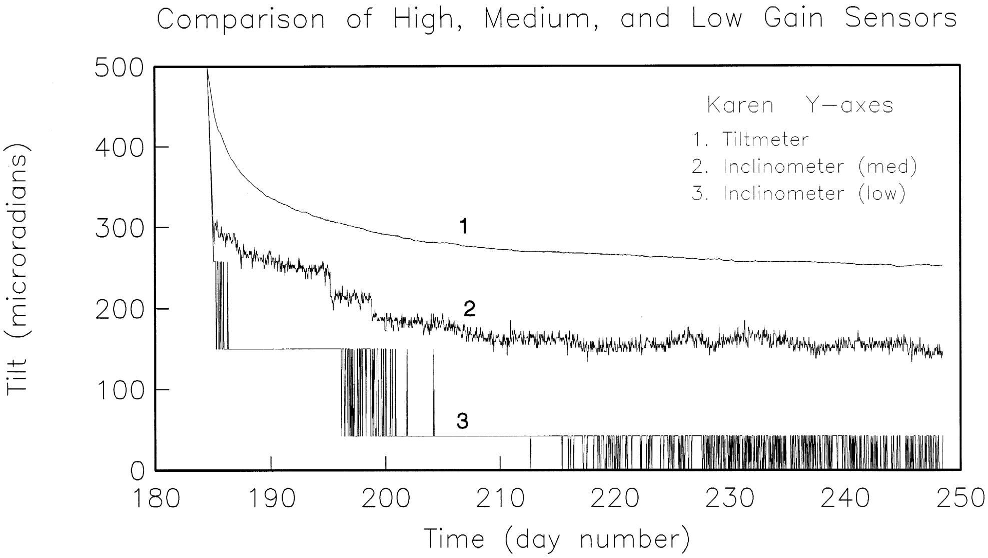

Fig. 6. Initial equilibration of Karen's *Y* channels, showing agreement between the high gain tiltmeters, medium gain inclinometers on the seismometer platform, and the low gain inclinometer on the equatorial ring.

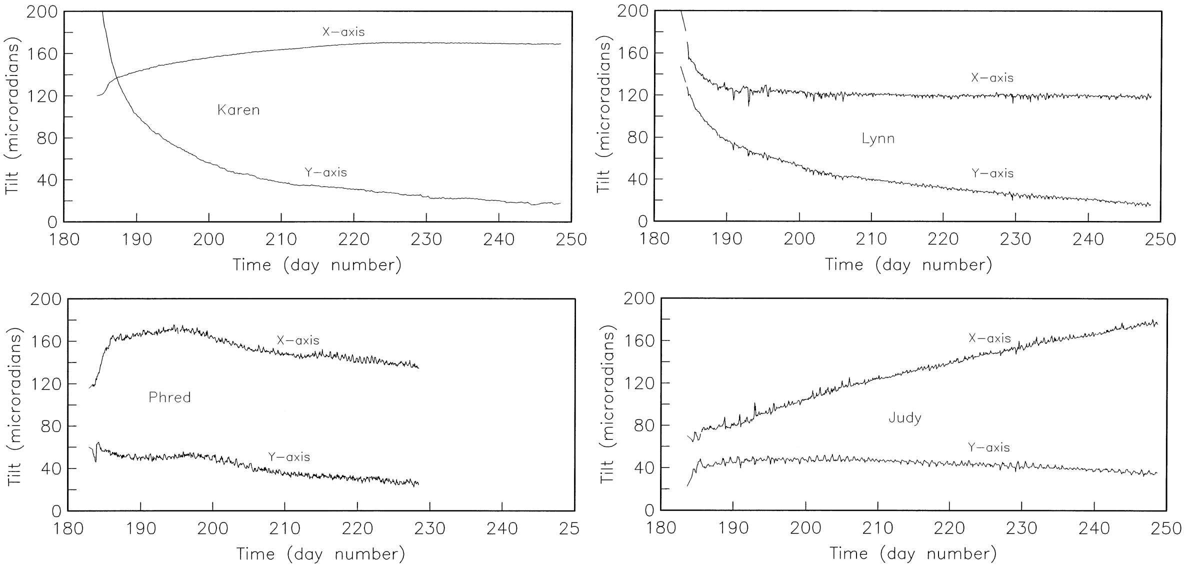

Fig. 7. Data from both X and Y channels of the bubble tiltmeters on four of the TILT-OBS, showing initial equilibration and long-term trends.

ment. This instrument was located where the attenuation anomaly was detected by Embley et al. Another instrument (Sharyn) operated for most of the time but a SeaScan clock error has so far made it impossible to play back the data. Tilt rates after initial equilibration vary from less than 1/10 to more than 10 μrad/day (about 10^{-7} to 10^{-5} m displacement over the 1 m baseline of the OBS), perhaps associated with varying success at establishing a stable resting place on the seafloor or perhaps in part a measure of Axial Seamount inflation. The extreme sensitivity of the short baseline sensor is demonstrated in Fig. 9, where the X-axis data from Karen are filtered at tidal frequencies and compared with a theoretical model of earth tides. The general agreement is good, and the amplitude enhancement of the tiltmeter tidal record may be the result of the thin lithosphere and extreme heterogeneity of the site. This result demonstrates that we have a resolution of better than 0.1 μrad at periods of 12 h to 1 day. While it is difficult to prove that earth tides are definitely the source of the signal, our measurements do at least put an upper bound on earth tides at this location. The high frequency variations evident in Fig. 8 are tidal in nature and probably due to tidal currents moving or deforming the instruments; Karen, deployed in the relative shelter of the caldera, was minimally affected by currents. The data from Karen set an upper limit for inflation at 0.4 μrad/day at an azimuth of 160°. This is a significant first result for a seafloor study. Even on the noisier instruments the

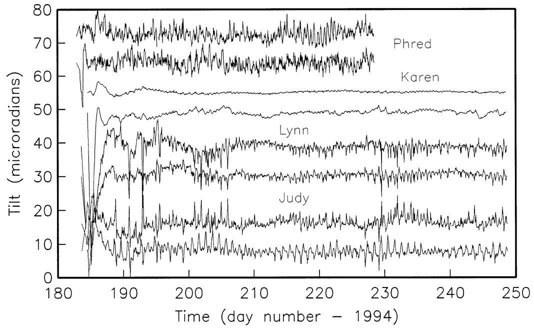

Fig. 8. Data from both X and Y channels of the bubble tiltmeters on four of the TILT-OBS with spline fit drift removed (Constable and Parker, 1988) to facilitate comparisons of short-term tilt rates. Energy that is coherent between instruments at tidal frequencies is evident. This is considered to be caused by tidal currents moving the instrument package; Karen was deployed inside the caldera and was thus sheltered from currents.

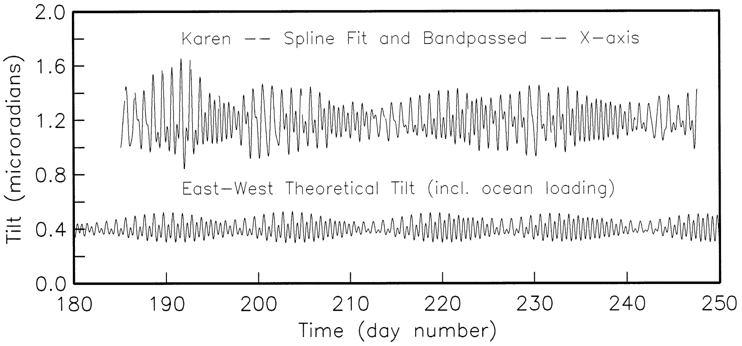

Fig. 9. Solid earth tilt tides with an ocean loading correction (bottom), and bandpassed X component data from Karen (top). The agreement is good, and the factor of three amplitude enhancement is reasonable given the limited lithosphere strength and heterogeneity of the site.

resolution is such that it is clear that no significant intrusive or extrusive activity occurred during our deployment. While this type of deployment is, therefore, more than adequate for monitoring such events, further significant improvements in resolution could be made by preventing the instrument rocking. We believe that securing the instruments to the seafloor, through cementing the anchor feet or other means, would allow consistent resolution at least as good as instrument Karen, which was sheltered from the currents.

7. Long baseline tiltmeter data

Fig. 10 shows raw data from the long-baseline tiltmeter Rhonda. A detailed analysis of the long-

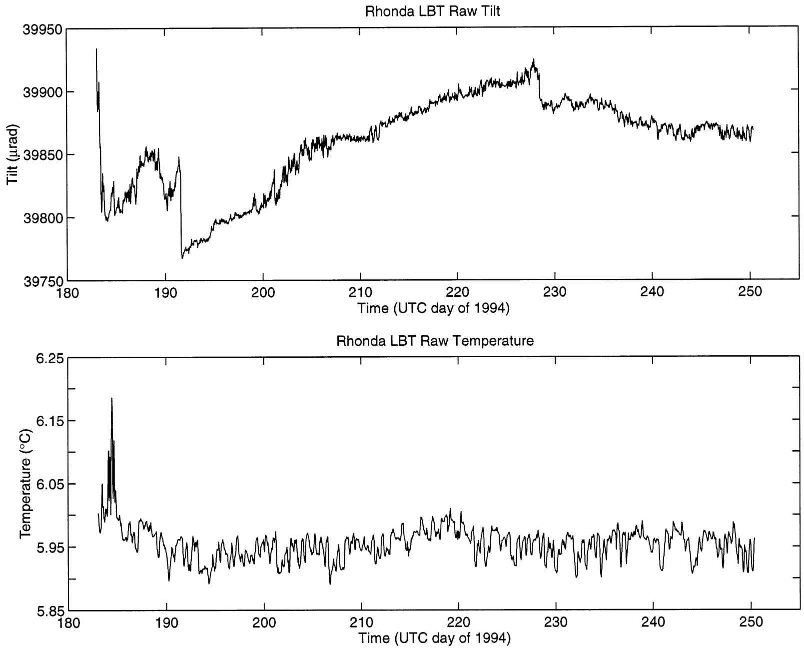

Fig. 10. Data from the long baseline tiltmeter and associated temperature sensor. In both the tilt and temperature records, we see an initial equilibration lasting only a day or so. There are two tares in the tilt record, with drift rates of 3 μrad/day before and 1 μrad/day after the second tare. A temperature signal is evident in the tilt record with a magnitude of order 10 μrad/0.1°C.

baseline data is given by Anderson et al. (1997); here, we summarize their arguments. After about 10 days of rapid instrument equilibration, a long-term signal is evident with tilt rates about 5 μrad/day near day 190, decreasing non-linearly to less than 1 μrad/day near day 240. Superimposed on this slow drift, which is likely due to continued instrument settling, there are two abrupt offsets at days 193 and 229, with amplitudes of 56 and 19 μrad, respectively. The offsets are likely due to settling of the fluid reservoirs or sensor block; if so, the offsets could be explained by about 5.6 and 1.9 mm relative height change over the 100-m instrument baseline. Additionally, there is an approximately tidal variation visible, with amplitudes of about ± 6 μrad, much higher than the 0.2 μrad expected tidal tilt.

There are several possible explanations for the 'tidal' signal, with the two most likely being temperature and ocean current forcing. The data from a temperature sensor on Rhonda are shown in Fig. 10. Anderson et al. (1997) use these data to reject temperature-driven tilt as a major effect, because the apparent temperature coefficient of the long-baseline tiltmeter is implausibly large and because spectral phase relationships show that temperature lags tilt by 40 min, which makes a simple causal relationship unlikely.

Ocean current forcing is the most likely explanation for the high-frequency variations seen in Rhonda's tilt data. Physically, currents could drive 'tilt' by vortex shedding or induced motion of either the fluid reservoir assembly or tubing. The electric field data record motionally-induced electric fields (Filloux, 1987), and thus may be used as proxies for ocean currents in comparisons with tilt data. We note significant, though weak, coherence between the electric field data from Pele and the tilt from Rhonda, which suggests that ocean currents are partially, though not completely, responsible for the high-frequency 'tilt' variations.

Long-term drift rates on both the long- and short-baseline tiltmeters are in the range from about 1–10 μrad/day, with the rates decreasing over time on both instruments. It is likely that both types of instruments would, over the course of a few months, reach a low, stable long-term tilt rate. A comparison of Figs. 8 and 10 shows that the data from Rhonda are only about a factor of two noisier than the data from Phred, Judy, and Lynn (Karen was deployed in the shelter of the caldera, where current-forced tilting is much lower).

8. Conclusions

We have developed two fundamentally different types of instruments capable of measuring seafloor tilt. Tilt rates on all the instruments are of the order of 1 μrad/day, and would have shown us all major deflation events in the Uwekahuna record (Fig. 1). Many of the inflation-events would have also been distinguishable given the observed tilt rates on these instruments. Tilt rates commonly accelerate before eruptions or major intrusive events, while rates for our instruments decelerate during the initial equilibration. We should clearly observe the sawtooth pattern of accelerated tilt, followed by sudden deflation.

Fig. 11 reviews our current level of tiltmeter performance in graphical form. It demonstrates, again, that most volcanic tilt signals would be within the capabilities of our instruments. It also suggests that, given resources to continue our program, improvements can be made. The stability of shallow borehole tiltmeters on land is limited by actual ground motion associated with temperature cycles and precipitation, but neither of these factors is of great consideration on the seafloor. The order of magnitude improvement we need to capture the full spectrum of volcanic deformation faithfully is achievable, given our progress so far. However, we would like to note that the long baseline instrument at Pinyon Flat (operated by Wyatt), representing the best of instrument performance, is one of only a handful of this quality in the world and took about a decade to develop to this stability. Among other things, it involves drilling boreholes at the ends for anchoring. It is probably safe to say that an instrument of this ilk could never be operated on the seafloor, and while we might be able to achieve one, or perhaps even two, orders of magnitude improvement in our seafloor instruments, it is unrealistic to expect quality comparable to the Pinyon installation from the seafloor.

The data from TILT-OBS Karen represents the most accurate seafloor tilt measurements made to

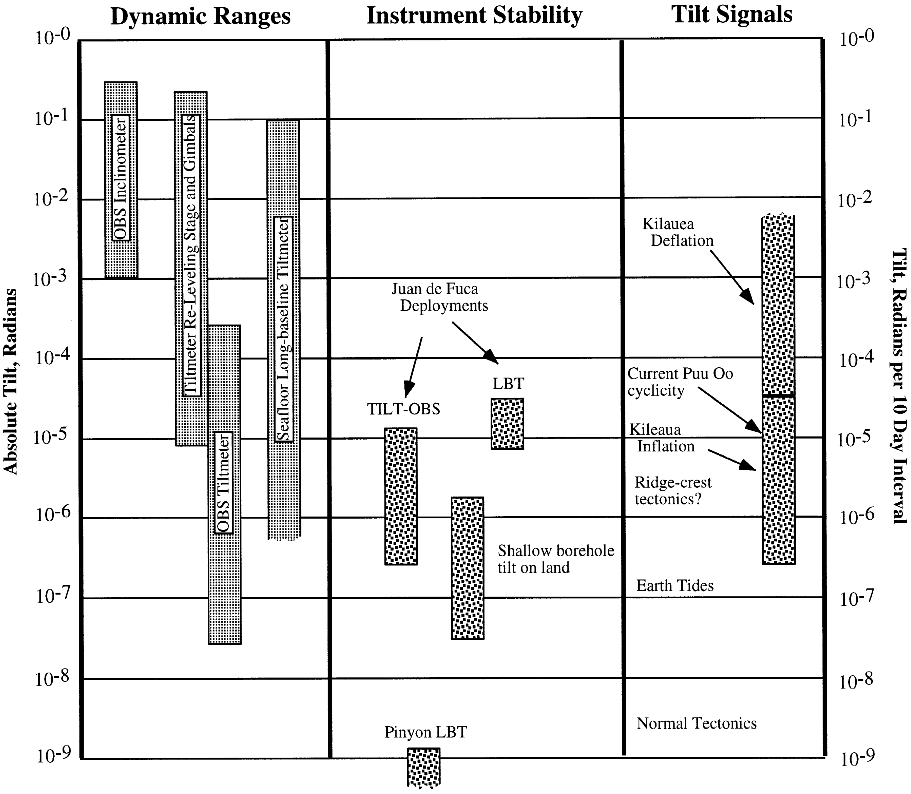

Fig. 11. Graphical comparison of instrument dynamic ranges, instrument stability, and geophysical signals. Most of the deformation measured at Kilauea volcano on Hawaii is within the range of our instrument stability, and since the character of instrument drift is likely to be very different from volcanic activity, our instruments will prove useful for their intended task.

date. The resolution exhibited of 0.1 μrad at periods of 12 h to one day we believe to be attributable to the relative shelter from currents of the caldera. In future deployments, sheltering the instruments from currents, or preferably fixing the instruments to the seafloor, should enable measurements of at least this accuracy to be made using all the TILT-OBS instruments on a routine basis.

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References

Agnew, D.C., 1986. Strainmeters and tiltmeters. Rev. Geophys. 24, 579–624.

Anderson, G., Constable, S., Staudigel, H., 1997. Development of a long-baseline seafloor tiltmeter. J. Geophys. Res., in press.

Baragar, W.R.A., Lambert, M.B., Baglow, N., Gibson, I.L., 1987. Sheeted dykes of the Troodos ophiolite, Cyprus. In: Halls, H.C., Fahrig, W.F. (Eds.), Mafic Dyke Swarms. Geol. Assoc. Canada, pp. 257–272.

Beavan, J., Bilham, R., 1977. Thermally induced errors in fluid tube tiltmeters. J. Geophys. Res. 82, 5699–5704.

Cann, J.R., 1970. New model for the structure of the ocean crust. Nature 226, 928–930.

Constable, C.G., Parker, R.L., 1988. Smoothing, splines and smoothing splines; their application in geomagnetism. J. Comput. Phys. 78, 493–508.

Decker, R.W., 1987. Dynamics of Hawaiian volcanoes: an overview. In: Decker, R.W., Wright, T.L., Stauffer, P.H. (Eds.), Volcanism in Hawaii. U.S. Geol. Surv. Prof. Pap. 1350, United States Government Printing Office, Washington, DC, pp. 997–1018.

Duennebier, F.K., Harris, D., 1990. Broad-band seismometers on the ocean floor. EOS Trans. Am. Geophys. Union 70, 1216.

Filloux, J.H., 1987. Instrumentation and experimental methods for oceanic studies. In: Jacobs, J.A. (Ed.), Geomagnetism. Academic Press, London, pp. 143–248.

Fox, C.G., 1990a. Results from three years of monitoring of ground deformation at Axial Volcano, Juan de Fuca Ridge, using a bottom pressure recorder. EOS Trans. Am. Geophys. Union 71, 1609.

Fox, C.G., 1990b. Evidence of active ground deformation on the mid-ocean ridge: Axial Seamount, Juan de Fuca Ridge, April–June 1988. J. Geophys. Res. 95, 12813–12822.

Fox, C.G., 1993. Five years of ground deformation monitoring on Axial Seamount using bottom pressure recorder. Geophys. Res. Lett. 20, 1859–1862.

Fox, C.G., 1995. Special collection on the June 1993 volcanic eruption on the Coaxial segment, Juan de Fuca Ridge. Geophys. Res. Lett. 22, 129–130.

Fox, C.G., Dziak, R.P., Matsumoto, H., Schreiner, A.E., 1993. Potential for monitoring low-level seismicity on the Juan de Fuca Ridge using military hydrophone arrays. Mar. Technol. Soc. J. 27, 22–30.

Heinson, G., Constable, S., White, A., 1996. Seafloor magnetotelluric sounding above Axial Seamount. Geophys. Res. Lett. 23, 2275–2278.

Kidd, R.G.W., 1977. A model for the process of formation of the upper oceanic crust. Geophys. J. R. Astron. Soc. 50, 149–153.

Kidd, R.G.W., Cann, J.R., 1974. Chilling statistics indicate an ocean-floor spreading origin for the Troodos Complex, Cyprus. Earth Planet. Sci. Lett. 24, 151–155.

Langmuir, C.H., Bender, J.F., Batiza, R., 1986. Petrological and tectonic segmentation of the East Pacific Rise, 5°30′–14°30′N. Nature 322, 422–429.

Okamura, A.T., Dvorak, J.J., Koyanagi, R.Y., Tanigawa, W.R., 1988. Surface deformation during dike propagation. In: Wolfe, E.W. (Ed.), The Puu Oo Eruption of Kilauea Volcano, Hawaii: Episodes 1 Through 20, January 3, 1983, Through June 8, 1984. U.S. Geol. Surv. Prof. Pap. 1463, pp. 165–181.

Rubin, A.M., Pollard, D.D., 1987. Origins of blade-like dikes in volcanic rift zones. In: Decker, R.W., Wright, T.L., Stauffer, P.H. (Eds.), Volcanism in Hawaii. U.S. Geol. Surv. Prof. Pap. 1350, United States Government Printing Office, Washington, DC, pp. 1449–1470.

Sakata, S., Shimada, S., 1984. Development of the ocean bottom tiltmeter. J. Geodetic Soc. Jpn. 30, 50–58.

Shimamura, H., Kanazawa, T., 1988. Ocean bottom tiltmeter with acoustic data retrieval system implanted by a submersible. Mar. Geophys. Res. 9, 237–254.

Sigurdsson, H., 1987. Dyke injection in Iceland: a review. In: Halls, H.C., Fahrig, W.F. (Eds.), Mafic Dyke Swarms. Geol. Assoc. Canada, pp. 55–64.

Sigurdsson, H., Sparks, S.R.J., 1978. Lateral magma flow within rifted Icelandic crust. Nature 274, 126–130.

Staudigel, H., Wyatt, F.K., Orcutt, J.A., 1991. Ocean bottom tiltmeter developed for submarine volcano monitoring. EOS Trans. Am. Geophys. Union 72, 289–295.

Staudigel, H., Gee, J., Tauxe, L., Varga, R.J., 1992. Shallow intrusive directions of sheeted dikes in the Troodos ophiolite: anisotropy of magnetic susceptibility and structural data. Geology 20, 842–844.

Tolstoy, M., Vernon, F., Orcutt, J.A., 1997. Magmatic activity on axial seamount: a combined ocean bottom seismic and tilt experiment. EOS Trans. Am. Geophys. Union, Fall AGU Meeting.

Varga, R., Staudigel, H., Gee, J., Tauxe, L., 1991. Structural evidence fro horizontal emplacement of sheeted dikes in the Troodos ophiolite. Contributed paper at AGU Fall meeting, San Francisco.

Willoughby, D.F., Orcutt, J.A., Horwitt, D., 1993. A microprocessor-based ocean-bottom seismometer. Bull. Seismol. Soc. Am. 83, 190–217.

Wolfe, E.W., Garcia, M.O., Jackson, D.B., Koyanagi, R.Y., Neal, C.A., Okamura, A.T., 1987. The Puu Oo eruption of Kilauea volcano, episodes 1–20, January 3, 1983 to June 8, 1984. U.S. Geol. Surv. Prof. Pap. 1350, pp. 471-508.

Wyatt, F., Orcutt, J., Sasagawa, G., Staudigel, H., Zimmer, P., 1996. Towards in situ monitoring of active submarine volcanoes: a progress report. In: Salisbury, G.P., Salisbury, A.C. (Eds.), Fifth Circum-Pacific Energy and Mineral Resources Conference Transactions. Gulf Publishing, Houston, TX, pp. 757–773.