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SEISMIC EVIDENCE FOR MAGMA IN THE VICINITY OF MT. KATMAI, ALASKA

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Abstract. P-wave traveltime delays of as much as 0.9 sec are consistently observed at one seismic station from local and regional earthquakes 70 to 150 km deep. This station is on the southwest flank of Mt. Trident, the most recently active volcano within Katmai National Park, Alaska. Delays from local shallow earthquakes are typically less than 0.3 sec, suggesting that most of the major delay results from anomalous material at depths of more than a few kilometers. This station is located near the center of a bowl-shaped low in the Bouguer gravity field that is approximately 15 km in diameter and more than 25 mgals deep. These anomalies suggest, but do not prove, the presence of considerable amounts of magma in the shallow part of the crust that could have been the source for all magma erupted in the vicinity of Mt. Katmai and Mt. Trident this century.

Introduction

Travel-time delays and attenuation of seismic waves, especially shear waves, from local and regional earthquakes have been reported from many volcanic regions of the world and have been interpreted as caused by bodies of magma within the crust [e.g. Utnasin et al., 1976; Einarsson, 1978; Latter, 1981; Sanders, 1984; Elbring and Rundle, 1986; Harjono et al., 1989; Peppin et al., 1989]. Some of the clearest examples of such attenuation were reported by Kubota and Berg [1967] and Matumoto [1971] for seismic waves traveling through the Katmai group of volcanoes, located on the Alaska Peninsula, about 400 km southwest of Anchorage, Alaska. In 1987, we began operating a network of seismographs in this region in order to try to resolve the physical properties of the magma plumbing system within the crust.

The Katmai group of volcanoes are most famous for the 1912 eruption attributed to Mt. Katmai but actually centered 10 km to the west at Novarupta [Hildreth, 1983, 1987]. This was the world's largest rhyolitic eruption in 1800 years during which approximately 15 km^3 of magma erupted and the summit of Mt. Katmai collapsed to form an 8-km^2 caldera. Between 1949 and 1963, a new vent formed on the southwest flank of Mt. Trident and numerous ash eruptions were often accompanied by blocky, viscous lava flows. Explosive eruptions continued intermittently until 1974 [Simkin et al., 1981]. Thus while these volcanoes are not currently erupting, magma reached the surface several times during this century and may still reside in the crust.

Instrumentation

In September, 1987, we installed 6 seismograph stations within Katmai National Park and reactivated 4 old seismograph stations just west of the park [Pulpan and Kienle, 1979]. All stations had a 1 hertz vertical seismometer and 3 of the stations within the park had 2 horizontal seismometers each. The signals from all 16 components were telemetered by FM radio to King Salmon, Alaska, where a SUN 3/50 computer saved the data for events detected by a long-term vs. short-term averaging technique [Ward and Cutler, 1987]. In August, 1988, the network was increased to include 24 components at 14 stations. Earthquake locations were calculated using the computer program HYPOINVERSE [Klein, 1989] and the "Western" velocity model developed for the Cook Inlet region [Fogleman et al., 1988].

Seismicity

We calculated hypocenters for 1900 earthquakes occurring between September, 1987, and December, 1990. Locations of 647 shallow events that were well recorded at many stations and that could be most accurately located are shown in Figure 1. Near the volcanoes nearly all events have a calculated error, or precision, of less than ±1 km in the horizontal direction and less than ±2 km in depth. Some hypocenters near Naknek Lake, the Shelikof Straits, and Mt. Martin have calculated errors of less than ±2 km in the horizontal direction and less than ±5 km in depth. The accuracy of the earthquake locations is unknown particularly because there have been no direct measurements of the crustal velocities within the Park. The accuracy, however, is probably no worse than twice the precision.

The primary volcanic peaks in this region, Mts. Martin, Mageik, Trident, Katmai, and Snowy lie on a straight line striking N65° E. Most shallow earthquakes lie along a line that strikes more northerly (N55° E) and at a distance of typically less than 7 km northwest of the volcanic line. Events near Mt. Martin and Mt. Mageik cluster close to the volcanic peaks. Near Mt. Trident the earthquakes cluster midway between the most recently active vent and Novarupta, a distance of 4.6 km. On Mt. Katmai, the shallow earthquakes cluster under the northern and eastern edges of the caldera. More than half of the shallow earthquakes recorded are located in a cluster 18 km northeast of Mt. Katmai and 7 km north-northwest of Snowy Mtn. This is

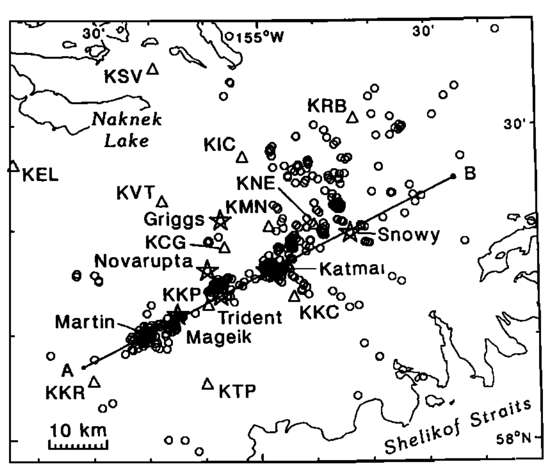

Fig. 1. Shallow earthquakes located within or close to the seismograph network within Katmai National Park. Stars are volcanoes, triangles are seismic stations, and circles are earthquake epicenters.

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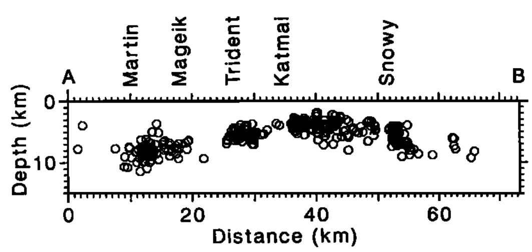

Fig. 2. Earthquakes located within 10 km of the volcanic line (AB) shown in Figure 1 are projected on a vertical cross section along the line. Only earthquakes with calculated horizontal errors of less than 1 km and errors in depth of less than 2 km are shown.

the same area where Matumoto and Ward [1967] found the greatest concentration of shallow earthquakes in 1965. These events lie near the center of the largest group of Tertiary hypabyssal intrusives mapped within the National Park [Riehle et al., 1987]. These intrusives have outcrop dimensions of as large as 10 km, consist chiefly of quartz diorite or tonalite with patches of deuteric alteration, and outcrop only northwest of the volcanic line.

Figure 2 shows the depth of earthquakes located within 10 km of the volcanic line on a cross-section along line AB in Figure 1. The increase in depth of earthquakes near Mt. Martin and Mt. Mageik and northeast of Snowy Mtn. may simply reflect a decrease in accuracy of the locations near the edges of the network. The depths of earthquakes more than 10 km from the volcanic line are between 6 and 18 km. No earthquakes were located within the map area at depths of 18 to 63 km. Earthquakes deeper than 63 km are assumed to be related to the subduction zone and their locations are not discussed in this paper.

Earthquakes located in this study have duration magnitudes between 0.8 and 3.3. There is about one magnitude 3 or greater earthquake every two years and 50 magnitude 2 or greater earthquakes every year. This level of activity is greater than that observed during the eruptions of Mt. Redoubt [Bob Page, oral communication, 1991] and Mt. St. Augustine [Reeder and Lahr, 1987; Power, 1988] to the northeast and is about 2 orders of magnitude less than the level of activity at Kilauea volcano in Hawaii [Fred Klein, oral communication, 1991] or Long Valley in California.

Travel-time Delays

P-waves traveling from the cluster west-northwest of Snowy Mtn. to station KKP are delayed approximately 0.3 sec. The locations of shallow earthquakes closer to KKP are substantially controlled by the travel-time to KKP. Thus it is hard to separate the effects of travel-time delay and biased location.

Large travel-time delays are observed at KKP for deep local and regional earthquakes that were located without relying on the arrival-time at KKP. The locations of regional events to the northeast and southwest were constrained with P-wave and S-wave data from the south-central Alaska seismic network [Fogleman et al., 1988] and the Schumagin Island network [Davies et al., 1981] respectively. The travel-time residuals for P-waves arriving at various seismic stations in the Katmai network from regional earthquakes are summarized in Figure 3 as a function of azimuth from the station to the earthquake. These earthquakes are located between 16 and 380 km from station KKP and at depths of 70 to 150 km. Most residuals for stations other than KKP are between -0.3 and 0.3 sec. Residuals at KKP are all positive, range up to 0.9 sec, and are significantly greater than 0.3 sec at azimuths ranging clockwise from southwest to east. P-wave arrivals at KKP are clearly delayed significantly compared to arrivals at all other stations in the network. These upcoming waves emerge at angles from the vertical of 5 to 42 degrees.

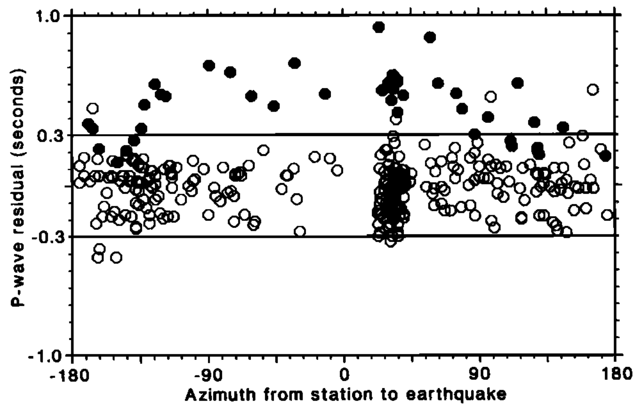

Fig. 3. P-wave travel-time residuals at station KKP (solid symbols) and all other stations (open symbols) in the Katmai network as a function of azimuth from the station to the earthquake for earthquakes located between 16 and 380 km from station KKP and at depths of 70 to 150 km. Note that while most residuals lie between ±0.3 sec, residuals for station KKP are consistently larger.

A Magma Body?

Station KKP is located near a minimum in the Bouguer gravity field mapped by Decker [1964] and Kienle [1969]. David Barnes [Written communication, 1990] prepared a complete Bouguer anomaly map for the Katmai region. A portion of his map is shown in Figure 4. On a regional basis, the Bouguer anomaly decreases to -15 mgal approaching the volcanic axis. Superimposed on this broad decrease is a localized bowl-shaped minimum in the vicinity of KKP reaching -42 mgal. The diameter of this 25 mgal deep "bowl" is approximately 15 km. Most measurement points are along a north-south line passing through this bowl, so that the contours drawn by computer that show the east and west limits of the bowl are poorly defined. The narrow bowl shape implies a shallow body of lower than normal density with lateral extent of less than 10 km. Kienle [1969] calculated from the shape of the gravity anomaly that the depth to the top of the anomalous zone is less than 1.9 km. Travel-time delays of up to 0.9 sec imply that the body has a significant vertical extent. If, for example, the velocity of P-waves within the body was 5.5 km/sec compared to 6.5 km/sec outside, the body would have to have to be 20 km tall to provide a 0.5 sec delay. Hildreth [1983, 1987] notes that many petrologically distinct small volumes of magma have been erupted frequently throughout the Katmai group of volcanoes and concludes that the magmatic plumbing system is more likely to be a plexus of dikes, sills, and small chambers, rather than one large, homogeneous magma chamber.

P-wave travel-time delays are plotted in Figure 4 relative to station KKP at the azimuth from the station to the earthquake and at a distance that is proportional to time. The thick-lined polygon is created by joining adjacent delays. Note the general agreement in shape between the polygon and the -20 mgal line. Both the location of station KKP relative to the gravity anomaly and the shape of the delay polygon suggest the station is over the anomalous body, but offset slightly south of the center of the body.

Novarupta, the vent of the 1912 eruption, is filled with a dome of rhyolite mixed with some dacite. A few kilometers to the southwest are two dacitic domes at Falling Mtn. and Mt. Cerberus. The only other dacitic domes mapped by

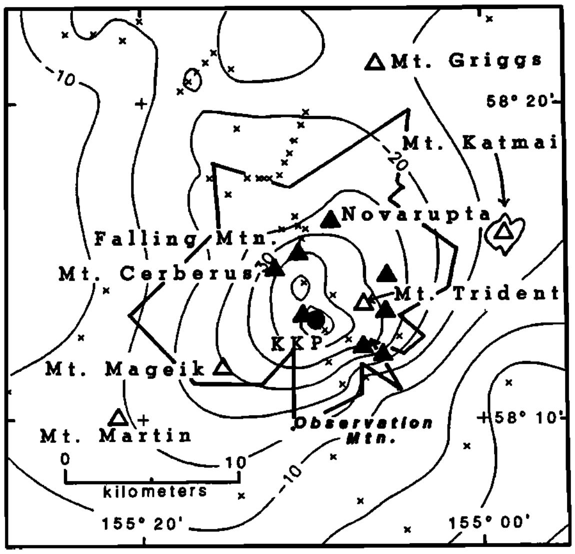

Fig. 4. P-wave travel-time residuals at station KKP as a function of azimuth are shown by the thick-lined polygon and compared to the Bouguer gravity low (contours lines in mgals) between Mts. Mageik and Trident. Open triangles are volcanoes, solid triangles are rhyolitic and dacitic domes, the station KKP is shown as a solid circle, and the observation points for gravity data are shown by X's.

Riehle et al. [1987] in the vicinity of Mts. Katmai, Trident, Mageik, and Martin lie several kilometers south of the volcanic line a few kilometers southeast of station KKP (Figure 4). Hildreth[1991] mapped 3 other smaller dacite domes just northeast, southeast, and west of the most recently active vent on Mt. Trident. Note that all of these domes, which are shown as solid triangles in Figure 4, lie around the margin of the Bouguer gravity bowl-shaped low except for the one dome near the center of the anomaly. This spatial relationship suggests a possible genetic relationship of the dacite domes to the inferred crustal magma body.

Wallman et al. [1990] conclude that the direction of maximum regional stress, the strike of regional joint systems, and the line of fractures between Mt. Trident and Novarupta favor the hypothesis that magma for the 1912 eruption moved from Trident to Novarupta and that collapse of the summit of Mt. Katmai was related to withdrawal of magma towards Mt. Trident rather than directly towards Novarupta. Thus the magma source for the 1912 eruption may well have been the edge of the magma body inferred in this paper.

Attenuation

Kubota and Berg [1967] and Matumoto [1971] were not able to resolve travel-time delays because they only had data from a few stations. Both groups did report major attenuation of both P and S waves crossing the volcanic axis in many different places. The attenuation was so severe that S waves disappeared along certain paths. There is evidence of severe attenuation in our data, but the disappearance of S waves is not obvious. The details will be discussed in a future paper along with pre-S arrivals similar to those observed by Peppin et al. [1989] near a possible magma body under Long Valley California.

Three seismic stations in our network were located near sites occupied by Matumoto in order to try to reproduce his observations. The fact that we do not observe clear S-wave screening might be related to the fact that his equipment was more sensitive to higher frequencies. Matumoto shows that the dominant attenuation of seismic waves that he attributes to magma occurs in the frequency range of 10 to 40 htz. His instruments were most sensitive in the 2 to 70 htz range, whereas the equipment used in this study has the greatest sensitivity in the range of 1 to 25 htz [Eaton, 1980]. If the magma bodies are relatively small, low frequency waves might pass by them relatively unaffected. Kubota and Berg [1967], however, also observed clear attenuation with instruments whose high frequency response is less than those used in this study. Thus we think a possible explanation for the decrease in S-wave screening is that the magma bodies have cooled significantly in the last 25 years. These bodies may have been left from the 1912 eruption or they may simply be small bodies related to eruptions of Mt. Trident ending only 27 years ago. Such rapid cooling implies the magma bodies are relatively thin. This preliminary conclusion will be tested substantially through ongoing work.

Conclusions and Future Work

Traveltime delays of up to 0.9 sec at station KKP on the southwest flank of Mt. Trident suggest the presence of a large low-velocity body or plexus of bodies between Mts. Mageik and Trident. A large, bowl-shaped Bouguer gravity anomaly in the same area also suggests the presence of low-density and thus low-velocity material in the upper crust. We plan to install four new seismic stations in this region in 1991 in order delimit the extent and shape of this low-velocity volume. With ongoing studies of attenuation, we hope to be able to determine whether the anomalous body is in fact magma.

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