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A serpentine diapir as a source of magnetic dipole anomalies inferred from aeromagnetic and surface susceptibility data

- As a case study of the central Shikoku, Southwest Japan -

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Abstract

Using a fine-scale magnetic anomaly data based on high density air-borne surveys, we have identified several dipole anomalies aligned east-west direction exactly on the Kurosegawa Tectonic Zone, which constitutes a part of an accretionary prism in the southwest Japan. A plausible candidate for the magnetic source is serpentine diapirs associated with dehydration of subducted slabs. Surface geological evidences also suggest the existence of serpentines. We applied a magnetic inversion to one of the dipole anomalies found here, and figured out the magnetic source as a spheroidal shape standing in parallel to the tectonic line and slightly inclined southward. The source is magnetized roughly in the same direction to the current geomagnetic field. This implies that the induced magnetization is dominant rather than remanent component.

INTRODUCTION

Magnetic dipole anomalies are generally observed in rocks, volcanoes or seamounts of basaltic origin. However, serpentinite related magnetic anomalies are often identified in onland tectonic zones together with Bouguer gravity anomalies. Nine distinct magnetic dipole anomalies are recognized along the Kurosegawa Tectonic Zone. This is characterized by a serpentine melange of various ages (from Silurian through Jurassic). These anomalies lie not in basalts, but in serpentinite bodies of the tectonic zone. There are also serpentinites without anomalies. This is partly due to the differing serpentinization conditions of the ultramafic rocks and the tectonics after serpentinization. Modern analogues of serpentinite bodies are well documented in the Izu-Bonin-Mariana forearc serpentinite seamounts. Some of these have magnetic dipole anomalies. We conclude that these anomalies are formed by the serpentinization of mantle peridotite and are uplifted as a diapir. These serpentinite seamounts were formed at the present location by a transcurrent fault. These form the Kurosegawa Tectonic Zone (here after abbreviated as KTZ). Using fine-scale magnetic anomaly data based on high density air-borne surveys, we have identified several dipole anomalies aligned in an east-west direction exactly along the KTZ. This constitutes part of an accretionary prism in the southwest of Japan. Plausible candidates for the magnetic source are serpentine diapirs associated with the dehydration of subducted slabs. Surface geological evidence also suggests the existence of serpentine. The localities of a Bouguer gravity anomaly, geomagnetic dipole anomaly and an apparently aseismic area were found to coincide with the distribution of serpentinite in KTZ.

We apply a magnetic inversion to one of the dipole anomalies found here, and hypothesize the magnetic source to be a spheroidal shape standing parallel and slightly inclined to the tectonic line. We also performed geophysical investigation with susceptibility meter and sampling along KTZ. More than 100 ultramafic rock samples were collected along KTZ. Magnetic intensity, susceptibility, sonic velocity, density and petrologic properties were subsequently measured on 100 core specimens and thin sections. The source is magnetized roughly in the same direction as the current geomagnetic field. This implies that the induced magnetization is the dominant, rather than the remanent component. Recent geological surveys, sampling both on land and on the seafloor indicate the existence of serpentinized materials between the trench and the volcanic front (e.g., Fryer et al. 1992). These materials are thought to come from the shallow mantle wedge as a diapir (e.g., Fryer and Fryer 1987; Maekawa et al. 1993) because of their low density (Toft et al. 1990) caused by reactions with water supplied by subducted slabs (e.g. Tatsumi 1989). In some regions, these serpentine diapirs form a chain of small seamounts parallel to the trench (Fryer et al. 1992).

Since serpentinization process accompany magnetite formation (O'Hanley 1996), serpentine diapirs are expected to have a relatively high magnetic susceptibility (Toft et al. 1990; Nazarova 1994). This enables us to observe them as a series of magnetic dipole anomalies. Southwestern Japan is a suited field for this purpose because a fine-scale magnetic data set (GSJ 1996) is available and there is a wide enough (120km) magnetically silent zone between the highly magnetized oceanic crust and the volcanic front (Fig. 1b). In this point of view, we cast around for such signals using air-borne based magnetic data, then estimate the aspects of the magnetic source by using an inversion in discussion about the tectonic framework of this region.

TECTONIC AND GEOLOGICAL SETTINGS

The outer arc of southwestern Japan is a typical accretional zone, having a long history of being subducted with oceanic plates. These convey and adjust sediments, seamounts, oceanic crust, and continental fragments (e.g., Taira et al. 1992). Thus accreted materials have formed several tectonic lines and terranes striking in an E-W direction as shown in the geological map (Fig. 1a) compiled by GSJ (1995). The KTZ (Kurosegawa Tectonic Zone) is one of the most distinct tectonic lines in this region, where number of models on its structure and the history of its formation have been presented (Maruyama et al. 1984; Yoshikura 1985; Taira et al. 1989; Yoshikura et al. 1990). Serpentine and ultramafic rocks are sporadically observed along the KTZ. The oldest one dates back to the Silurian (Maruyama 1981).

This accretional zone is clearly recognized on the topographic feature as bounded by the Nankai Trough to the north, where the Philippine Sea plate is subducting from the south and by the Medium Tectonic Line, where Miocene and Quaternary volcanoes have developed on the north side.

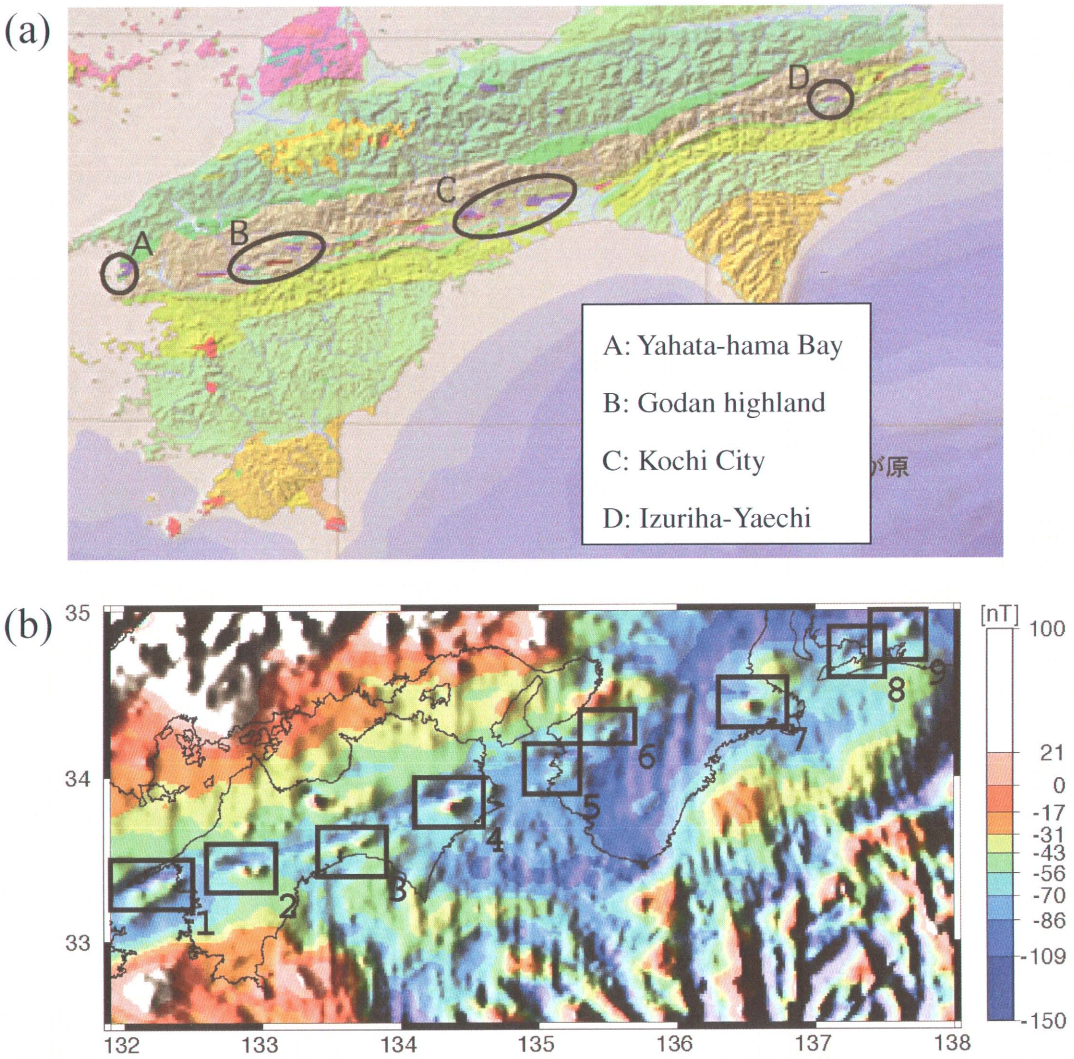


Figure 1 (a) Geological map of Shikoku (GSJ, 1995) for the area indicated by a rectangle in the regional map to the right. Tectonic lines are developed parallel to the trench, which is typically observed in accretionary complexes. Regions A, B, C and D are on the KTZ (Kurosegawa Tectonic Zone), (b) Magnetic anomaly maps (GSJ, 1996) for SW Japan including the corresponding area. The magnetic anomaly is relative to the IGRF and is coordinated with upward continuation at 3000 m. Several magnetic dipole anomalies, indicated by boxes are recognized along the KTZ. Box number 1, 2, 3 and 4 are corresponding to regions A, B, C and D in Fig. (a), respectively. No topographic signals corresponding to the dipoles are observed.

MAGNETIC ANOMALIES

A fine-scale grid data of residual magnetic anomaly to the IGRF around the East Asia is available from GSJ (1996). The data set is a compilation of various types of surveys, such as air-borne and shipboard observations, by merging into a uniform grid with an upward continuation of 3000 m. The actual resolution reaches 1 min. on land in the region of interest, which is suitable for detecting the small scale dipole anomalies considered in this study.

Magnetic anomaly shown in Fig. 1b clearly presents two areas of strong signals. One is associated with Miocene and Quaternary volcanoes at the northern part and the other is magnetic lineations of oceanic crust at the south part. It should be noted that the magnetic lineations are still observed after subducting beyond the trench axis. As it is wedged between the two areas, the magnetic anomaly is flat in the accretionary zone. However, several dipole anomalies are recognized just along the KTZ indicated by the boxes. Although amplitudes of these dipole anomalies are 70 nT at most and are much smaller than those originating in igneous rocks, the S/N ratio is pretty good owing to the lack of magnetic sources except for our interest.

MEASUREMENT OF MAGNETIC SUSCEPTIBILITY

Along the KTZ we have performed geophysical investigation with magnetic susceptibility meter and rock sampling by drilling tool. Magnetic susceptibility meter SM-30 are handy and useful tool for field measurement of outcropping rocks, drill cores or rock samples. It is also available to determine a boundary of rock types, volume of magnetic minerals and alteration ratio. Fig. 3c shows that an example of magnetic susceptibility data of one of dipole areas at Aitani serpentine quarry of Engyoji, Kochi City. Numbers attached photo are value indicating strong serpentine minerals and weak sedimentary rocks. Most normal serpentinite include high susceptibility value (10^{-3}~10^{-2} emu). It's also clear indicator of alteration ratio.

MAGNETIC SOURCE INVERSION

In this study, Box 4 in Fig. 1b is employed as an example to estimate the magnetic source because the dipole anomaly can be seen here most clearly. We use the Genetic Algorithm (GA) inversion technique (Kido et al. 1998) to minimize the misfit of the magnetic field. The essence of the GA is an analogue to the evolutionary theory of life that a model having a smaller misfit is assigned a larger probability to be endowed with the right to leave offspring into the next generation of models through iterations of the inversion. The iteration process is also an analogue to the cross fertilization of genes in two selected models among others, whose parameters are expanded into a chromosome map. Using this procedure, the GA is extremely efficient to find a global minimum of a model space compared to the classical Monte Carlo inversion, which walks around a model space with an even probability. An advantage of the GA is its simple modular coding uses only a forward calculation. Considering the non-uniqueness of magnetic inversions, the number of free parameters describing a magnetic source should be as small as possible. We employ a uniformly magnetized tri-axial ellipsoid, which is a better representation of the shape of a diapiric source than a fourth facet of the polyhedron widely used in this kind of analysis. A magnetic field is calculated as a sum of magnetic dipoles, which are aligned at every 500 m grid point within the ellipsoid. The ellipsoid representation consists of 11 parameters at most, as listed in the left column of Table 1.

Results of the inversion are listed in the second column of Table 1. The best fit model generates a magnetic anomaly field shown in Fig. 1b and projections of the source onto orthogonal three planes are shown in Fig. 2c. The best fit ellipsoid is flattened in the N-S direction (Be), lying along the KTZ (De) and is inclined southward (Ie), whose magnetization (Im and Dm) is roughly parallel to that of the IGRF. (Fig. 2) We also test a spherical representation of the source. Im and Dm is fixed to the IGRF, and m is also fixed at 0.1 A/m, since m is inversely proportional to Ae^3 (volume) for the case of a sphere. Now the free parameters are only the x-y-z positions and a diameter of the sphere. The results are listed in the third column of Table 1. Although the spherical representation scores are still an acceptable misfit, they can not reproduce the obliquely elongated feature in the magnetic field. Therefore, we believe that the ellipsoid representation is not over parameterized and the obtained parameters are effective for further interpretation. Moving on other areas, Box 7 and 8 have very similar anomalies to that in Box 4. On the contrary, other Boxes encompass two or more dipoles, which implies split magnetic sources. However, the basic nature of the magnetic field in each dipole, such as oblique elongation, remains unchanged. So we expect that the obtained parameters are roughly applicable to other Boxes, except for the size and magnetic intensity of the source.

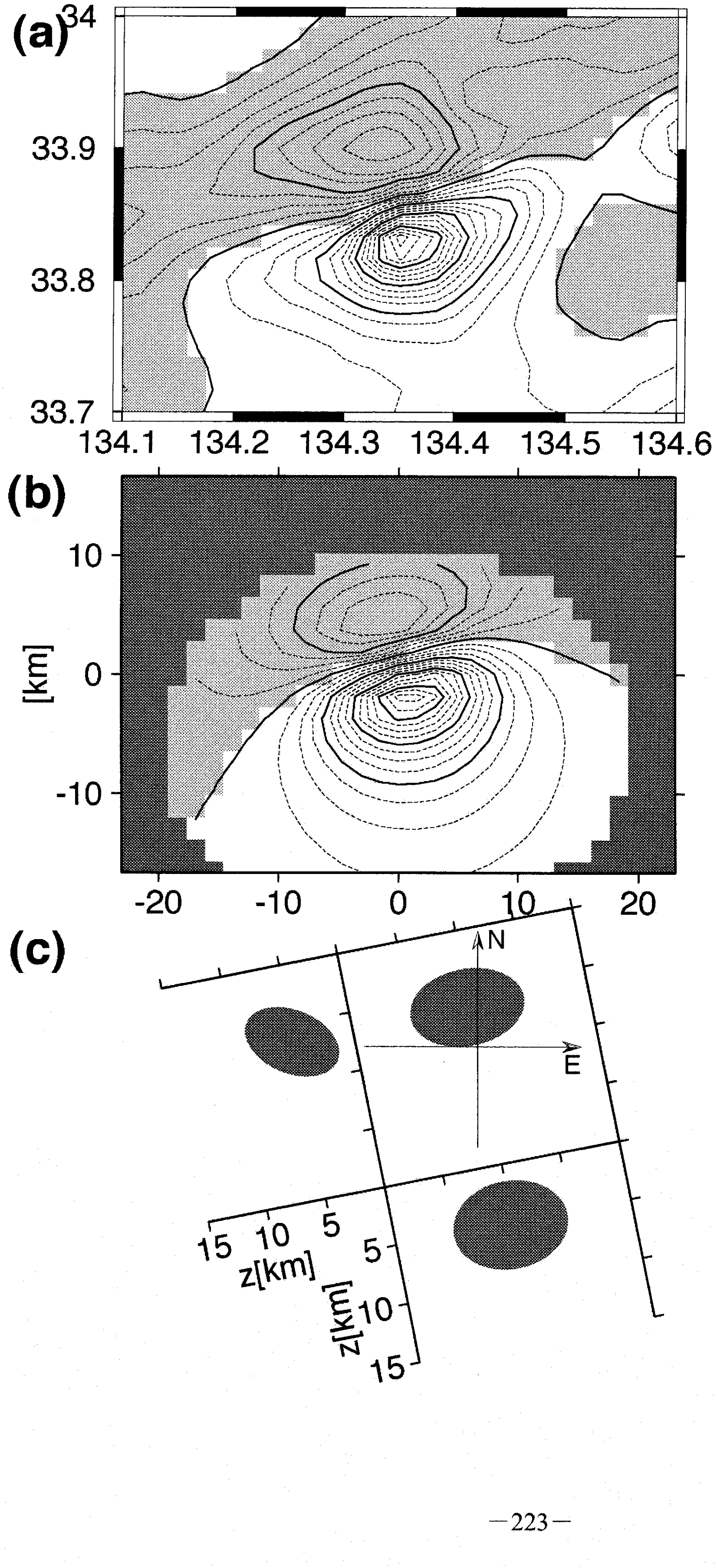


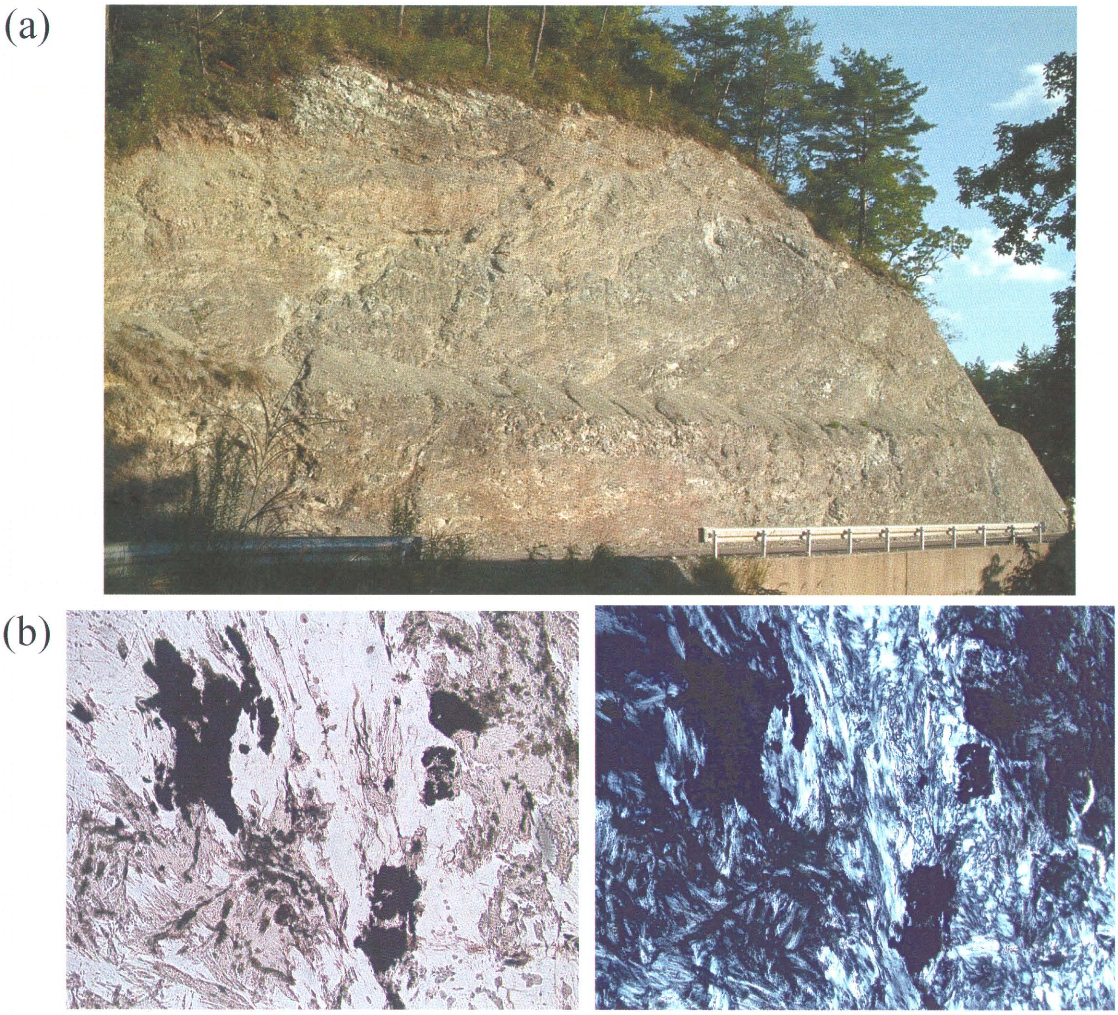
Figure 2 (a) An enlarged view of the magnetic dipole anomaly in the Box 4 in Fig. 1b. Long wavelength components (> 75 km) are filtered out. Solid contours are every 20 nT and dashed contours are 5 nT. Negative anomalies are shaded, (b) Predicted magnetic anomaly (3000 m height) for the best fit source. The masked area (dark shade) is excluded from evaluating the misfit in the inversion, (c) Projections of the best fit source onto the three orthogonal planes, one of which is set perpendicular to the surface and declination of the ellipsoid.

Table 1 Results of the inversion. Xe, Ye, and Ze, are the positions of the ellipsoid in longitude, latitude, and depth. Ae, Be, and Ce are lengths of the tri-axis in E-W, N-S, and vertical directions. Ie and De are the inclination (north-ward down-dip) and declination (Clock-wise from north) of the ellipsoid, while Im and Dm are those of the magnetization. "m" is the magnetic intensity. "delta M" is a Root Mean Squares of the misfit in the inversions. Bold faces indicate fixed values.

	unit	ellipsoid	sphere
Xe	[deg]	134.34	134.35
Ye	[deg]	33.88	33.86
Ze	[km]	5.15	7.21
Ae	[km]	9.71	8.26
Be	[km]	5.3	-
Ce	[km]	8.12	-
Ie	[deg]	-33.84	-
De	[deg]	-11.29	-
Im	[deg]	32.7	45
Dm	[deg]	-22.41	-7
m	[A/m]	0.196	0.196
dM	[nT]	4.28	9.47

DISCUSSION

The southward inclination of the source (Ie = -33.84 degree) is consistent with the stratal slope in this region (e.g., Kurashimo et al. 2002). Results of inversion method are coincident with magnetic susceptibility value obtained at Region D (Box 4), and also estimated volume of surface magnetic distribution by boundary condition using a susceptibility meter. Concerning the fact that magnetic dipole anomalies are distributed only along the KTZ, we propose here two scenarios. One is that the serpentine diapirs that came up from the mantle wedge were once trapped at the underground KTZ and then were upraised to the near surface along the KTZ. The other is that Triassic serpentine seamounts are incorporated with sedimentary accretion, which have formed the KTZ. In this connection, compatibility of the magnetized direction (Im and Dm) with the IGRF indicates dominance of the induced magnetization because remanent magnetization can not keep its direction during such complex upwelling or accretion processes. A linear magnetic anomaly with a small amplitude is apparently observed along the western-half of the KTZ (Fig. 1b). This implies that the KTZ itself is slightly magnetized for a widely diffused part of the serpentine diapirs due to the accretion process or possible transcurrent fault activity in the past. Some of the dipole anomalies accompany positive Bouguer gravity anomalies. However, for uncertainty in the density difference between the serpentine and surrounding materials and for large lateral variation in the density of surface rocks other than serpentine, we do not take it into account for the source analysis as a joint inversion. Turning around other subduction zones, the existence of serpentine seamounts becomes apparent in the Izu-Bonin-Mariana forearc (e.g., Fryer et al. 1992). However, no clear dipole anomaly is observed from ship-board magnetic survey, since it is too sparse to detect small scale anomalies in 2-D. High-density air-borne magnetic surveys can be a powerful tool to delineate the distribution of serpentine diapirs, which give insight into the dehydration process of subducted oceanic plates. Field magnetic susceptibility measurement is also useful to estimate surface geological boundary and volume of magnetic mineral.



01112902Azo 01112902Azx

Figure 3 (a) Huge serpentine outcrops located at the southern slope of Godan highland, Ehime Prefecture (region B), (b) Photomicrographs of thin sections showing open and cross Nicole of magnetic minerals (black color). Sample number is 01112902A, region C, Engyou-ji, Kochi City.

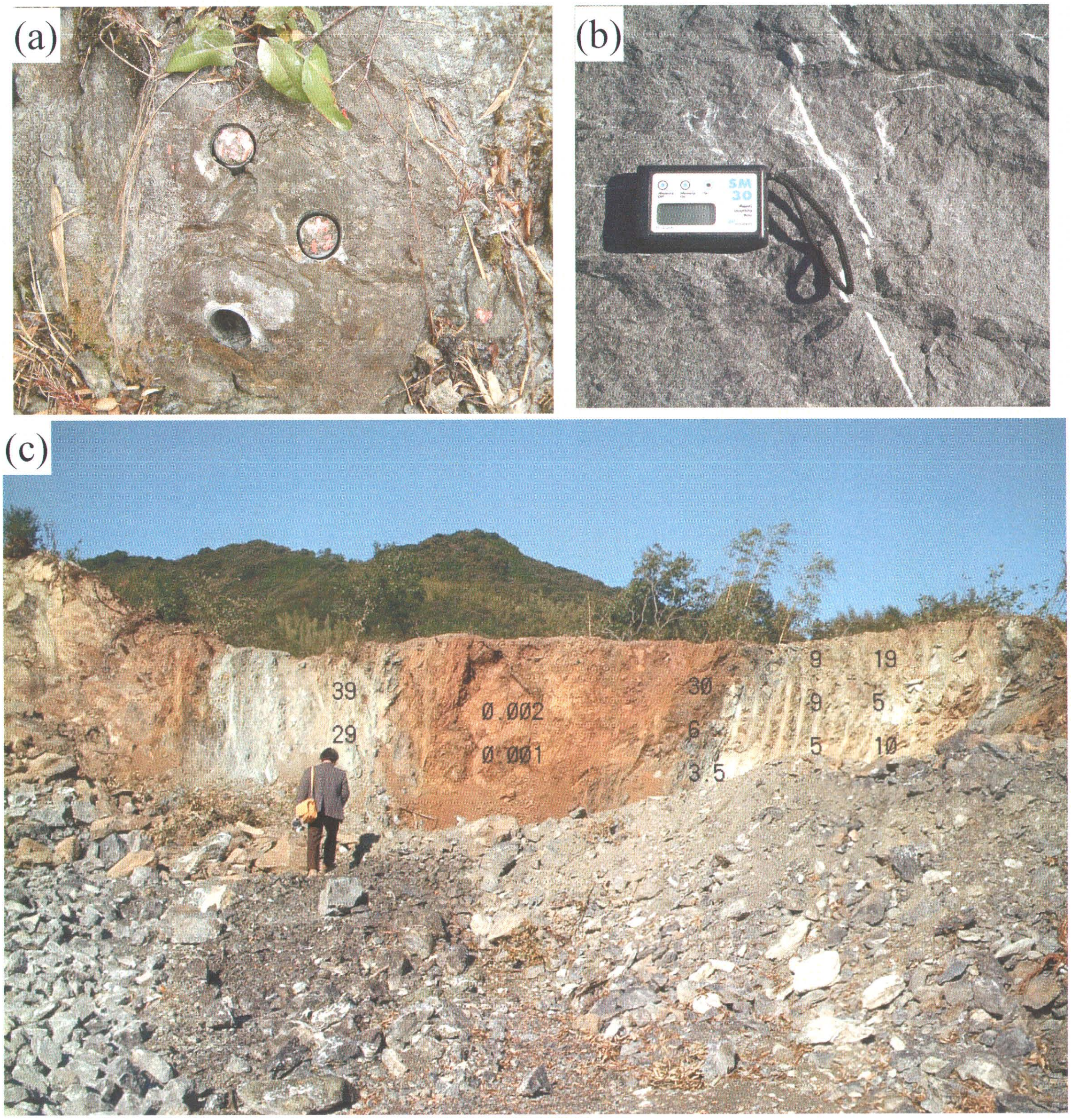


Figure 4 (a) Field drill core samples of serpentine at Region B, Godan highland, Ehime Prefecture, (b) Handy magnetic susceptibility meter SM-30 at Aitani serpentine quarry in Region C, Kochi City, (c) Photo at Aitani serpentine quarry in Region C, Kochi City showing boundary zone of serpentinite, sediment and chert zone. Attached numbers are susceptibility value (unit: 10 ~ -3 SI).

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