Results from Prior NSF Support

Award Number OCE−11965
Amount $304,958
Period 08/15/98−11/30/00
Title Active Seismic Imaging of Axial Volcano, **PI's** William Menke & Maya Tolstoy

The region of Axial Volcano, Juan de Fuca Ridge region provides an excellent opportunity to study the interplay between active "hot spot" and "mid−ocean ridge" magmatic systems. Important questions include how the two magma systems are fed; their magma and heat budgets; the degree of interconnectedness (or interaction) between them; their relationship to seismicity and geodetic strains; the role of each in plate−tectonic spreading and and crustal formation; and their effect on the geochemistry (e.g. mixing, fractionation) of erupted basalts. Information on the physical layout of the magma systems is critical to the study of each of these issues. The purpose of this research was to investigate these questions through the tomographic imaging of the region using seismic data from an active seismic airgun−to−obs experiment. The experiment was remarkably successful, both in the sense that voluminous high−quality data were obtained, and in the sense that very clear signials associated with magma were detected in that data. The key elements of the new three−dimensional compressional velocity model of the Axial and Coaxial magma systems are (West, 2001):

1. **A Very Large Axial Magma Chamber.** At a depth of 2.25 to 3.5 km beneath Axial caldera lies an 8 by 12 km magma chamber containing 10−20% melt (West 2001). At depths of 4−5 km beneath the sea floor there is evidence of additional melt, in lower concentrations (a few percent) but spread over a larger area. Residence times of a few hundred to a few thousand years are implied (West et al. 2001).
2. **A smaller Coaxial Magma Chamber, unconnected with the one at Axial.** The magma chamber is loacted at the "Source Site" of the 1993 eruption (Menke et al., 2001). It is at least 6 cubic km in volume and contains at least 0.6 cubic km of melt, enough to supply at least several eruptions of size equal to the one in 1993.
3. **Several other small low velocity zones are possibly outlier magma chambers from Axial.** Two other low−velocity zones occur in the shallow crust near Axial volcano, one about 10 km north of the caldera on the North Rift, and the other about 10 km south of the caldera but displaced to the west of the South Rift (West 2001). They appear unconnected to the main Axial magma chamber and might possibly represent small accumulations of melt left over from past lateral diking events.
4. **Strong thickening of the crust beneath Axial volcano.** The crust thickens from about 6 km far from Axial to 8 km near Axial to 11 km beneath the summit (West 2001).

Publications:

1. Menke−W, Shallow crustal magma chamber beneath the axial high of the Coaxial Segment of Juan de Fuca Ridge at the "Source Site" of the 1993 eruption, submitted to Geology, 2001.
2. West−M, The deep structure of Axial Volcano, Ph.D. Thesis, Columbia University, 2001.
3. West−M; Menke−W; M−Tolstoy; S−Webb; R Sohn, Magma reservior beneath Axial volvano, Juan de Fuca Ridge is far larger than eruption size; submitted to Nature, 2001.

Data and other products This project collected new data, which is freely available on−line at http://www.ldeo.columbia.edu/user/menke/AX/. Some software, including the tomograhy code, that was written for the project is available at http://www.ldeo.columbia.edu/user/menke/software/.

Introduction. Axial volcano, in the Northeast Pacific, is a large ridge−centered seamount associated with the Cobb−Eickelberg hot spot. Its position on the actively−spreading Juan de Fuca ridge (JdF, 60 mm/yr full spreading rate), its proximity to western North America, its shallow (1600 m) summit depth, its prominent (3x8 km wide) caldera (figure 1A), and it vigorous hydrothermal activity have led to its being the focus of numerous research efforts (e.g. the special sections in the Journal of Geophysical Research (vol. 95, 1990), Geophysical Research Letters (vol. 22, 1995 and vol. 26, 1999), etc.). Two recent volcanic eruptions in the area (described below) attest to the vigorous magmatic activity of Axial and the nearby Coaxial segment of the JdF ridge.

In 1993 a large seafloor volcanic eruption occurred along the CoAxial segment of the JdF, immediately to the northeast of Axial Volcano. This eruption was detected during its early stages by hydroacoustic observations (Dziak et al., 1995), and subsequently studied intensively (e.g. special section in January 15, 1995 issue of Geophys. Res. Lett.). The eruption appears to have been caused by the lateral propagation of a dike from the magma chamber of on the southern part of Coaxial segment to a site 25 km to the northeast (Dziak et al., 1995). The sequence of events seems to be similar to the 1974−1985 rifting episode in northern Iceland, which involved the lateral propagation of dikes away from Krafla Volcano (Brandsdottir and Einarsson, 1979). The Iceland rifting episode led to about 9 meters of spreading of the North American − Eurasian plate boundary. The amount of spreading associated with the CoAxial eruption is not known.

In 1998 a second eruption occurred in which a dike propagated from near the Axial caldera to a point about 50 km to the south (Dziak and Fox 1999). The propagation of this dike was also monitored by hydroacoustic means (Dziak and Fox 1999). This eruption caused 3 m of subsidence of the Axial caldera floor (Fox 1999). Geological mapping of lava flows along Coaxial and their chemistry, which is distinct from Axial basalts, have been used to argue that the sources of the Axial and Coaxial lavas are distinct (Embley et al. 2000).

This region thus provides an excellent opportunity to study the interplay between active "hot spot" and "mid−ocean ridge" magmatic systems. Important questions include how the two magma systems are fed; their magma and heat budgets; the degree of interconnectedness (or interaction) between them; their relationship to seismicity and geodetic strains; their role of each in plate−tectonic spreading and and crustal formation; and their effect on the geochemistry (e.g. mixing, fractionation) of erupted basalts. Information on the physical layout of the magma systems is critical to the study of each of these issues. Such a model, based on tomographic imaging using seismic data from an active seismic airgun−to−obs experiment that we performed in 1999, is now available. The key elements of this three−dimensional compressional velocity model of the Axial and Coaxial magma systems are (West, 2001):

1. **A Very Large Axial Magma Chamber (figure 1B).** At a depth of 2.25 to 3.5 km beneath Axial caldera lies an 8 by 12 km region of very low seismic velocities (figure 1C,D) that can only be explained by the presence of magma (West 2001; West et al. 2001). In the center of this magma chamber the crust is at least 10−20% melt. At depths of 4−5 km beneath the sea floor there is evidence of additional melt, in lower concentrations (a few percent) but spread over a larger area. The total volume of the magma chamber is about 200 cubic km, of which 5−26 cubic km is melt. This large volume of magma, compared with that erupted in 1998, imply residence times of a few hundred to a few thousand years (West et al. 2001).

2. **A smaller Coaxial Magma Chamber, unconnected with the one at Axial.** The magma chamber is loacted at the "Source Site" of the 1993 eruption (Menke et al., 2001) (figure 2B). It is at least 6 cubic km in volume and contains at least 0.6 cubic km of melt, enough to supply at least several eruptions of size equal to the one in 1993. No mid−crustal connection of this magma chamber with the magma chamber of nearby Axial volcano is evident, confirming previous geochemical and geological studies that argued against mixing between the two. The lack of connectivity implies that magma transport though the uppermost mantle and lower crust are very highly focused into narrow (<5−10 km) conduits.

3. **Several other small low velocity zones are possibly outlier magma chambers from Axial.** Two other low−velocity zones occur in the shallow crust near Axial volcano, one about 10 km north of the caldera on the North Rift, and the other about 10 km south of the caldera but displaced to the west of the South Rift (West 2001) (figure 2B). They appear unconnected to the main Axial magma chamber and might possibly represent small accumulations of melt left over from past lateral diking events.

4. **Strong thickening of the crust beneath Axial volcano.** The crust thickens from about 6 km far from Axial to 8 km near Axial to 11 km beneath the summit (West 2001). The long−wavelength 6−8 km thickening is consistent with predictions based on gravity data (Hooft & Detrick 1995). The shorter wavelength 8−11 km thickening, which creates a three km thick crustal root beneath the volcano, is not predicted to have an observable gravity signature. A sharp, normal Moho boundary is detected at the base of the crust (including at the base of the root).

Proposed Research At present, the integration this new understanding of the magmatic structure of Axial with other geophysical data has been largely qualitative, which is ironic given that they provide a very quantitative and detailed description of the subsurface. We therefore propose to develop quantitative stress/deformation and thermal models that allow specific, testable predictions to be made:

1. **3D stress and deformation model based on the cavity assumption.** The release of pressure within a magma chamber during an eruption causes changes in the state of stress within the surrounding rock (and hence possibilty to a change in seismicity), geodetic displacments of the ocean floor (e.g. subsidence and tilt), and changes in the pressure in neighboring, unconnected magmatic systems. We propose to develop a 3D model that can predict these effects. We expect that the very lage lateral gradients in material properties will have a major effect on the stress field, and will give rise to phenominon that would not be modeled in a simple homogeneous halfspace model.

   We will proceed by developing a 3D quasi−static elastic/fluid model, in which the crust is modeled as an elastic solid containing irregularly−shaped compressible fluid−filled cavities whose shape is taken from the tomographic model. Some versions of this model will also contain dikes, represented as thin fluid−filled cracks with a position that follows the seismicity data. The effect of eruptions can be modeled by changing the pressure in the cavities and dikes. Plate−tectonic extensional stress can also be imposed over the whole region as a boundary condition. This model will be applicable to time scales that are short compared to the relaxation time of the crust as a whole (decades to centuries) but long compared to the viscous relaxation time of the magma (minutes to hours). It will thus be useful for examining processes that occur, say, in the days to years following and eruption, a time period for which many observations are available.

   We will use the inexpensive, commercially−available *Beasy* analysis code (see http://www.beasy.com) for the stress calculations. Beasy is based on a boundary−element method. The earth is divided into homogenous regions delimited by surfaces composed of triangular (or quadilateral) tiles. These surfaces can be shaped to match sea floor bathymetry and the surface of the magma chambers. Stress is calculated both on the surface itself and at selected points in the interior of the regions. We have considerable experience with this code at Lamont, and it has proven reliable for a variety of stress analyses in a geophysical context (e.g. ten Brink et al. 1996) (figure 3). It is also well−match with the tomographic velocity model, which is represented with a tetrahedral mesh. We will use the stress model to:

   - Examine how the deflation of one of the magma chambers brings regions of the surrounding rock closer to (or farther from) brittle failure. Because of the irregular shape of the magma chamber, we expect the pattern to significantly depart from simple the ideal axial−symmetric case. We will compare these predictions with the observed pattern of seismicity following the 1993 and 1998 eruptions (which were well−monitored, both by hyroacoustic means (Dziak et al. 1995,Dziak et al. 1999; Dziak & Fox 1999) and by temporary OBS deployments (Sohn et al. 1999). These sesimicity patterns have several unusual features. For instance, in the year following the 1998 eruption, an area about 5−10 km east of the Axial caldera was unusually seismically active (Sohn et al. 1999) (figure 4A). While this region is well east of the actual eruption, our model shows it to be underlain by a deep extension of the Axial magma chamber. Thus deflation of the magma chamber could possibly lead to loading of this region.

- Examine how ocean tidal loading effects stresses above magma chamber. M. Tolstoy, at the 1999 RIDGE workshop in Seatle, presented data that demonstrated that the rate of occurrence of both small, shallow earthquakes and harmonic tremor beneath the Axial caldera is modulated by the ocean tidal cycle. The harmonic tremor has a semidiurnal period, and is probably hydrothermal (water moving through cracks), as contrasted to magmatic in nature. The rate of seismicty is highest at the times of lowest ocean tides. The underlying reason for this modulation is not fully understood. It may be related to the decrease in confining pressure when the weight of the water is decreased. The large difference in the compliance of the magma chamber and the surrounding rock may concentrate stress around the edges of the caldera. Flucuations in pore pressure and in the permeability of the uppermost crust (through changes in normal stress across joint surfaces) may also play a role. Tolstoy et al. (1998) also presented evidence from ocean bottom tiltmeters that the overall magnitude of the deformation associated with tides is much larger, by a factor of 4, than what would be expected from a halfspace model (figure 4C), suggesting that the very compressible material in the magma chamber might be amplifying the tidal signal. We will model this "flexure" of the magma chamber lid and quantitatively assess whether it can explain these diverse phenomena.

- Examine how the deflation of one of the magma chambers and diking leads to subsidence, tilting and displacement of the sea floor. Two important uses of geodetic measurements are to determine the net volume loss after an eruption (i.e. estimate the eruption’s size) and to measure any widening of the rift zones that may have occurred (i.e. estimate plate−tectonic spreading). We will address three issues: First, we will first assess whether the 3D model provides significant improvement over the simple "point source in a homogenous halfspace" models that have been applied elsewhere (e.g. Linde et al. 1993). The very signifcant complexity in the Axial region suggests to us that it will. Second, we will examine the currently available tilt (Anderson et al. 1995; Tolstoy et al. 1998), subsidence data (Fox 1990; Fox 1993; Fox 1999) and extension (Chadwick et al. 1999) data are consistent with the model. The tilt data are fairly limited in scope, with tilt being limited to 9−weeks data from an array of 5 sea floor instruments operated during 1994 (a volcanically quiescent period during which tides were the major signal). The subsidence data, measured using pressure sensors deployed around the caldera, are more voluminous and include the very interesting caldera subsidence that occured during the 1998 eruption. The extensometer data (figure 4B) includes a very interesting shortening of the north rift of Axial during the 1998 eruption. This is a region that does not contain large accumulations of magma, so the shortening probably represents an elastic response to the deflation of the neighboring Axial magma chamber during the eruption. Our modeling effort may be able to assess whether the North Rift is more or less stiff than neighboring parts of the volcano.

- Examine whether stress interaction between the Axial and Coaxial magmatic systems can plausibly effect the timing of their eruptions. The Coaxial magma chamber is about 15 km from one at Axial, and only about 8 km from the axis of the Axial’s North Rift Zone. One might expect some degree of interaction between the two. Unfortunately, the historical record of eruptions is not long enough to define any sort of eruption recurrence time, and so to interpret the 7 year interval between the 1993 Coaxial and 1998 Axial eruptions. On the other hand, the southward propagation of the 1998 dike is consistent with the 1993 dike having decreased tensional stresses along the North Rift Zone, thus having made northward diking less likely. Our long−term goal here is to develop methodology that will allow the state of stress of the volcano to be tracked over the course of many eruption cycles, and be used to assess the likelihood of future eruptions in various parts of the volcanic system. Such tracking of stress−evolution has proved possible in southern California (Deng & Sykes, 1997) and Turkey (Parsons et al. 2000)

2. **Regional Thermal Model.** Axial volcano is a region of intense heat flow, owing to the presence of magma at only 2 km depth below the sea floor. This heat flow is associated with very vigorous hydrothermal activity (Malahoff et al. 1984). The ASHES field in the Axial caldera, for instance, dischares 15−75 MW of heat energy into the water column (Rona & Trivett 1992). We propose to develop a regional thermal model that can quantitatively evaluate its heat budget. The BEASY code (see above) is also suitable for this purpose. The key problem will be how to model the heat transport in the shallow crust due to the hydrothermal circlulation, an in particular whether the hydrothermal system should be dynamically modeled, and include coupling between advection rate, bouyancy and temperature in a permeable medium; or whether its should be modeled more approximately through an "effective" (and high) thermal conductivity in a conductive regiem. Each method had its advantages and pitfalls. The dynamic model has the potential for greater accuracy, but is more dependent upon the less−well known, fine structure of the uppermost crust that controls its permeability. Our inclination is to start by building a regional, "effective" model, but to examine the effect of dynamic heat transport in several better−studied small areas (e.g. the caldera) with finer−scale "dynamic" models. We will use the thermal model to address the following questions:
    - What is the "steady−state" heat loss of the volcano? Many of the hydrothermal fields are short−term phenomena driven by shallow diking in their immediate vicinity. We seek to compare their heat output (Baker et al. 1995; Cannon et al. 1998; Baker et al. 1999) with estimates of the more continuous and "diffuse" cooling that involves low−termperature fluids and conduction.
    - How fast are the magma chambers cooling? The process of crystalization of the magma is an important one with significance to both the evolution of the chemical composition of the magma itself, and to the production of lower crust though the production of solid gabbroic cumulates. We seek to place some constraints on the time scales over which these processes occur.
    - How much stress is developing due to the cooling? Is this likely to be a significant source of seismicity? (The Beasy code is set up to handle thermal stresses).

BENEFITS OF THE PROPOSED RESEARCH

This research seeks to build upon the detailed structural information of the volcanic system provided by a 3D tomographic compressional velocity model by using the model to predict geodetic stresses and displacements and temperature. The study region, Axial volcano and its immediate vicinity, is one that has attracted intense interest over the years, and which shows prospects of continuing observation (e.g. the Neptune project for a permanent fiber−optic telemeterd observatory, http://www.neptune.washington.edu/). Many different types of geophysical data are available now, with features that cannot be explained by models that ignore the strong lateral gradients in material properties related to the presence of magma at shallow depths. Furthermore, more data are likely to become available in the future. This project takes an initial step towards building an integrated model of the volcano, one that has the prospect of allowing a wide variety of data to mode modeled; one consistent with the long−term goal of tracking the evolution of the volcano over its next several eruptive cycles.

MANAGEMENT PLAN

Menke, who has broad experience in geophysical modeling efforts, will be responsible for the timely completion of the project. Menke, assisted by a GRA, will perform the research.

TIMETABLE

This research is expected to take one year.

DISSEMINATION OF RESULTS

We will maintain archives of data and preliminary results on our institutional web sites (as we now do for previous studies, see for example http://www.ldeo.columbia.edu/user/menke). We will make the final BEASY models freely available, so that others can use them. We will present results at scientific national meetings, such as the Fall AGU, and make a best−faith effort to publish them rapidly in a peer−reviewed journal.

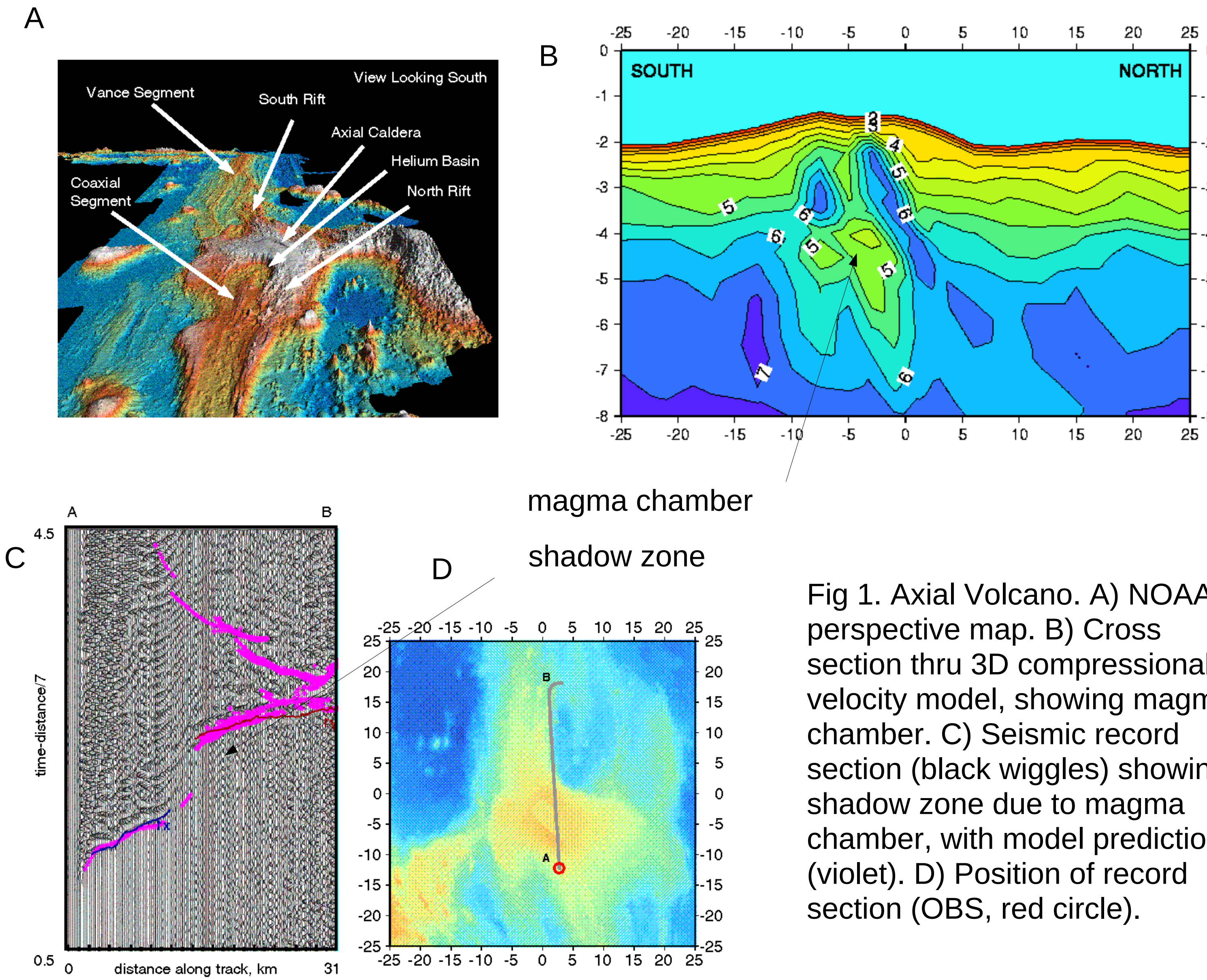

Fig 1. Axial Volcano. A) NOAA perspective map. B) Cross section thru 3D compressional velocity model, showing magma chamber. C) Seismic record section (black wiggles) showing shadow zone due to magma chamber, with model predictions (violet). D) Position of record section (OBS, red circle).

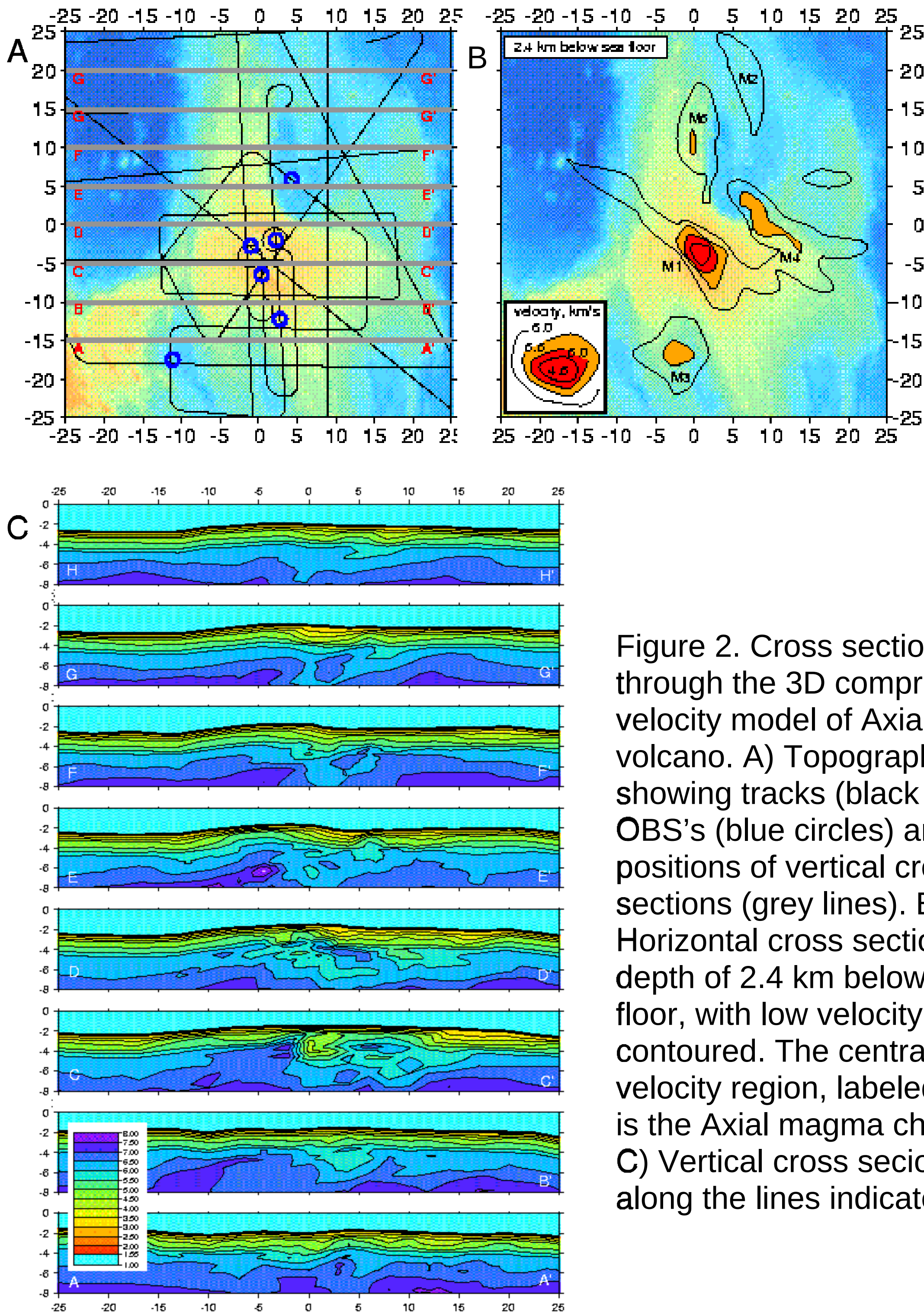

Figure 2. Cross sections through the 3D compressional velocity model of Axial volcano. A) Topographic map showing tracks (black lines), OBS's (blue circles) and positions of vertical cross sections (grey lines). B) Horizontal cross section at a depth of 2.4 km below the sea floor, with low velocity regions contoured. The central low velocity region, labeled M1, is the Axial magma chamber. C) Vertical cross secions, along the lines indicated in A.

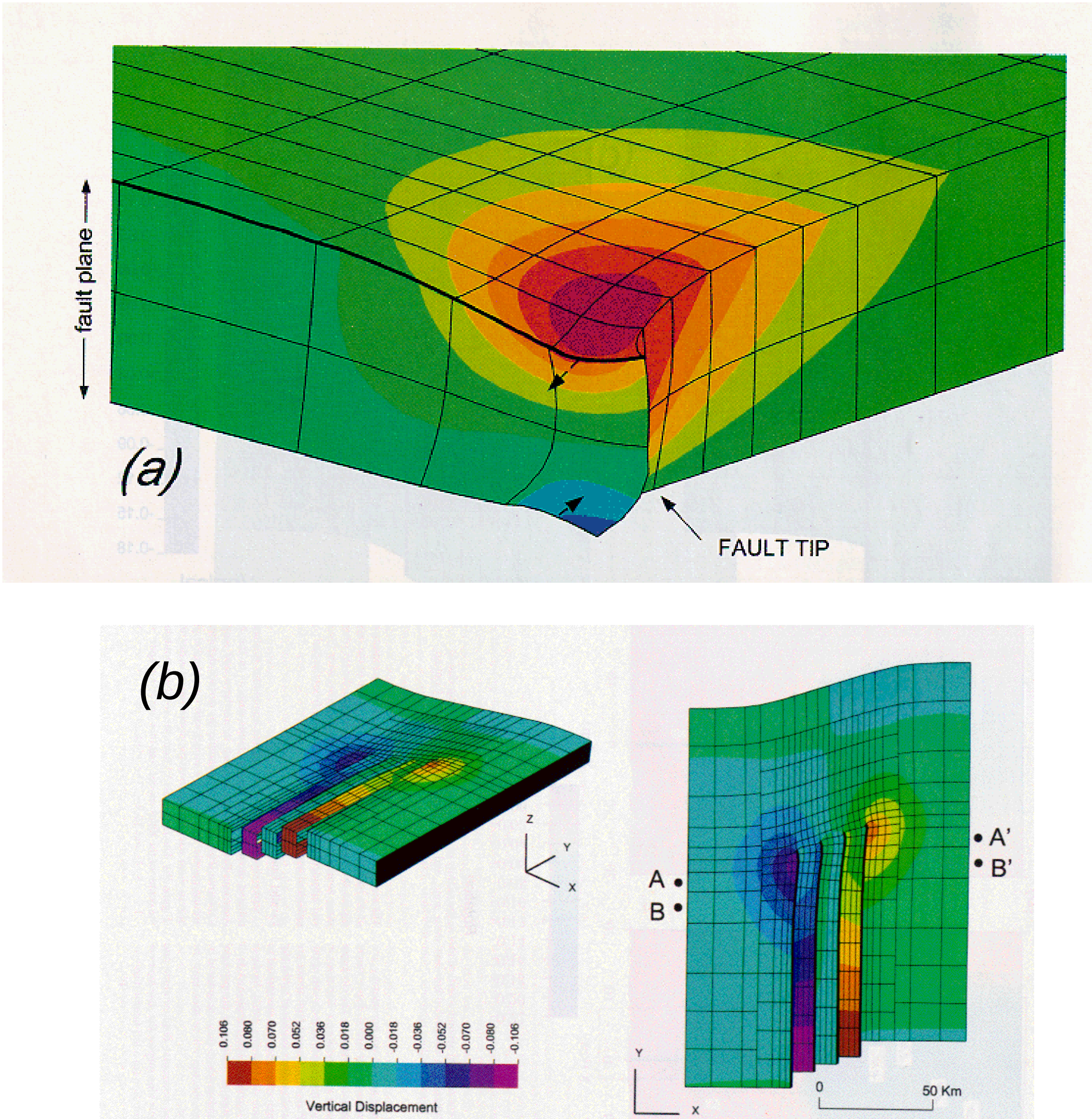

Figure 3. An example, taken from ten Brink et al. (1996) of the use of the Beasy code in a geophysical context. Here the displacements around strike slip faults that intersect the surface of the earth are modeled. (A) The horizontal displacement of the earth due to a strile slip fault. (B) The vertical displacement due to several interacting facults. The grid represents deformation of the originally orthogonal mesh.

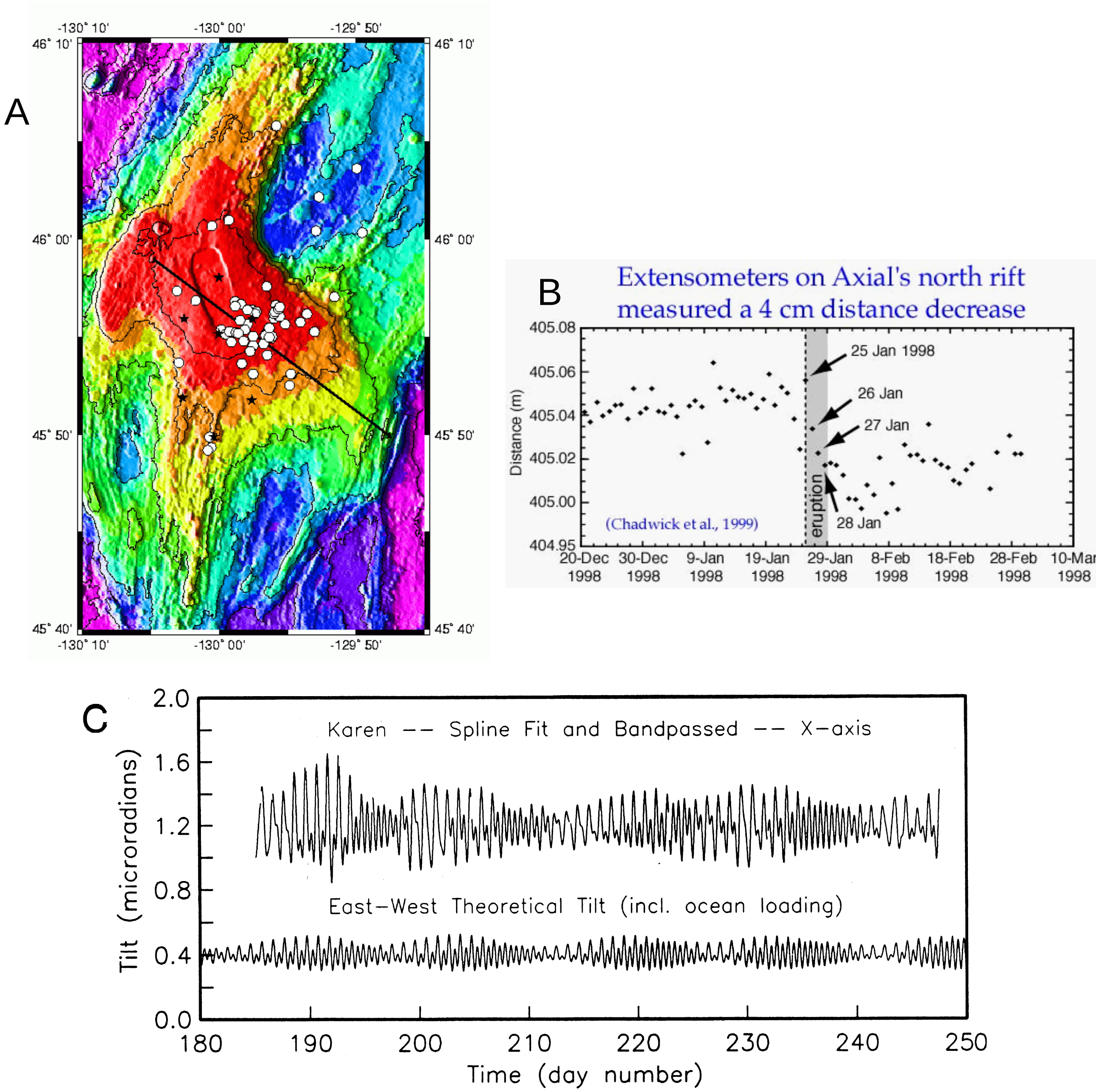

Fig 4. Examples of data we will model. A) Post 1998-eruption siesmicity (as in Sohn et al. 1999, but relocated in 3D model), showing events well to the west of the eruption site, possibly due to flexuarl stresses in the lid of the magma chamber. B) Extensometer data (Chadwick et al. 1999) from North rift during eruption time. C) Tilt (Totstoy et al. 1998) showing observed tidal signal (top time series) that is 3-4 times the amplitude of the predicted one, possibly due to flexure of the magma chamber lid.