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Geophysical Research Letters

Volume 28
Number 9
Page range 1819-1822
Year 2001

URL http://hdl.handle.net/10097/50777
Source and path of magma for volcanoes in the subduction zone of northeastern Japan

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Abstract. The assumption that the source of magma for volcanoes in subduction zones is located in the mantle immediately above the top of the subducting slab, at approximately 100 km depth and straight beneath the volcanoes is incorrect in northeastern Japan. The combination of evidence from velocity tomography in the mantle wedge above the slab and mapping of earthquake size distribution within it strongly points to a source of fluids at the top of the slab at 140 to 150 km depth, from where material rises along an inclined path to the volcanoes.

1. Introduction

Volcanoes in subduction zones are typically aligned in a chain that runs parallel to the plate boundary. The majority of these volcanoes are located between 100 and 200 km above the inclined zone of deep earthquakes. Therefore, it is generally assumed that magma for arc volcanism is generated at this depth. Textbooks on earth science show cross sections of subduction zones with a volcano located above a deep seismic zone, with magma collecting above the 100 km deep earthquakes and rising in a relatively thin conduit straight up to the volcano. Here, we challenge the universal applicability of this picture, based on new results.

Important information about the state of the volume in which the earthquakes occur is contained in the variations in the frequency-magnitude distribution of earthquakes (Fig. 1).

\[ \log N = a - bM \]

where \( N \) is the number of events with magnitude, \( M \), larger or equal to \( M \). The constant \( b \) measures the ratio of small to large events. Any epicenter map shows that \( a \) (seismicity rate) is heterogeneous; clusters are located next to patches without earthquakes. On the other hand, \( b \) is generally observed in large volumes [Frohlich and Davis, 1993; Kagan, 1999].

For \( b=1 \), equation (1) means that there are about 10 times more small events per unit magnitude decrease. However, local variations of \( b \) between 0.5 and 1.5 exist [e.g., Ogata and Katsura, 1993]. Along fault zones, high \( b \)-values are found in creeping segments [Amelung and King, 1997; Wiemer and Wyss, 1997], and low values identify asperities [Wiemer and Wyss, 1997; Wyss et al., 2000]. Magma chambers can be mapped by anomalies of high \( b \) [Murru et al., 1999; Wiemer and McNutt, 1997; Wiemer et al., 1998; Wyss et al., 1997].

Most perturbations of \( b \) range from 0.5 to 1.7 (Fig. 1). A plausible cause for high \( b \)-values is low ambient stress [Scholz, 1968; Urbancic et al., 1992], which may be brought about by high pore pressure [Wyss, 1973]. Along the creeping section of the San Andreas fault, high \( b \)-values are associated with numerous small earthquakes and the stress level is thought to be low, possibly because of high pore pressure.

Mapping the \( b \)-value in the deep earthquake zones of Alaska and New Zealand, Wiemer and Benoit [1996] have shown high values at 95 km depth. They interpreted this observation as possibly due to dehydration in the descending slab, yielding high pore pressure, and suggested that these anomalous volumes at the top of the deep seismic zone may be the source of fluids, which generate magma for the volcanic arc. Here, we combine a similar observation with a tomographic image of low velocity volumes in the mantle wedge above the deep seismic zone.

The velocity structure in subduction zones is becoming better known due to advances in techniques of tomographic inversions of travel times of seismic waves and thanks to more high-quality data. The cool, high-velocity slab has been mapped successfully in many parts of the globe [van der Hilst et al., 1991; Zhao et al., 1995; Zhao and Hasegawa, 1993]. Now, the deployment of dense seismograph networks in northeastern Japan makes it possible to image the velocity structure of the mantle wedge above the slab in detail and with high accuracy [Nakajima et al., 2000]. In this article, we show the coincidence of low velocity volumes in the mantle wedge beneath northeastern Japan with the segment of the deep earthquake zone that exhibits anomalously high \( b \)-values.

2. Data and Analysis

The locations of active volcanoes in Tohoku are shown in Fig. 2a. The Pacific plate subducts beneath northeastern Japan in a direction from east to west, along a plate boundary 300 km east of the volcanoes. Hypocenters within the area in the dashed rectangle of Fig. 2a are shown in Fig. 2b. The crustal seismicity is limited to the top 20 km; the deep earthquakes outline the descending slab with a double seismic zone.

In this 130 km wide cross section there occurred 7,500 earthquakes with \( M \geq 2.0 \) between 1981.0 and 2000.5. The magnitude of complete recording, \( M_c \), estimated by the method of Wiemer and Wyss [2000], is \( M_c \leq 2.0 \), up to the western edge of the landmass of Japan. There, the deep seismicity ranges from 130 to 180 km. Further west, \( M_c \) rises to \( 2.4 \leq M_c \leq 2.5 \). This resolution does not change as a
The mantle wedge above this location. The b-value anomaly is dehydration at this depth and that partial melt is generated in earthquakes at 140 to 150 km depth may be due to of these events fit a straight line well (Fig. 1b).

We propose that the anomalous preponderance of small earthquakes surround magma chambers. These events occur at 25-40 km depth, well below the brittle seismogenic layer which is ~15 km thick. Their predominant frequencies are anomalously low, for both P- and S-waves, and their focal mechanisms are different from the usually observed double-couple sources, suggesting that they are generated by deep magmatic activity [Hasegawa et al., 1991]. The number of these events strongly increased during the volcanic crisis at 25-40 km depth beneath the volcanoes. As partial melt may be formed at about 150 km depth above the slab, it begins to rise nearly vertically (red arrow in Fig. 3a). However, the flow in the mantle wedge (open arrows in Fig. 3a) deflects the rising function of time. The hypocenter errors are 2 to 3 kilometers. They are about 10 times smaller than the anomalies we map.

The b-values in the cross section are mapped (Fig. 3a) by the gridding-technique of Wiemer [Wiemer, 1996]. At each node with 1 km spacing, the nearest 120 earthquakes are selected and their b-value is plotted in a color code. We chose 120, such that the b-value for the deepest samples are still based on nearly 100 earthquakes, even if the number used for the estimate is reduced because the Mc is higher than 2. Mapping b with samples ranging from 80 to 200, and various widths for cross sections, we found no substantial differences in the results. We also mapped b in the cross section outlined by a solid square in Fig. 2A, which is centered on the cross section of the velocity analysis. The result is the same as that seen in Fig. 3a, but the coverage does not include all nodes, because some have not enough earthquakes with \( M \geq M_c \) locally. We did not include data from further north, because that degrades the anomaly by mixing with data from normal volumes. Thus, we present the data set that covers the entire seismic zone (Fig. 3a). This image is essentially the same, no matter what exact cross section is selected.

Examples of frequency-magnitude distributions selected in this way are shown in Fig. 1. The pattern of b-values that emerges in Fig. 3a is typical for cross sections throughout northeastern Japan. The two outstanding locations of high b-value anomalies are at 10 to 30 km depth where the upper and lower zones merge (Fig. 2b). At 0 to 10 km depth the upper and lower zones merge (Fig. 2b). It is remarkable that the image of this anomaly persists in all cross sections we plotted, because one might expect that in a 130-km-long projection, volumes with different b-values might overlap and yield a value of \( b = 1 \) as an average. We conclude that the deep b-value anomaly persists parallel to the plate boundary along 100 km long segments in northeastern Japan.

Our recent tomographic study [Nakajima et al., 2000], based on data from a dense temporary network of more than 200 seismographs in northeastern Japan has updated the previous results [Zhao et al., 1992] by improving the accuracy, particularly that of S-wave velocity imaging, to about 1% at the depths of interest. The spatial resolution is 25 km in the horizontal and 30 km in the vertical direction. Signals from 4,338 local events furnished 169,712 P-wave and 103,993 S-wave arrival times, about 10 to 20 times the numbers available in previous studies. These data were inverted, using the method of Zhao et al. [1992].

The detailed S-wave velocity structure in the mantle wedge thus obtained (Fig. 3b) shows a relatively narrow low velocity zone that initiates at 140 km depth above the deep seismic zone, extends upward, first vertically, then at an angle to the east, ending at the volume containing the anomalously low frequency earthquakes [Hasegawa et al., 1991] at 30 km depth beneath the volcanoes. P-wave results also show a low velocity anomaly at the same locations as that of the S-waves shown in Fig. 3b [Nakajima et al., 2000]. We have less confidence in the ratio of \( V_p/V_s \) because the errors afflicting the two parameters propagate. For this reason we show the well-determined \( V_s \) anomalies.

**3. Discussion**

We propose that the contorted low velocity zone in Fig. 3 is the path of the magma or fluids that rise from the deep seismic zone to the volcanoes. As partial melt may be formed at about 150 km depth above the slab, it begins to rise nearly vertically (red arrow in Fig. 3a). However, the flow in the mantle wedge (open arrows in Fig. 3a) deflects the rising
plume in a trenchward direction. The velocity vector of the rising material may result from the vector addition of the velocity due to its buoyancy and the velocity of the mantle back flow. Between 20 and 70 km depth, the angle of ascent is about 45°; hence the two velocities may be approximately equal. Although these estimates make sense, qualitatively, we do not suggest that we know the values of these velocities.

The excellent correlation of the two completely independent data sets, that measure different phenomena, strongly suggests that the b-values map the presence of magma or fluids at the two ends of the low velocity zone and that the latter maps the path of the magma from its point of generation to its intrusion into the crust.

The double seismic zone is seen in several descending slabs, but most clearly in northeastern Japan at 70 to 150 km depth [Hasegawa et al., 1978; Matsuzawa et al., 1986]. The upper and lower parts of the seismicity are thought to be expressions of different stress systems due to forces acting on the descending slab. The upper seismicity occurs within the subducted oceanic crust, which shows 6% lower P-wave velocity than the ambient mantle [Matsuzawa et al., 1986]. This indicates that the basalt-eclogite phase transition does not complete at least till 150 km depth, since the phase transition causes a higher velocity for the subducted crust. In addition, the reflector found at the top of the seismic zone in the Kanto area at depths between 70 and 120 km [Obara, 1989; Obara and Sato, 1988] suggests that liquids may be present at these depths. We assume that such liquids are generated by dehydration of the oceanic sediments at the top of the slab along the way down. Even the basalt-eclogite phase transition may start at these depths, but according to the results reported here, it only culminates at 150 km depth to a point where a major source for a low velocity disturbance of the mantle wedge is generated.

Our model, in which magma does not rise straight up to the volcanoes from the nearest point of the deep seismic zone, is supported by the latest estimates of the depth of dehydration associated with the basalt-eclogite phase transition in the subducted oceanic crust. The general idea that dehydration in the descending slab plays an important role in generating the magma supply for subduction zone volcanism has been proposed long ago [Anderson et al., 1980; Peacock, 1993]. It is now argued on mineralogical grounds that dehydration at 140 to 150 km depth should occur [Abers, 2000; Iwamori, 1998; Iwamori and Zhao, 2000; Peacock and Wang, 1999]. Thus, our model of an inclined path for the magma (Fig. 3) that rises from about 150 km depth to the volcanoes makes sense and, for the case of northern Japan, we have to question the textbook view, of magma rising from 100 km depth straight upward to the volcanoes.

The path of transport we propose also fits the models of mantle flow in the wedge above the slab. Starting in the earliest years of the discovery of plate tectonics, researchers realized that subducting plates had to introduce an eddy-like back flow in the mantle wedge above the slab. A recent model of this phenomenon shows that from a depth of 150 km at the top of the deep seismic zone, the flow is expected to be directed first away from the slab [Davies, 1994] and then rise vertically and eventually turn in the direction of the plate boundary. This agrees with the low velocity channel seen in Fig. 3, which rises vertically to 70 km depth, and finally ascends at an angle in a direction towards the volcanoes, just as the wedge material in the eddy is assumed to flow.

There exist other cases in which the magma supply to volcanoes follows an inclined path. The mantle plume beneath Hawaii is centered southeast of the island creating

**Figure 3.** (a) b-values mapped using the earthquake catalog with M ≥ 2.0 from 1981 to 2000.5 in a 130 km wide section projected onto the profile AB (Fig. 2). In each sample N=120 events are selected at nodes separated by 1 km. The radii for samples in the deeper parts of the slab are 20 to 30 km. Triangles mark locations of active volcanoes. Volumes with S-wave velocities slower than 2% below average are gray. Open arrows indicate the assumed flow directions in the mantle wedge; red arrows sketch the flow direction in the ascending plume. (b) S-velocity structure (along profile CD, Fig. 2) of the descending slab (fast because it is cool) and the mantle wedge above it in which a low velocity zone winds its way from 140 km depth, just above the deep seismic zone to the sub-crustal volume at 30 km depth just beneath the volcanoes. Unlike in Fig. 3a, the western edge is limited to the mantle beneath the landmass of Japan, because further west tomographic results are not reliable. Dots mark hypocenters of events used in the tomography study.
Loihi, a new volcano still below sea level, and supplying Kiluaea along an inclined path from the southeast [Klein et al., 1987]. This geometry is assumed to be due to the relative motion of the Pacific plate over the more stationary mantle. Of the many volcanoes that have inclined magma paths in the crust beneath them, Unzen is a clear example [Umakoshi et al., 1994]. In these cases, the mechanisms generating the path geometry are probably varied and they are not thought to be due to relative movements of parts of the host materials of either the paths or the volcanic edifice. However, tomographic inversions for the mantle wedge beneath the central Andes also show an inclined low velocity-high attenuation channel [Schurr et al., 2000].

The depth of deep seismic zones beneath volcanoes varies from 400 to 80 km, although in the vast majority of cases the range is 100 to 200 km [Gill, 1981, p.14-15]. Now that Wiemer and Benoit [1996] have mapped b-value anomalies straight beneath some volcanoes, and we mapped an inclined path from an anomaly located tens of kilometers sideways from the volcanoes, the door is open for the possibility of paths of various shapes, reaching volcanoes from various depths. It will be necessary to map the types of anomalies we report here in many cases to reach an understanding of where the magma for arc volcanism is coming from.

Acknowledgments. We thank S. Wiemer for the use of his software and for help with using it, and C. Nye, S. Wiemer, D. Zhao, M. Ohtake, H. Sato and J. Eichelerberger for comments on the manuscript. This work was supported by NSF grant EAR 9902177, by the Wadati foundation at the University of Alaska, Fairbanks and by a travel grant from Tohoku University.

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(Received 10/31/00; revised 02/05/01; accepted 02/07/01.)