Thicknes of a submarine lava flow determined from near-bottom magnetic field mapping by autonomous underwater vehicle

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Abstract. Magnetic field surveys obtained near the seafloor can map the boundaries of recent volcanic eruptions and can provide thickness estimates of these lava flow units independent of bathymetry differencing methods. Magnetic thickness estimation requires knowledge of the intensity of magnetization of the new lava and surrounding terrain, but this can be satisfactorily obtained by representative sampling of the various volcanic units. While bathymetry differencing requires pre-existing data to assess the thickness of new lava eruptions, magnetic surveys can be obtained after an eruption has occurred. In this study, near-bottom magnetic surveys were obtained using an autonomous underwater vehicle (AUV), which operates without a tether or human intervention. AUV technology offers rapid deployment and an efficient surveying approach for remotely mapping recent lava eruption sites on the seafloor.

Introduction

The upper ocean crust is comprised of a sequence of extrusive lavas that form a layer several hundreds of meters thick and which is thought to be the primary source of magnetic anomalies in young crust [e.g., Tivey, 1996]. Understanding the constructional fabric of this layer is important in elucidating the processes of crustal accretion, magma delivery and supply, and the evolution in physical properties of ocean crust. Determining the extent and thickness of individual lava flow units is difficult, and has only been successful for very large lava flows [Macdonald et al., 1989] or for known volcanic eruption events [Embley et al., 1991; 1995; Gregg et al., 1996; Chadwick et al., in press]. Repeat swath mapping of seafloor bathymetry [Fox et al., 1992; Chadwick et al., 1995] provides important information on the extent and volume of the lava products, critical for quantifying and characterizing eruption parameters [e.g., Gregg et al., 1996]. Pre-eruption surveys are not always available, however, which precludes using differential bathymetric mapping to determine lava flow thickness.

Near-bottom magnetic field surveys can provide alternative constraints on the thickness and spatial extent of young lava flows, and furthermore, this information can be obtained after the lava has been emplaced. Young, newly erupted basalt is highly magnetized and can produce significant near-bottom magnetic field anomalies; in some cases up to 50% of Earth’s field intensity [Tivey and Johnson, 1995]. The boundaries of young lava flows should provide sufficient magnetization contrast with the surrounding older lava to produce well-defined magnetic anomalies.

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The rock magnetization of the new flow and older surrounding terrain must be measured in addition to underway magnetic field mapping, in order to determine the thickness of a new eruption and to correct for topographic effects upon the observed magnetic field. Assuming that remanent magnetization intensity is relatively uniform throughout the flow and older terrain, these rock measurements provide constraints for forward and inverse modeling of the observed magnetic field. The direction of magnetization must also be determined, although for young crust this would be in the local geomagnetic field direction. Magnetic surveys also offer some potential advantages over differential bathymetric mapping. Surface ship swath bathymetry has a relatively large footprint of 100 m and a limiting depth resolution of 5 to 15 m [Fox et al., 1992], although near-bottom bathymetric mapping could improve on this resolution by an order of magnitude. Depending on the geometry and density of the magnetic survey tracks and the magnetization contrasts of the lavas, near-bottom magnetic mapping could have both a small effective footprint and the ability to map flows thinner than 5 m.

In this paper, we present the results of a survey over a young seafloor lava flow and calculate the thickness of the flow based on an estimate of its magnetization. We chose this approach to demonstrate that an estimate of lava flow thickness could be obtained independently of differential bathymetric mapping, although clearly the combination of these data sets would also be highly informative. This survey is also unique in that it is the first scientific results collected by an autonomous underwater vehicle, specifically as part of an ongoing research program. Autonomous underwater vehicles are intelligent roving robots that operate without a tether or human supervision, and are relatively fast and efficient survey platforms. The Autonomous Benthic Explorer “ABE”, under development at Woods Hole Oceanographic Institution, was used to carry out a near-bottom magnetic survey over a lava flow erupted in 1993 on the CoAxial segment of the Juan de Fuca (JDF) Ridge [Yoerger et al., 1996; Tivey et al., 1997]. ABE was used in “lawn-mower” survey mode, where straight tracklines were navigated across the seafloor collecting data with a sensors that included: a 3-axis fluxgate magnetometer, depth and altitude sensors, CTD, and digital video cameras.

Geologic Setting

Seismicity associated with the 1993 seafloor lava eruption on the CoAxial segment of the JDF was monitored in real-time by the SOSUS hydrophones located off the west coast of the continental United States [Fox et al., 1995]. T-phase epicenters, initially located near 46°15’S, 129°53’W, migrated 60 km north over of period of 2 days to a region near 46°31.5’N, 129°35’W [Dziak et al., 1995]. Subsequent cruises confirmed that a seafloor eruption had occurred at this latter site, forming a lava flow up to 30 m thick, 2500 m long and 400 m wide [Chadwick et al., 1995; Embley et al., 1995]. Remotely-operated vehicle (ROV) and submersible dives mapped a fresh basaltic lava flow
Figure 1. Bathymetry map of CoAxial eruption site (contour interval 10m) with the 1993 lava flow shaded gray. ABE tracklines are shown in bold and identified as indicated. Lava flow boundary is based on ROV, Alvin dives and sidescan imagery (W.W. Chadwick and R.W. Embley, personal communication, 1997; Tivey and Johnson, unpublished data).

with hydrothermal venting and bacterial mats distributed over the crest of the extruded lava [Embley et al., 1995]. Hydrothermal activity was also located along narrow grabens to the north and south of the flow, oriented along the same trend as the 1993 lava flow (Figure 1). The grabens and associated hydrothermal activity are interpreted as evidence of the presence of a shallow subsurface dike that fed the 1993 lava flow [Chadwick and Embley, in press].

Magnetic field data were collected by ABE during two consecutive field seasons in the CoAxial area (Figure 1). In 1995, ABE surveys were conducted as a night-time component to an ALVIN deep submersible dive program and collected approx. 35 km of tracklines over the northern half of the newly erupted lava. In 1996, ABE operated alternately with ROV JASON and collected an additional 23 km of tracklines over the central and southern end of the 1993 lava flow (Figure 1).

Results and Discussion

The 1993 lava flow produces an extremely strong magnetic field anomaly of approximately 15,000 nT in the near-bottom field (Figure 2). The observed anomaly arises from a combination of the magnetization of the new flow and the topographic effect of the ridge upon which the new flow erupted. The ABE magnetic field data were first corrected for the magnetization of the vehicle [e.g., Tivey, 1996] and then upward continued from the uneven observation path to a level plane above the topography. Traditional magnetic field analysis inverts the magnetic field data for crustal magnetization to remove the effects of topography and the skewness effect of latitude [Parker and Huestis, 1974]. We inverted for crustal magnetization, assuming a constant thickness layer whose upper surface is defined by the bathymetry. A thickness of 30 m was used, based on estimates from differential Sea Beam mapping [Chadwick et al., 1995]. This inversion technique also assumes two-dimensionality perpendicular to the profile and a magnetization vector in the direction of the present field (inclination 67.2°, declination 19.8°E).

Figure 2. Observed magnetic anomaly field data measured along the ABE tracklines (Figure 1), projected east-west and plotted overlying the 1993 lava flow extent shown in gray. Y-axis is arbitrary.

Figure 3. Magnetization inversion profiles calculated from the observed magnetic field for a constant 30 m thick layer plotted overlying the 1993 lava flow shown in gray. Y-axis is arbitrary.
A mean crustal magnetization of 60 A/m was obtained for the 1993 lava, consistent with an average from rock sample measurements of 67 A/m [Johnson and Tivey, 1995]. The maximum anomaly gradient in magnetization is generally located at the edge of the new flow as determined from differential bathymetry, sidescan mapping and on-bottom observations [Embley et al., 1995; Chadwick et al., 1995; W.W. Chadwick, personal communication, 1997]. There is clear variability in the computed magnetization of the 1993 lava flow, but this likely reflects changes in lava flow thickness rather than variations in magnetization intensity (Figure 3). Thus, the assumption of a constant thickness source layer is unlikely to be appropriate for the 1993 lava flow, requiring a different approach.

The lava flow thickness required to create the observed anomaly can be estimated by assuming a mean magnetization for both the old and new lava and then calculating the resultant anomaly using a variable thickness layer. An iterative forward modeling approach is used because direct inversion for source layer thickness is an unstable process. Specifically, anomaly data were upward continued to a level plane and the topographic effect of the present-day seafloor was removed, assuming a mean magnetization of 26 A/m, estimated from rock sample values of the surrounding terrain [Johnson and Tivey, 1995]. The residual magnetic field was then modeled by calculating an iterative forward model that varied the thickness of the source layer, assuming a constant magnetization of 34 A/m (i.e. the difference between the new and old magnetization, 60-26 A/m).

The initial starting thickness was assumed to be zero and then incremented by 1 m in thickness for each iteration. The computed magnetic field was compared to the residual magnetic field and the thickness of the new lava was adjusted appropriately. Finally, the resultant thickness profiles were interpolated to produce a map of lava flow thickness (Figure 4). The top of the source layer was assumed to be the bathymetry measured by ABE along-track or from high-resolution bathymetry obtained from ALVIN and JASON scanning sonar surveys.

The resultant “magnetic” thickness map is remarkably consistent with both the mapped flow boundaries and the lava thickness derived from differential bathymetry (Figure 4). From the thickness map we estimate a total lava volume of 8.8 x 106 m³, which includes a correction estimate of 1.8 x 106 m³ for the northern and southern extremes of the flow and eastern tongue not traversed by ABE (Figure 4a). This volume is consistent with previous estimates of the 1993 CoAxial lava flow [Chadwick et al., 1995; Chadwick et al., in press]. The high-resolution magnetic data identifies the presence of the 1993 lava flow where it was too thin for detection by the differential bathymetry method (Figure 4). Differential depth anomaly is also less reliable in areas of steep slopes because small shifts in navigation can produce artificial depth anomalies [Chadwick et al., 1995]. An example of this is shown in the differential depth anomaly at the south end of the eruption, where the 1993 lava flow abuts the side of the small seamount, and flow thickness is overestimated (Figures 1 and 4). Magnetic thickness estimates thus provide an independent measurement that is unaffected by these bathymetry problems. The magnetic estimates do, however, have their own set of resolution limitations and problems.

The error in the magnetic thickness estimate depends primarily on the constant remanent magnetization assumption. The extent to which remanent magnetization varies within a single flow is not well-known, but it is reasonable to assume that the 1993 lava flow has an overall constant magnetization because it erupted as one single flow and cooled relatively quickly. From rock magnetic measurements, the standard deviation estimate for the 1993 lava magnetization is ±15 A/m or ~20% of the mean measured value [Johnson and Tivey, 1995], which translates into a ~20% error in the thickness estimate. There is greater likelihood of variation in remanent magnetization of the older terrain because it may be composed of several flows from different ages and eruption events. Rock magnetic measurements of the older terrain found a standard deviation of ±15 A/m [Johnson and Tivey, 1995]. Uncertainty in this value af-
fects the topographic modeling and increases the total error in the thickness estimates based on the difference in magnetization of the old and new lava. By quadratic addition of the error estimates we obtain a standard deviation of ±21 A/m for the error in the magnetization difference, which would result in a thickness estimate uncertainty of about ~30%. It is difficult to estimate how well the magnetic modeling fits the true lava flow thickness because the only constraints are the differential bathymetry thickness data, which represent a spatially-filtered and thickness truncated version of reality. Nevertheless, differential bathymetry does provide an upper constraint on lava thickness [Chadwick et al., 1995].

We also estimated how well the computed boundary of the magnetic thickness model fit the known spatial extent of the lava flow. A few profiles were edited for spurious anomalies outside of the main body of the 1993 lava flow, but these were limited to the more convoluted eastern boundary (Figures 1 and 4). Thus, magnetic thickness estimates need editing for spurious data similar to differential bathymetry data. An average of 55 m is obtained for the mismatch between the magnetic lava flow edge (2 m contour) and the actual lava flow boundary along a given profile, as determined by observation and sidescan data [W.W. Chadwick, personal communication, 1997]. Another source of error in this study arises from the two-dimensional algorithm used in the anomaly modeling, which can result in incorrect thickness estimates if the anomalies have three-dimensional sources. These problems could be overcome by a tighter trackline spacing and the use of a three-dimensional modeling approach.

Finally, there are issues concerning the spatial resolution of the data. Previous on-bottom submersible profiles across the 1993 lava flow observed a narrow (25 m wide) central low in the anomaly field interpreted as due to a non-magnetic feeder dike zone [Tivey and Johnson, 1995]. The ABE trackline spacing (~150 m), survey altitude (>10 m) and upward continuation requirements reduce the spatial resolution required to properly resolve this feature. Better resolution would require less than 5 m altitude and line spacing of tens of meters over the whole flow.

Conclusions

High-resolution near-bottom magnetic field surveys can help to quantify the geometry of young, recently-erupted seafloor lavas and can provide thickness estimates that are consistent with other observations such as differential bathymetry estimates. Magnetic fields offer some advantages: e.g., in mapping lava flows that are too thin for detection by the differential bathymetry method and where steep topography causes the differential bathymetry method to be unreliable. Magnetic surveys can also be undertaken after an eruption, removing the need for pre-existing data over the site. Near-bottom magnetic field mapping can complement differential bathymetry mapping of newly erupted lava flows, although the relationship between magnetic anomaly and thickness of the extrusive unit can be complicated by crustal magnetization variations due to thermal structure, subsurface feeder dikes, hydrothermal alteration and three-dimensional magnetic sources. For magnetic anomaly data to provide independent estimates of flow thickness, crustal magnetization over the old and new lavas must be determined by representative rock sampling. Rapid decay in magnetization with age, although still not well-determined (see Johnson and Tivey, 1995), also limits this technique to the zone of active crustal accretion, where the contrast in magnetization between young and older lava is at a maximum. Nevertheless, important insight into the processes of lava emplacement and crustal accretion can be obtained by studies focused at the axis of spreading.

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References


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