Serpentines as a capsule of the deep subsurface biosphere: Evidence from the Chamorro Seamount, Mariana forearc

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We propose here the existence of a new biosphere called the "serpentinite biosphere", and suggest that serpentinites act as a receptacle of the deep biosphere. Analyses of the biology, geology, and chemistry of these "serpentinite capsules" are useful for determining the deepest limits of the subsurface biosphere. We obtained geophysical, geochemical and microbiological data from the Chamorro Seamount, a serpentinite seamount in the Mariana forearc. These data reveal that serpentinite flows are the alteration products of upper mantle peridotite 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 source for the extremophile life and induces buoyant rise of serpentinite diapirs that are likely to capture and transport portions of the deep biosphere during ascent to the surface. The conditions and characteristics of serpentinite seamounts indicate that the serpentinite diapir is a transported capsule, or "postcard" from the deep subsurface biosphere, as if meteorites are the packages from the space and the snow is a letter from the heaven.

Keywords : Serpentinite, serpentinite seamount, subsurface biosphere, serpentinite biosphere, extremophile life, mantle peridotite

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INTRODUCTION

Recent advances in microbiology have revealed the existence of a deep, extremophile-dominated biosphere in the Earth's interior whose estimated volume is greater than the total surface biomass of the Earth (L' Haridon et al., 1995; Stevens et al., 1995; Kerr, 1997; Parkes et al., 1994). Currently there are several debates over the possible existence of such extremophile microbes on Mars or Europa (Aldiss, 2001; Rothschild and Mancinelli, 2001). Sampling and investigating subsurface microbes requires either direct drilling down to the upper mantle or indirect sampling from material "capsules" being transported from the 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 types of packages or capsules from the deeper parts of the Earth: diamond pipes, magma intrusions, salt domes, and mud and serpentinite diapirs. Estimated minimal temperatures of the former two are too high (>1000˚C) to support life, but the remaining three are estimated to have temperatures lower than 500˚-300˚C, within possible upper temperature limits of living extremophiles (Stetter, 1999). Serpentinite diapirs come from the upper mantle, deeper than mud diapirs and salt domes. If serpentinites capture subsurface life during ascent to the surface, petrological and mineralogical analyses can be used to estimate the pressure and temperature conditions of the deep biosphere. Serpentinites are the products of hydrothermal and low temperature alteration and metamorphism of upper mantle peridotites, which are composed mostly of olivine, orthopyroxene, clinopyroxene and spinel and/or garnet (O'Hanley, 1996). During serpentinization of peridotites by addition of H_2O, serpentine minerals (Chrysotile, antigorite, lizardite etc), hydrogen gas and magnetites are produced by the reaction

Olivine + Vapor = Serpentine + H_2 + Magnetite (1) (O'Hanley, 1996).

Hydrogen gas will reduce coexisting CO_2 to methane by the Fischer-Tropsch reaction

$CO_2 + 4H_2 = CH_4 + 2H_2O$ (2)

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). Serpentine minerals commonly contain enough water (H_2O, OH up to 15 wt %) that their density is considerably lower than that of other ambient minerals and rocks. Serpentinites are so soft and viscous that they easily envelop and entrain the surrounding rocks and minerals to form xenoliths or xenocrysts. The negative buoyancy of serpentinites causes them to rise to the surface as diapirs, and repeated diapir intrusion creates serpentinite seamount edifices on the seafloor (O'Hanley, 1996, Toft et al., 1990). Serpentinite bodies are restricted to slow spreading centers and fracture zones along Mid-Ocean Ridges, the forearc regions of immature island arcs, and backarc rift basins (Stetter, 1999). Three examples of animal communities coexistent with serpentinite bodies 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 a window 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 (Iwamori, 1998) is so small that living organisms should survive in deeper regions of the lower crust and upper mantle.

The Chamorro Seamount (Bloomer and Hawkins, 1983; Fryer, 1996; Fryer et al., 1985; Fujioka et al., 1994; 1995, Ishii, et al., 2000; Maekawa et al., 1993) lies 2500km south of Tokyo, about 100km east of Guam Island, Mariana Arc-Trench system, 13˚47'N, 146˚00'E (Fig. 1). Near the summit of the 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 Chamorro seamount using the Remotely Operated Vehicle "*Kaiko*" and R/V *Kairei* of JAMSTEC in 2000.

The data include several geophysical survey lines, 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 (Fig. 2). The Chamorro seamount is 1.5km in height with a conical shape (25km bottom diameter). The estimated volume of serpentinites is 5 x $10^2 km^3$, and we infer that a volume of l x

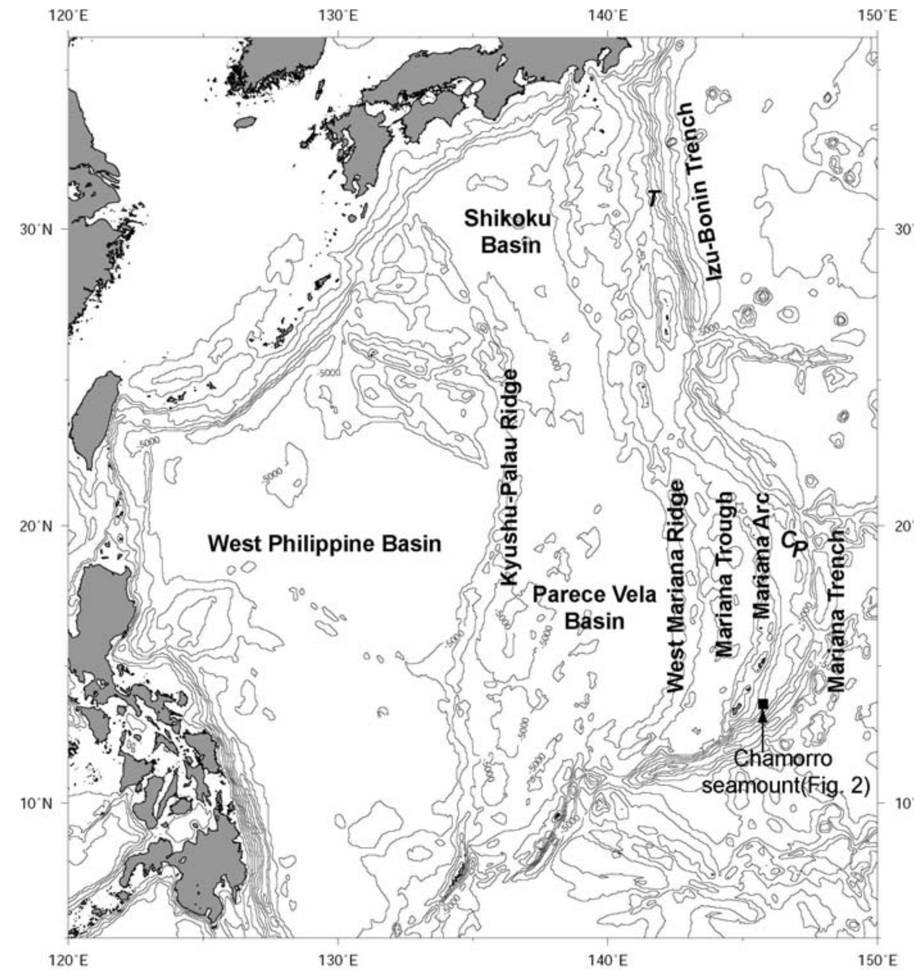

Fig. 1a Index map of the Philippine Sea and the location of the Chamorro Seamount, Mariana forearc. C: Conical Seamount, P: Pacman Seamount, T: Torishima Seamount.

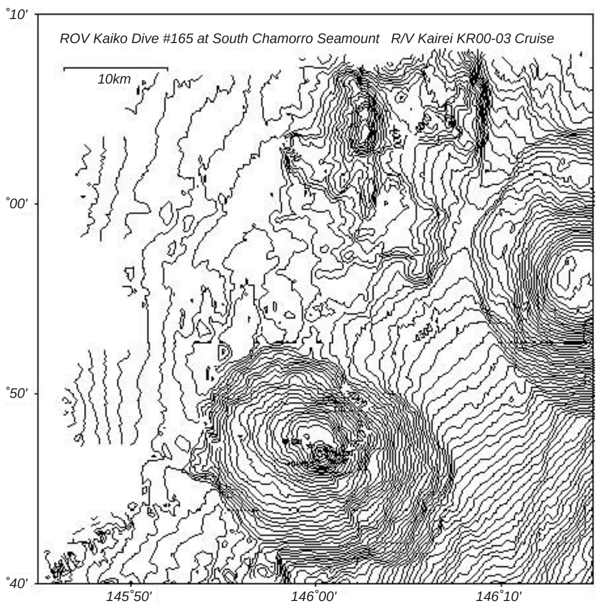

Fig. 1b Detailed topographic map of the Chamorro Seamount drawn during *Kaiko* dive # 165 by *Kairei*'s SEABEAM2112 (Contour is every 50m).

10^{18}g of water is needed from the subducting slab in order to produce the observed volume of serpentinite (Fig. 1b). This estimated volume of serpentinite should produce about 1.6 x 10^{16}g of H_2.

On Conical 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 serpentine mound at Conical and Pacman seamount (Fryer, 1996; Fryer, et al., 1985; Fujioka et al., 1994; 1995; Iwamori, 1998). The ratio between serpentine matrix and boulders is estimated to be 9:1 from visual observations and photographs. The sediments were confirmed to be soft, loose, and fragile, i.e. low-density materials, when picked up by *Kaiko*'s manipulator (Fig. 2b & 2c). The magnetic survey of the seamount shows a dipole magnetic anomaly, indicating the existence of abundant, strongly magnetized, small size, single domain magnetites formed by

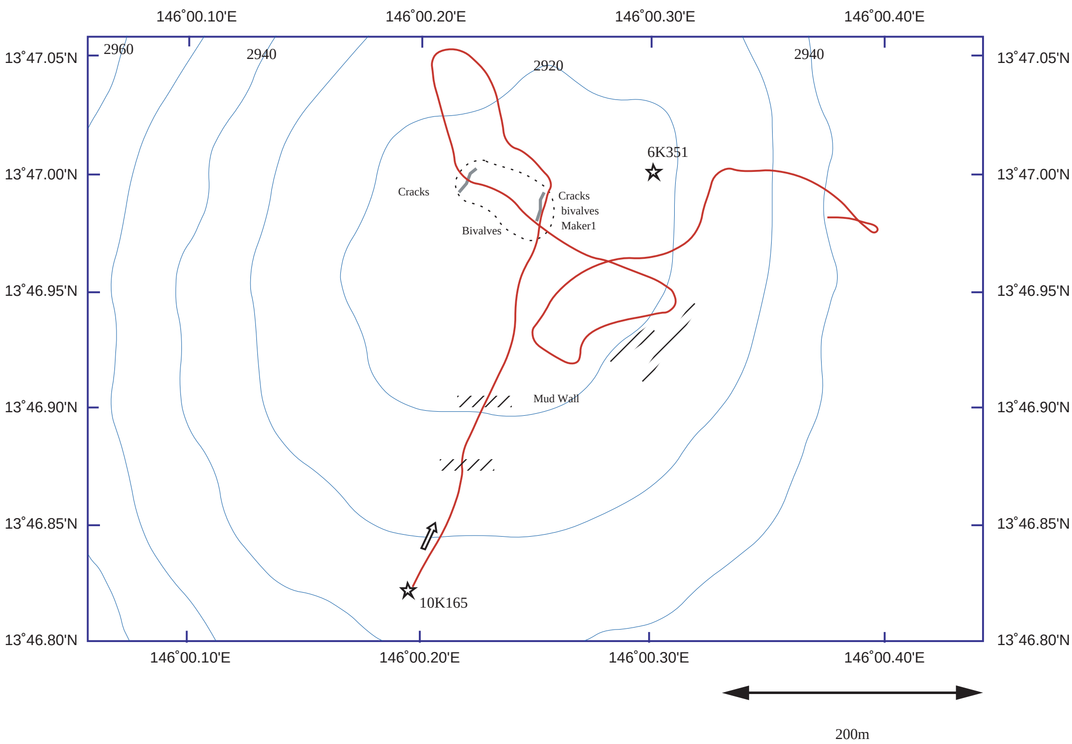

Fig. 2a ROV *Kaiko* Dive 165 track with events on the Chamorro Seamount. 6K351 is the *Shinkai* 6500 dive site[15]

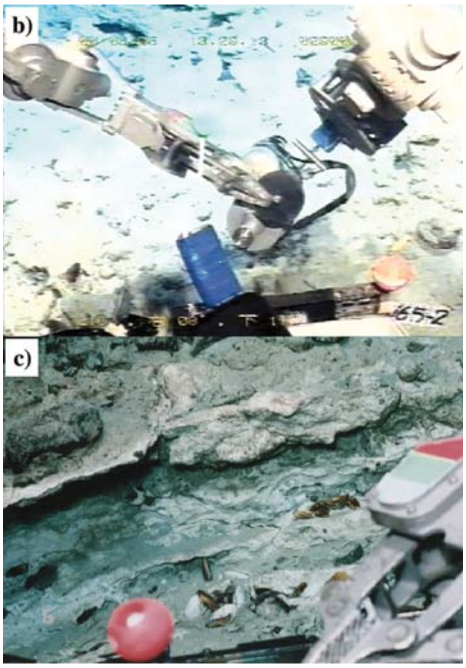

Fig.2b ROV Kaiko external photo from Dive 165 shows operation of water sampling by Alvin-type water sampler using Kaiko's manipulator. The water sample was taken from the hole after retrieving mussel samples.

Fig.2c 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.

the above-mentioned reaction (Figs. 3a & 3b).

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

Previous geochemical studies of hydrogen, oxygen and carbon ions revealed that the fluids and gases sampled along subduction zones are partially derived from the lower crust and the upper mantle (Haggerty, 1991; Kato et al., 2001; Mottl, 1992; Sakai et al., 1990; Yamanaka et al., 2001). The concentration of CH_4 in the sample water from the Chamorro seamount is at least 100 times higher than that of ambient seawater (Yamanaka et al., 2001). The $\delta^{13}C$ value of dissolved CH_4 in the sampled water is -14‰ (relative to PDB),

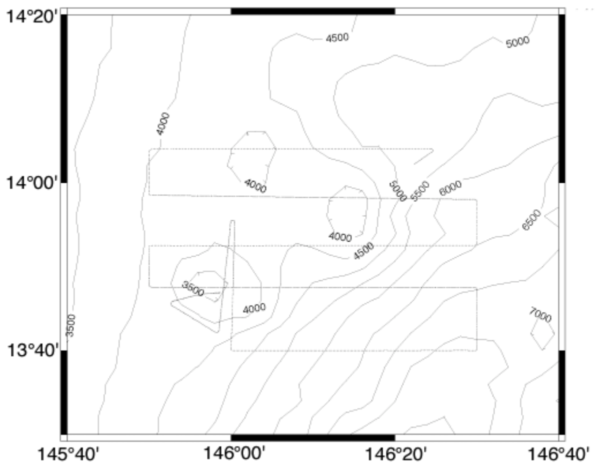

Fig. 3a R/V *Kairei*'s Ship tracks at the Chamorro Seamount

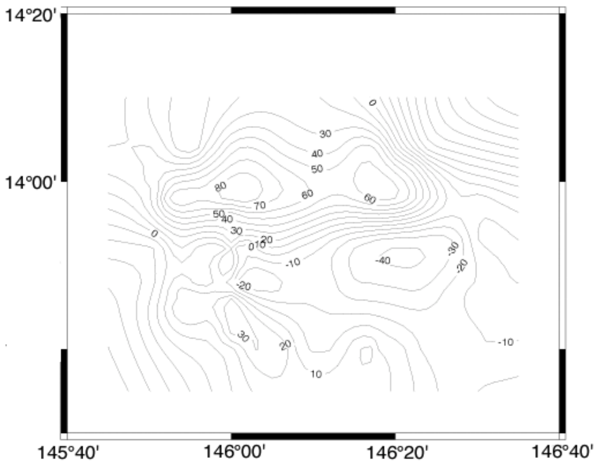

Fig. 3b Magnetic anomaly of the Chamorro Seamount (Contour interval is 10 nT)

considerably heavier than that of seawater (Yamanaka et al., 2001). This may indicate that hydrogen gas produced during serpentinization inhibits the resultant formation of methane from inorganic CO_2. The $\delta^{34}S$ value of sulfide from serpentine mud is -32.3‰ (relative to CTD), significantly lighter than that of seawater sulfate (Yamanaka et al., 2001). 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 the mussels, organic matter in a quantity high enough to act as a significant electron donor for bacterial sulfate reduction could not be identified (Yamanaka et al., 2001). This indicates that sulfate reduction reactions using CH_4 as an electron donor are vigorous in the subsurface. The $\delta^{34}S$ values of mussels are approximately +10‰, heavier than that of bacterial sulfide, but this value is intermediate between seawater sulfate and bacterial sulfide. This indicates that the mussels take energy both from CH_4 and H_2S, namely dual-symbiosis (Yamanaka et al., 2001). CH_4, H_2, and even H_2S are important energy sources for bacteria in the deep subsurface environment (Suyehiro et al., 1996; Kamimura et al., 2000). The existence of endosymbiotic animal communities on the Chamorro Seamount strongly suggests that the large biomass found there is dependent on energy from the deep subsurface environment below the serpentinite seamount. These chemical data strongly support the potential for maintenance of 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. The other serpentinite seamounts are dormant, or dead. Active volcanoes emit gases such as CH_4 and 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 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 model for the structure of serpentine biospheres, shown in Figure 4.

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

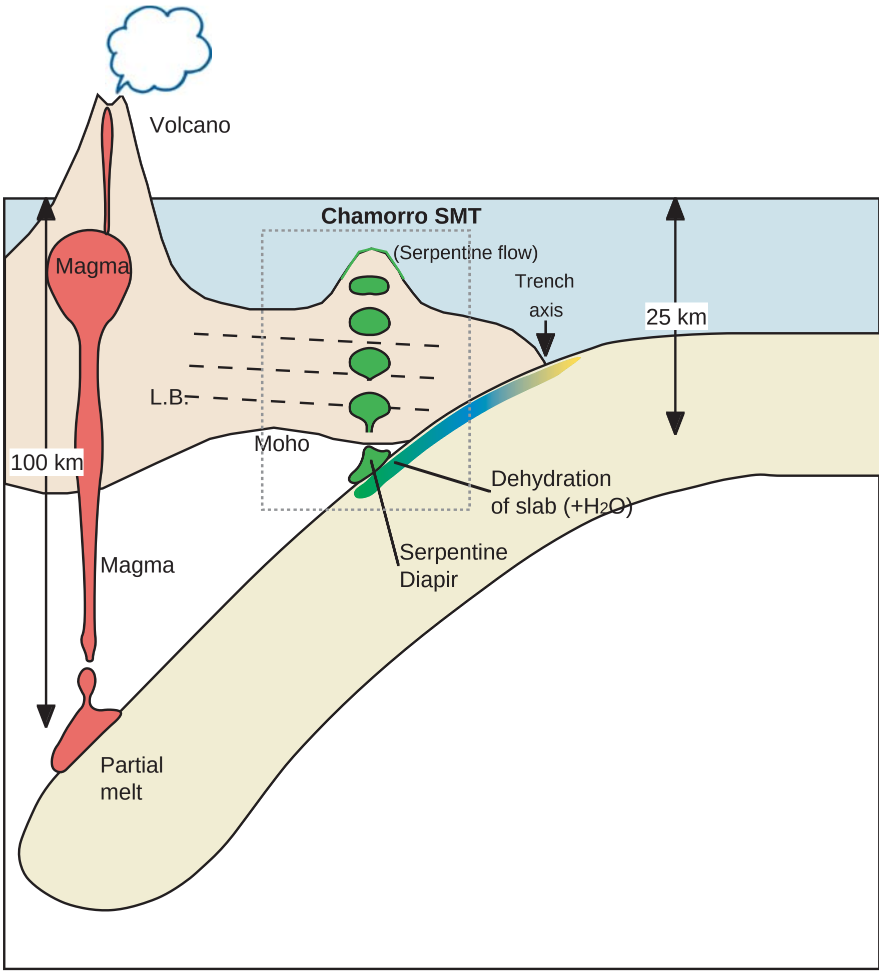

Fig. 4a A schematic model for the formation of serpentinites diapirs and serpentinite flows with deep biosphere, "serpentinite biosphere" as a capsule for microbes in deep subsurface biosphere.

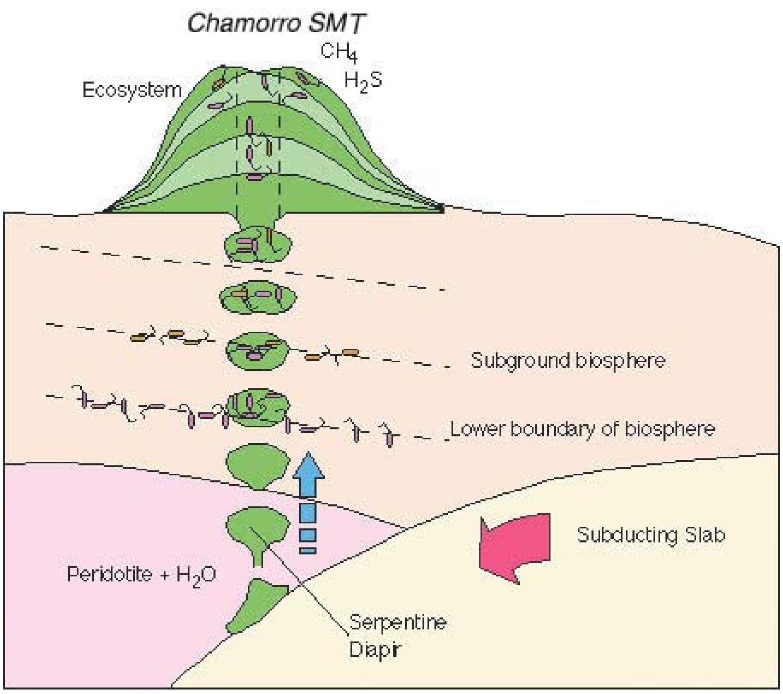

Fig. 4b Blow up diagram of serpentinite diapir and serpentinite seamount Serpentinite biosphere

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* Japanese with English Abstract

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