

# An Introduction to the Serpentinite Biosphere in the Mariana Forearc

## —Capsule of the Deep Subsurface Biosphere from the Chamorro Seamount—

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### Abstract

In this paper we propose the possible existence of a new biosphere called the “serpentinite biosphere.” We also suggest that serpentinites act as a receptacle of the deep biosphere. Analyses of geology, geophysics, biology, and chemistry of these “serpentinite capsules” are useful for determining the deepest limits of the subsurface biosphere. We obtained bathymetry, sediments, geochemical, and microbiological data from the Chamorro Seamount, a serpentinite seamount consisting of a pile of serpentinite flows in the Mariana forearc. These data reveal that serpentinite flows are products of upper mantle peridotite altered by the addition of water from the subducting slab. Alteration of peridotite to serpentinite provides hydrogen gas and methane, which are the most important energy sources for extremophile life. It also induces a buoyant rise of serpentinite diapirs, which are likely to capture and transport portions of the deep biosphere during their ascent to the surface. The conditions and the characteristics of serpentinite seamounts indicate that the serpentinite diapir is a transported capsule, or a “postcard” from the deep subsurface biosphere, as if meteorites are packages from space and snow is a letter from heaven. We should read them carefully to obtain a broader understanding of the subsurface biosphere.

**Key words :** Serpentinite, serpentinite seamount, subsurface biosphere, serpentinite biosphere, extremophile life, mantle peridotite

### 1. Introduction

Recent advances in microbiology have revealed the existence of a deep, extremophile-dominated biosphere in the Earth's interior, whose estimated volume is comparable to or greater than the total surface biomass of the Earth (L'Haridon *et al.*, 1995 ; Stevens *et al.*, 1995 ; Kerr, 1997 ; Parkes *et al.*, 1994). Extreme environments are estimated to exist not only on the Earth but also on other planets, which may be more severe than those of the Earth. Currently there are several debates over the possible existence of such extreme microbes on other planets

such as Mars or Europa, which are thought to offer more severe conditions for microbes (Aldiss, 2001 ; Rothschild and Mancinelli, 2001). Two means are available to investigate subsurface microbes : (1) direct drilling to the upper mantle, (2) indirect sampling from material ( “capsules”) transported from deeper parts of the Earth. Although we have many deep holes in both land and sea, we have never reached the upper mantle by drilling. However, we have several different packages or capsules from deeper parts of the Earth : diamond pipes, magma intrusions, salt domes, and mud and serpentinite dia-

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pirs. Estimated minimal temperatures of the former two are too high ( $>1,000^{\circ}\text{C}$ ) to preserve living organisms, but the remaining three are estimated to have temperatures lower than  $300\text{--}100^{\circ}\text{C}$ , within the possible upper temperature limits of extremophile cells living under high-pressure conditions which are normally thought to be around  $120\text{--}150^{\circ}\text{C}$  (Stetter, 1999).

Along the Izu-Bonin-Mariana fore arc there are many serpentinite seamounts with and without carbonate chimneys and animal communities. We have visited these serpentinite seamounts both by surface ship and submersible, and collected data and samples. In this paper we propose a new possible biosphere called a "serpentinite biosphere" and suggest that serpentinites act as a receptacle of the deep biosphere through analyses of these data and samples (Fujioka, 2000).

## 2. Serpentinites and serpentinite seamounts

### Mariana serpentinite seamounts

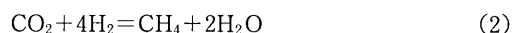
Serpentinite seamounts were found along the Mariana forearc during the Kana-Keoki cruise for the first time, and subsequently the bathymetric and petrologic features of the serpentinite seamounts were investigated with samples and data collected by dredged hauls, submersible dives, and deep sea drilling (Fryer, 1996). Serpentinite seamounts form a stratovolcano-like structure, which consists mostly of serpentine flows from the summit as diapirs, like a mud volcano, with carbonate chimneys and rarely with chemosynthetic communities (Fryer and Mottle, 1997).

### Diapir of serpentinite and serpentinitization

Serpentinite diapirs come from the upper mantle, deeper than mud diapirs and salt domes. If serpentinites capture subsurface life during their ascent to the surface, petrological and mineralogical analyses can be employed to estimate the in situ pressure and temperature conditions of the deep biosphere. Serpentinites are the products of hydrothermal and low temperature alteration and metamorphism of the upper mantle peridotites, which are composed mostly of olivine, orthopyroxene, clinopyroxene, and spinel and/or garnet (O'Hanley, 1996). During serpentinitization of peridotites caused by the addition of  $\text{H}_2\text{O}$ , serpentine minerals such as chrysotile, antigorite, lizardite, hydrogen gas, and magnetites are produced by the reaction

Olivine + Vapor = Serpentine +  $\text{H}_2$  + Magnetite (1)  
(O'Hanley, 1996).

Hydrogen gas will reduce coexisting  $\text{CO}_2$  to produce methane by the Fischer-Tropsch reaction



using a metallic iron or iron oxide catalyst (Berndt *et al.*, 1996). Both hydrogen gas and methane are favorable energy sources for chemosynthetic and/or lithotrophic bacteria (Stevens and McKinley, 1995).

### Physical property of serpentinite

Serpentine minerals commonly contain enough water ( $\text{H}_2\text{O}$ , OH up to 15 wt%) for their density to be considerably lower than that of other ambient minerals and rocks. Serpentinites are so soft and viscous that they easily envelop and entrain the surrounding materials to form xenoliths or xenocrysts. The buoyancy of serpentinites causes them to rise to the surface as diapirs, and repeated diapir intrusion creates serpentinite seamount edifices on the seafloor (Fryer, 1996; O'Hanley, 1996; Toft *et al.*, 1990; Fujioka, 2000).

## 3. Distribution of serpentinites in the world and animal communities

The present distribution of serpentinite bodies in the world is restricted to slow spreading centers and fracture zones along Mid-Ocean Ridges, the forearc regions of immature island arcs, and backarc rift basins in the ocean floor (Fujioka, 2000), and ophiolite and metamorphic terrains on land. Only three examples of living animal communities coexistent with serpentinite bodies on the seafloor are known at the "Rainbow" and "Lost City" hydrothermal fields on the Mid-Atlantic Ridge (Fouquet *et al.*, 1997; Kelley, 2001) and the Chamorro Seamount in the Mariana forearc region (Fryer and Mottle, 1997). The hydrothermal vents are thought to be windows to the deep biosphere (Deming and Baross, 1993; Delaney *et al.*, 1999), but the thermal gradient at the ridge crest seems to be so large that the estimated temperature below the vents and deeper parts is too high to sustain life. In contrast, the thermal gradient beneath subduction zones in the Western Pacific Rim (Maekawa *et al.*, 1993; Iwamori, 1998) is so small that living organisms should survive in deeper parts of the lower crust and even the upper mantle.

#### 4. Chamorro Seamount in the Mariana Forearc

The Chamorro Seamount, a twin seamounts, lies 2,500 km south of Tokyo, about 100 km east of Guam Island, Mariana Arc-Trench system, 13° 47'N, 146° 00' E (Bloomer and Hawkins, 1983 ; Fryer, 1996 ; Fryer *et al.*, 1985 ; Fujioka *et al.*, 1994 ; 1995, Ishii, *et al.*, 2000 ; Maekawa *et al.*, 1993) (Figs. 1 and 2). Near the summit of the South Chamorro Seamount there is a chemosynthetic animal community consisting of mussels, galatheid crabs, and gastropods living near and on carbonate chimneys found during a *Shinkai 6500* dive program in 1996 (Fryer and Mottle, 1997). We investigated the South Chamorro Seamount using the Remotely Operated Vehicle "*Kaiko*" and the R/V *Kairei* of JAMSTEC in 2000.

We used several bathymetric survey line data, deep-sea photos, sediment and *Bathymodiolus*-like mussel samples taken using *Kaiko*'s manipulator, and water samples taken from the hole after bivalve sampling using an *Alvin* type water sampler (Figs. 4 a, b). We mapped the whole edifice of the South Chamorro Seamount using SEABEAM 2112 during the ROV survey (Fig. 2). The Chamorro seamount is 1.5 km in height with a conical shape (25 km bottom diameter). The estimated volume of serpentinites is  $5 \times 10^2 \text{ km}^3$ , and we infer that a weight of  $1 \times 10^{18} \text{ g}$  of water is needed from the subducting slab to produce the observed volume of serpentinite. This estimated volume of serpentinite should produce about  $1.6 \times 10^{16} \text{ g}$  of Hydrogen.

On the Conical Seamount, north of the Chamorro Seamount serpentinite flows extend radially from the summit and form small, narrow, several meter high ridges that include boulders of peridotite. Carbonate chimneys stand on the serpentinite mound at Conical and Pacman seamounts (Fryer, 1996 ; Fryer, *et al.*, 1985 ; Fujioka *et al.*, 1994 ; 1995 ; Iwamori, 1998). The ratio of serpentinite matrix and boulders is estimated to be 9 : 1 from visual observations and photographs taken from the previous submersible *Shinkai 6500* dives. The sediments were confirmed to be soft, loose, and fragile, i.e., low-density materials, when picked up by *Kaiko*'s manipulator (Figs. 3 a, b). The magnetic survey of the seamount shows a dipole magnetic anomaly, indicating the existence of abundant, strongly magnetized, small, single domain magnetites formed by the above-mentioned reaction.

#### 5. Microbiological examination of serpentinite mud and water

A direct count of 4',6-diamidino-2-phenylindole (DAPI) stained cells using epifluorescence microscopy indicates that the total microbial biomass in the water sample and serpentinite mud matrix was  $7 \times 10^4$  cells/ml and  $2 \times 10^7$  cells/wet g, respectively. These abundances are similar to or higher than the values obtained from bottom water and surface mud in ordinary deep-sea animal communities (Rothschild and Mancinelli, 2001). These apparently normal values seemingly contradict our proposal that the serpentinitization process has a huge potential to sustain a large biomass. The starting point of our current research is the hypothesis that most of the biomass is embedded in the subsurface.

#### 6. Isotope geochemistry of water samples

Previous geochemical studies of hydrogen, oxygen, and carbon isotopes revealed that fluids, gases, and authigenic carbonate sampled along subduction zones are partially derived from the lower crust and the upper mantle at the Mariana Trench (Haggerty, 1991 ; Kato *et al.*, 2001 ; Mottl, 1992 ; Sakai *et al.*, 1990 ; Yamanaka *et al.*, submitted). The concentration of  $\text{CH}_4$  in the sample water from the Chamorro seamount is at least 100 times higher than that of ambient seawater (Yamanaka *et al.*, submitted) and is comparable with those of the cold-seepage fluids observed around Nankai and Suruga Trough accretion prism (Gamo *et al.*, 1992 ; Tsunogai *et al.*, 1998). The  $\delta^{13}\text{C}$  value of dissolved  $\text{CH}_4$  in the sampled water is  $-14$  (relative to PDB), which is considerably heavier than that of seawater in Suruga Trough water column and the cold-seepage fluids (almost lower than  $-35$  : Tsunogai *et al.*, 1998). This may indicate that methane is a reaction product of hydrogen gas produced during serpentinitization with deeper crust or upper mantle-derived  $\text{CO}_2$ . It may imply that hydrogen gas is emitting from the fissures with methane. The  $\delta^{34}\text{S}$  value of sulfide from serpentinite mud is  $-32.3$  (relative to CTD), which is significantly lighter than that of seawater sulfate ( $+21$  : Rees *et al.*, 1978). This value could indicate the effects of reduction by sulfate-reducing bacteria. However, due to quite low TOC values (0.05 weight %) in surface mud collected with mussels, organic matter in a quantity great enough to act as a significant electron donor for

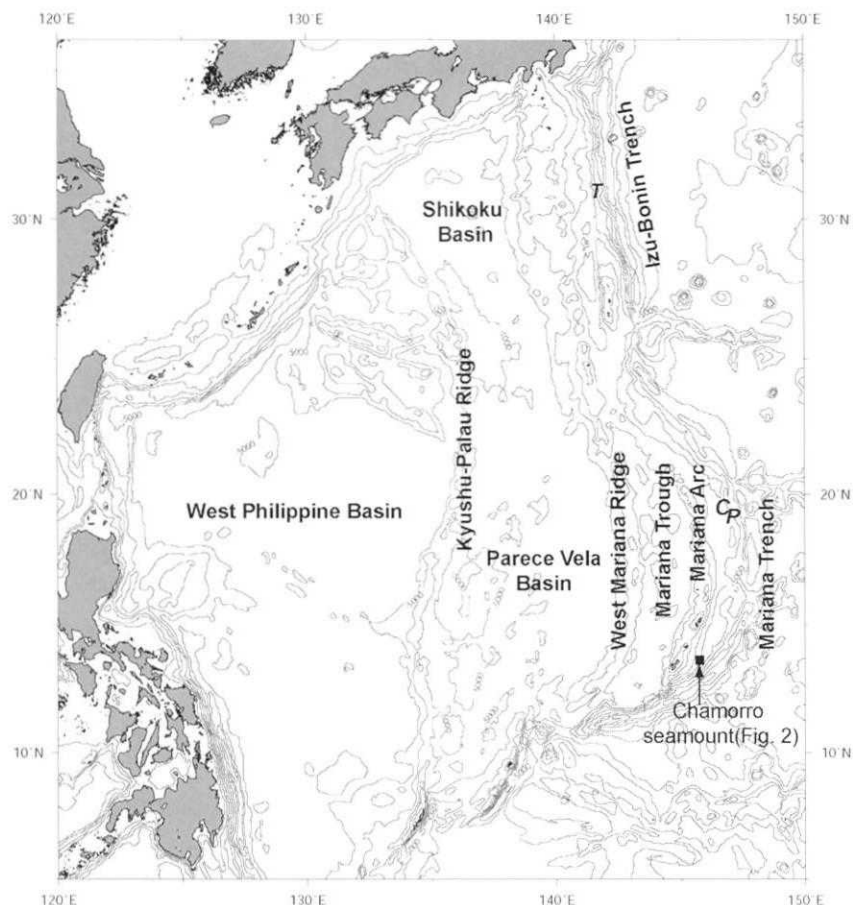


Fig. 1. Index map of the Philippine Sea and the location of the Chamorro Seamount, Mariana forearc. C : Conical Seamount, P : Pacman Seamount, T : Torishima Seamount.

bacterial sulfate reduction could not be identified (Yamanaka *et al.*, submitted). This may indicate that sulfate reduction reactions using  $\text{CH}_4$  and hydrogen as electron donors are vigorous in the subsurface. The  $\delta^{34}\text{S}$  values of soft tissues from the mussel samples are approximately +10, suggesting that the mussel species takes energy both from  $\text{CH}_4$  and  $\text{H}_2\text{S}$ , namely dual-symbiosis (Yamanaka *et al.*, submitted). It indicates that methane is not sufficient but is effective for sustaining this kind of animal.  $\text{CH}_4$ ,  $\text{H}_2$ , and even  $\text{H}_2\text{S}$  are important energy sources for bacteria in a deep subsurface environment.

## 7. Conclusion

The existence of endosymbiotic animal communities on the Chamorro Seamount strongly suggests that the large biomass found there is dependent on energy sources derived from a deep subsurface environment below the serpentinite seamount. These chemical data strongly support the potential for

maintaining animal communities on the Mariana serpentinite seamounts, similar to cold-seep animal communities in the Japan Trench forearc and other forearc regions around the world.

The structure of the serpentinite diapir was estimated from data obtained by ODP drilling at Conical and Torishima seamounts on the Izu-Bonin-Mariana forearc, and by a seismic survey on the Torishima SMT in the Izu-Bonin arc (Fryer *et al.*, 1985 ; Suyehiro *et al.*, 1996 ; Kamimura *et al.*, 2000).

Among the many serpentinite seamounts along the Izu-Bonin-Mariana forearc, only the Chamorro Seamount is an active serpentine mud volcano where serpentinite flows erupt repeatedly from the summit (Fryer, 1996). The other serpentinite seamounts are dormant or dead. Active volcanoes emit gases such as  $\text{CH}_4$  and  $\text{H}_2$ , but old ones are covered with sediments that are subsequently compacted and consolidated to cap their summits. Gases trapped inside or below these extinct seamounts and may sustain a

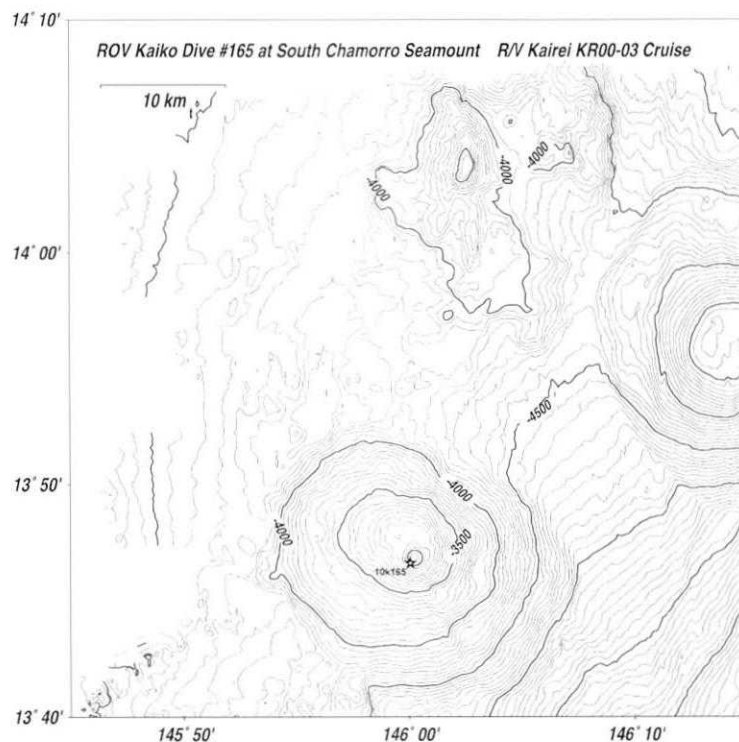


Fig. 2a. Detailed topographic map of the Chamorro Seamount drawn during *Kaiko* dive #165 by *Kairei*'s SEABEAM2112 (Contour is every 50 m).

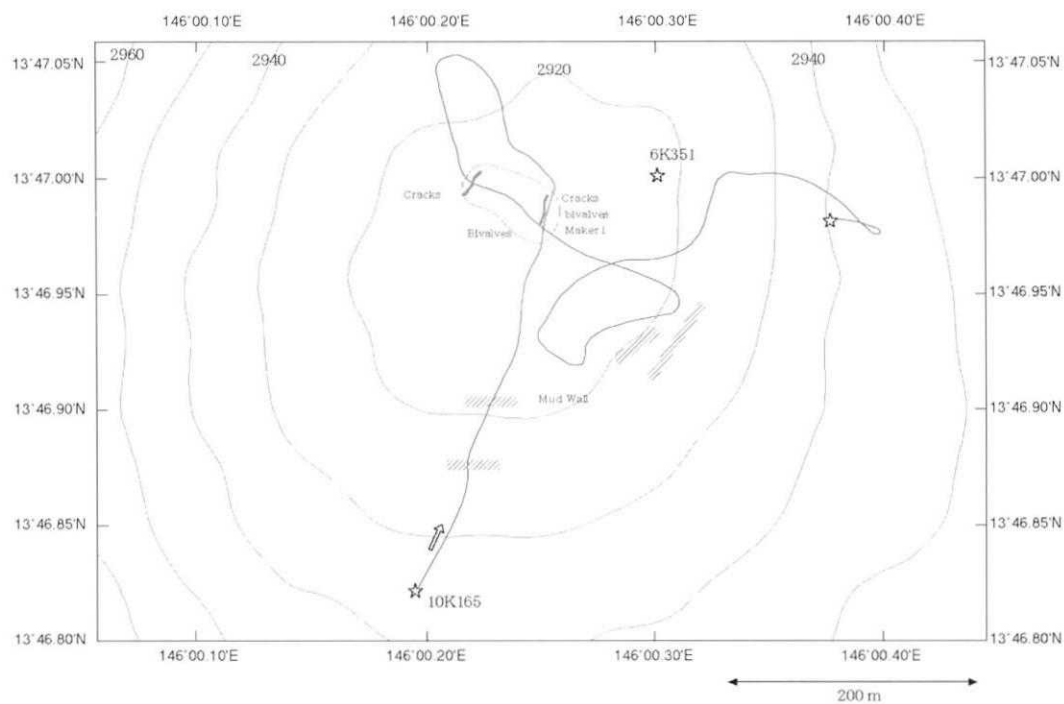


Fig. 2b. ROV *Kaiko* Dive 165 track with events on the Chamorro Seamount. 6K351 is the *Shinkai 6500* dive site. Both dives were restricted to a small area of the summit of Chamorro SMT in Fig. 2a.



Fig. 3a. ROV Kaiko external photo from Dive 165 shows operation of water sampling using an Alvin-type water sampler with Kaiko's manipulator. The water sample was taken from the hole after retrieving mussel samples.

Fig. 3b. ROV Kaiko external photo from Dive 165 shows semi-consolidated thin slab of pale yellowish green serpentine mud flow forming overhanging microtopography. Mussels are clustered along a small fissure.

special subsurface biosphere. We suggest this explanation for the absence of biological communities at serpentinite seamounts other than Chamorro. Taking into account all these data, we derive a image for the structure of serpentine biospheres, shown in Fig. 4.

The distribution of serpentinite bodies in time and space is so wide that serpentinites are the most suitable target for an investigation of the deep biosphere. The conditions and the characteristics of serpentinite seamounts indicate that the serpentinite diapir is a transported capsule, or a "postcard" from the deep subsurface biosphere, just as meteorites are packages from space and snow is a letter from heaven. Careful reading of these postcards from the deepest habitat,

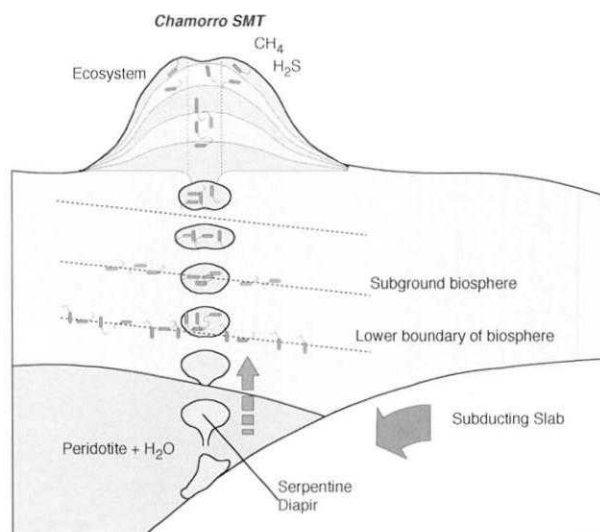


Fig. 4. A schematic model of the formation of serpentinites diapirs and serpentinite flows with deep biosphere, "serpentinite biosphere" as a capsule for microbes in the deep subsurface biosphere.

through detailed investigations of serpentinite seamounts and diapirs, will shed light on the structure and the character of the deep subsurface biosphere.

# Acknowledgments

We thank J. Kasahara and H. Masuda for their invitation to contribute to this special publication and critical reading the manuscript. Thanks are also due to T. Okamoto, H. Oda, D. Curewitz, K. Horikoshi, Y. Ohara, Y. Kido and shipboard scientists of R/V *Kairei* for their helpful discussions and criticisms.

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\* Japanese with English Abstract

(Received August 17, 2001)

(Accepted October 12, 2001)

## マリアナ前弧の蛇紋岩生物圏への招待

### —チャモロ海山からの地下生物圏のカプセル—

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#### 要 旨

我々は蛇紋岩生物圏と呼ばれる新しい生物圏の存在と蛇紋岩が地下生物圏の容器として働いている可能性を提唱する。地質学、地球物理学、生物学そして化学的な検討から蛇紋岩カプセルが地下生物圏の深さ方向の限界を知るのに有用であることを示した。マリアナ前弧の蛇紋岩フローの積み重なりからなる蛇紋岩海山の一つ、チャモロ海山から地形、堆積物、化学、微生物の試料やデータを得た。これらのデータは蛇紋岩フローは上部マントルのカンラン岩が沈み込むスラブからの水の供給によっ

て変質したものであることを示している。カンラン岩が変質して蛇紋岩になるときに極限の生命にとって有用なエネルギーである水素ガスやメタンを供給する。また蛇紋岩ダイアピルの浮力を生じそれが地表まで上昇してくる途中に地下生物圏の物質を捕獲する可能性がある。蛇紋岩海山は蛇紋岩ダイアピルが運搬されてきた地下生物圏のカプセルまたは手紙であることを示す。あたかも隕石が宇宙からの雪が空からの手紙であるように、地下生物圏を広く理解するためにこれらを注意深く読まなければならない。