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Volume 16, Number 3, September 1989

URI: https://id.erudit.org/iderudit/geocan16_3art15

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Publisher(s)

The Geological Association of Canada

ISSN

0315-0941 (print)

1911-4850 (digital)

[Explore this journal](#)

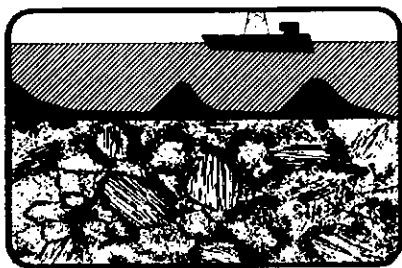
Cite this article

Keen, M. J., Salisbury, M., Burke, M. & Ishii, T. (1989). Serpentine seamounts of Pacific fore-arcs drilled by the Ocean Drilling Program: Dr. Hess would be pleased. *Geoscience Canada*, 16(3), 177–182.

Article abstract

Serpentine forms seamounts which rise as diapirs in the Mariana fore-arc of the western Pacific. These have been imaged by side-scan sonar and sampled by dredging, submersible dives and most recently by drilling in Leg 125 of the Ocean Drilling Program. The crust beneath the world's ocean basins is not dominated by serpentinite, so where do these serpentine seamounts come from? And where is this serpentine's water from? Water is incorporated into ocean crust in hydrous minerals like the serpentines and in sediments on the mid-ocean ridges, and then travels with the spreading sea floor to subduction zones, like the Mariana and Bonin Arcs. The water is released as sediment is squeezed and as hydrous minerals are heated in the down-going slab, and sometimes rises to serpentinize the ultra-mafic rocks of the overlying mantle wedge, so that serpentinite diapirs form which rise to the sea floor above. H.H. Hess once proposed that Layer 3 of the ocean crust was serpentinized mantle — serpentinized at mid-ocean ridges when water from inside the earth hydrated olivines and pyroxenes as the temperature cooled below 500°C near the sea floor. This hypothesis didn't stand up to subsequent tests, but Hess's proposal does seem to work in different circumstances in some island arc settings. And so, for example, we ask here if serpentinite-rich sediments are the products of ancient seamounts in Appalachian ophiolites?

Serpentine doesn't merely affect island arcs, ocean floors and ophiolites — it is mined as asbestos. And so in the mines of the Eastern Townships of Quebec serpentine unwittingly set the scene for the meeting of Jean Marchand, Gérard Pelletier and Pierre Elliott Trudeau in the great asbestos strike of 1949 — "La Grève des Amiantes", an usher, a prelude a political revolution, Quebec's Quiet Revolution.



Serpentine seamounts of Pacific fore-arcs drilled by the Ocean Drilling Program: Dr. Hess would be pleased¹

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Abstract

Serpentine forms seamounts which rise as diapirs in the Mariana fore-arc of the western Pacific. These have been imaged by side-scan sonar and sampled by dredging, submersible dives and most recently by drilling in Leg 125 of the Ocean Drilling Program. The crust beneath the world's ocean basins is not dominated by serpentinite, so where do these serpentine seamounts come from? And where is this serpentine's water from? Water is incorporated into ocean crust in hydrous minerals like the serpentines and in sediments on the mid-ocean ridges, and then travels with the spreading sea floor to subduction zones, like the Mariana and Bonin Arcs. The water is released as sediment is squeezed and as hydrous minerals are heated in the down-going slab, and sometimes rises to serpentinize the ultramafic rocks of the overlying mantle wedge, so that serpentinite diapirs form which rise to the sea floor above. H.H. Hess once proposed that Layer 3 of the ocean crust was serpentinized mantle — serpentinized at mid-ocean ridges when water from inside the earth hydrated olivines and pyroxenes as the temperature cooled below 500°C near the sea floor. This hypothesis didn't stand up to subsequent tests, but Hess' proposal does seem to work in different circumstances in some island arc settings. And so, for example, we ask here if serpentinite-

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Serpentine seamounts?

Serpentine is familiar to us as a hydration product of olivine and pyroxene found wherever ultramafic rocks are exposed at the Earth's surface (Box 1). Not only is the composition unusual, so are the geological settings in which it is found.

Serpentinites, radiolarian cherts and pillow lavas form the "Steinmann Trinity" or "ophiolites" (Gass, 1982). Indeed, serpentinites are a major component of ophiolites such as the Bay of Islands Complex in Newfoundland, the Troodos Complex in Cyprus and the Semail Ophiolite in Oman.

Serpentinized peridotites are common in layered intrusions such as the Muskox Complex, Northwest Territories (Aumento, 1970; Findlay and Smith, 1965).

Serpentinites containing massive sulphides and asbestos often occur along great sutures — the Thompson nickel belt, the Eastern Townships' asbestos belt of Quebec, and the Indus suture are examples (see, for example, Laurent, 1977).

Serpentinite mélanges are well known — in western Newfoundland, for example. Neale (1972) describes the Shoal Brook mélange in the following way: "... large blocks of sheared serpentinite occur at this locality ... slivers of sandstone in crushed shale occur with the serpentinite blocks." Indeed, "sedimentary" serpentinite is widespread (Lockwood, 1971).

Serpentinites have been recognized as a major lithology exposed in the floors and walls of oceanic fracture zones. Examples are the Mid-Atlantic Ridge with its Oceanographer Fracture Zone, and the Southwest Indian Ridge and its Atlantis II Fracture Zone (see, for example, Bonatti and Crane, 1984; Anon, 1988).

Some serpentinite bodies have been interpreted as diapirs — examples can be drawn from Mount Olympus in Cyprus, and from the southern Coast Ranges of California (Oakshot, 1968).

And serpentinite seamounts have been dredged and very recently have been drilled in the western Pacific (Figure 1) (Bloomer, 1983; Fryer *et al.*, 1989a,b).

Serpentinized ultramafic rocks are well known, but serpentinite seamounts?

The ocean connection

H.H. Hess described sea-floor spreading in his extraordinary paper of 1962 (Figure 2; Box 2). He not only suggested sea-floor spreading as a mechanism for continental drift, but he also wondered if the main part of the ocean crust, Layer 3 of refraction seismology, is made of serpentinized upper mantle material. The ultramafic mush would upwell at mid-ocean ridges, bringing water from inside the earth, he proposed, and upon cooling below 500°C, the rocks would serpentinize, swell by as much as 20%, and decrease in density from about 3.3 to the range 2.1 to 2.5 gm·cm⁻³ (Aumento and Loubat, 1971; Deer *et al.*, 1967; Ishii, 1985; see Box 1). These rocks would cool with spreading from the ridge axis, fractures would heal, and their velocities would become those typical of "Layer 3".

Hess was right about sea-floor spreading, as we all know, but the oceanic crust isn't all made of serpentinized upper mantle, and the process itself appears to use seawater, rather than water from the mantle.

The igneous rocks of ocean crust and mantle are formed from the same igneous rocks that make up ophiolites: pillow lavas, diabase dykes, massive gabbros, and peridotites such as Iherzolite, harzburgite and dunite. We think we know this from petrologic studies of ophiolites on land, mentioned already, from drilling by the Deep-Sea Drilling Project and the Ocean Drilling Program in holes such as 504B in the eastern equatorial Pacific Ocean, now drilled down to about 1300 m in oceanic crustal rocks, and by comparisons made between the seismic properties of ophiolites and ocean crust (Salisbury and Christensen, 1978; Peterson *et al.*, 1974). Serpentinized rocks are, of course, found on Mid-Ocean Ridges, on the Mid-Atlantic Ridge at 45°N for example, and, in this case, they appear to rise higher and higher away from the crestal regions (Figure 3). Serpentinized peridotites have been recovered from fracture zones in the Atlantic Ocean and elsewhere (Bonatti and Crane, 1984). But seismic velocities in serpentinized rocks are inappropriately low for them to be a major component of the ocean crust's Layer 3 or of the ocean lithosphere (Aumento and Loubat, 1971; Christensen, 1972; LADLE, 1983).

Serpentinized seamounts were found by dredging topographic highs at the break between the trench and slope of the fore-arc area of the Mariana Arc in the western Pacific (Bloomer, 1983; Bloomer and Hawkins, 1983; Evans and Hawkins, 1979; Fryer *et al.*, 1985; Fryer and Fryer, 1987; Ishii, 1985). Leg 125 of the Ocean Drilling Program has just finished drilling these seamounts, with Patty Fryer and Julian Pearce as Co-chief Scientists. If serpentinites don't dominate the ocean crust, where does so much serpentine come from? And indeed, where does the water for serpentinization itself come from?

¹ Geological Survey of Canada Contribution No 22089

Box 1 What is serpentine?

The Shorter Oxford English Dictionary:

"Serpentine ... A rock or mineral, consisting mainly of hydrous magnesium silicate, of a dull green colour with markings resembling those of a serpent's skin. ..."

Mineralogy (Deer et al., 1969, p. 242):

Sheet silicates

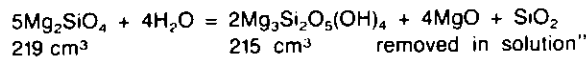
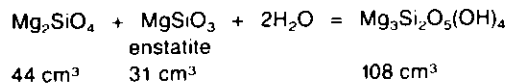
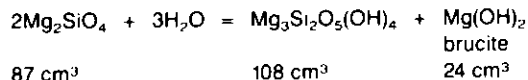
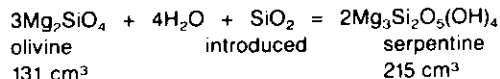
Serpentine $Mg_3[Si_2O_5](OH)_4$ Monoclinic

Chrysotile, Lizardite, Antigorite

Densities less than or equal to about 2.55

Origin: 20th Century (Best, 1982, p. 398):

"There has been a good deal of uncertainty and resulting controversy regarding the specific hydration reaction involved in serpentinization. Four possible reactions involving chiefly olivine are as follows:



See also Aumento (1970) and Coleman (1971). MacDonald and Fyfe (1985), and Fyfe (1988) discuss the significance of the volume expansion and the exothermic nature of serpentinization in terms of permeabilities, rates of reactions and stresses.

Origin: 19th Century (Leconte, 1882, p. 214):

"Serpentine is a compact, greenish magnesian rock. ... The origin of serpentine is not well understood; but it is evidently a changed magnesian clay. All gradations between such clays and serpentine may be found in the Tertiary and Cretaceous strata of the Coast Range of California."

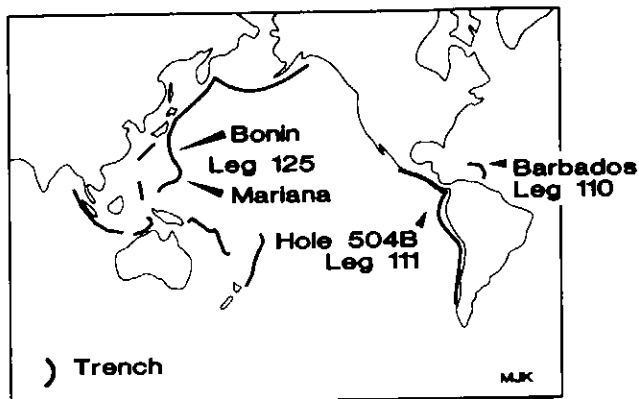
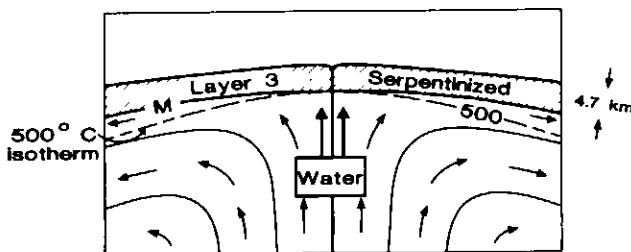


Figure 1 Location diagram. Leg 110 of the Ocean Drilling Program occupied sites on the Barbados Ridge complex and adjacent ocean floor in the region of the convergent boundary between the Atlantic Plate and the Caribbean Plate. Leg 125 occupied sites on the convergent boundary between the Pacific Plate and the Philippine Plate. The figure also shows the sites of most of the world's oceanic trenches.



Ocean crust as serpentinized mantle
Hess's ideas of 1962

Figure 2 Hess proposed that the ocean crust formed by serpentinization of mantle rocks when temperatures fell sufficiently. The original caption read: "Diagram to portray highest elevation that 500 degree C isotherm can reach over the rising limb of a mantle convection cell, and expulsion of water from mantle which produces serpentinization above the 500 degree C isotherm". (Redrawn from Hess, 1962, fig. 6).

Box 2 Serpentine, mid-ocean ridges and trenches

"Mid-ocean ridges ... are interpreted as representing the rising limbs of mantle-convection cells. ... Convective flow comes right through to the surface, and the oceanic crust is formed by hydration of mantle material starting at a level 5 km below the sea floor. The water to produce serpentine of the ocean crust comes from the mantle at a rate consistent with a gradual evolution of ocean water over 4 aeons. Ocean ridges are ephemeral features as are the convection cells that produce them. An ancient trans-Pacific ridge from the Mariana Islands to Chile started to disappear 100 million years ago. Its trace is now evident only in a belt of atolls and guyots which have subsided 1-2 km. ..."

(Hess, 1962)

"The crustal layer goes down with the descending limb of the convection cell until it reaches a temperature in the neighborhood of 500°C where a deserpentinization reaction takes place, releasing water ... Fluids, magma or water, rise, migrating toward the island arc or concave side of the structure ... [where] there will be a tendency for open fractures to form at right angles to the direction of compression (at right angles to the trench axis ..."

(Fisher and Hess, 1963, p. 430)

What are these serpentinite seamounts?

Normal seamounts, the regular kind of seamounts, are volcanic edifices, perhaps coral-capped, or perhaps planed off, transported and sunk and now guyots. Hess mapped these sorts of seamounts during World War II and pointed out in his 1962 paper that the region of abundant guyots ends abruptly "... against the eastern margin of the island-arc structures. Not a single guyot is found in the Philippine Sea west of the Mariana trench and its extensions, although to the east they are abundant right up to the trenches." Fryer and Smoot (1985) argue persuasively that subduction eats up these sorts of seamounts, and that many are being swallowed at the Mariana Trench (Figures 4 and 5). The serpentinite seamounts are different. They are found west of the trenches, as parts of the Mariana and Izu-Bonin arc-trench systems. Many have been discovered on the outer-arc high of the Mariana forearc, about 100 km west of the trench

axis on its concave (or "landward") side (Figure 5).

The Mariana Arc is a fine example of an arc-trench system formed wholly within oceanic plates, with active back-arc spreading (see Uyeda, 1982). The system is formed from the trench, forearc, island arc, and spreading backarc basin, with the Pacific slab dipping nearly vertically beneath the trench (Figures 4 and 5). Old crust, so perhaps cold crust, is being subducted, fast: the age of the crust is about 160 million years, and the rate of subduction is about 8 cm·yr⁻¹.

These seamounts are large, some 30 km in diameter, and 2 km high. They aren't very dense — gravity observations suggest values of 2.2-2.3 gm·cm⁻³ (Newsom and Fryer, 1987), and measurements of the density of serpentinitized peridotites from a seamount nearby were 2.3-2.4 gm·cm⁻³ on average (Ishii, 1985). SeaMarc II images and sampling from the ALVIN submersible showed that the seamounts are largely ser-

pentine: serpentinite apparently flows down from a central conduit. Fryer *et al.* (1987) described the flows as a matrix of serpentinite, chlorite, clay and carbonate, with clasts of serpentinitized mafic and ultramafic rocks. The water vented from the seamounts is colder than ambient seawater (Haggerty, 1987). One of the authors of this paper (T. Ishii) has recently described similar rocks from forearc seamounts west of the Bonin Trench: "Dredged rocks include many pebbles covered with blue-green, soft sediment, consisting of serpentinite muds. The appearance of the sediments is very similar to serpentinite flows observed on ALVIN dives at the Mariana forearc ..." (Ishii *et al.*, in prep.).

The 1882 text-book quoted in Box 1 which called serpentinite a "changed magnesian clay" doesn't seem so curious after this (see Box 3).

Leg 125 of the Ocean Drilling Program drilled these serpentinite seamounts: "Serpentinitized peridotite and metamorphosed mafic rocks were recovered as clasts entrained within a serpentine matrix in drill holes into the flanks and summit of the serpentinite seamounts that are located within 100 km of the trench in the Mariana and Izu-Bonin forearcs ..." (Fryer *et al.*, 1989a). The "basement" into which the serpentinite diapirs intruded has been sampled by dredging in grabens near the seamounts; basalts and gabbros dominate, but boninites (the Bonin Trench is nearby to the north) and andesites were found in small quantities (Johnson *et al.*, 1987; see Figure 6).

Where does the water come from?

Fisher and Hess (1963) pointed out that serpentinitized ocean crust would lose its water on descent at a trench, which would rise into the overlying rocks of the island-arc system. Vents have indeed been observed at the walls of trenches. Unlike the situation with hydrothermal systems of mid-ocean ridges, the water does not have to be circulating local seawater. Water can be transported in

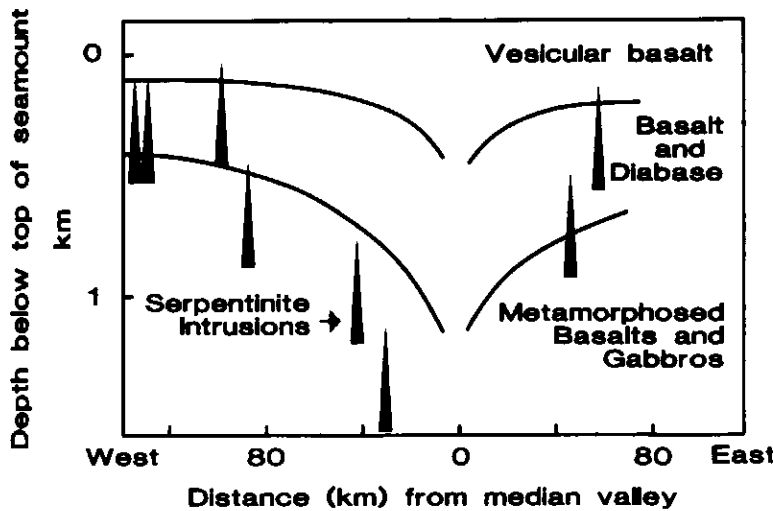


Figure 3 Serpentinite intrusions appear to rise higher with distance from the axis of the Mid-Atlantic Ridge. The original caption read in part: "A plot of the depth below the top of the nearest seamount for those locations yielding serpentinite against distance from the axis of the Ridge. The plots are superimposed on the probable layering of the crust prior to block faulting as observed by Barratt and Aumento (1970)." (Redrawn from Aumento and Loubat, 1971, fig. 2).

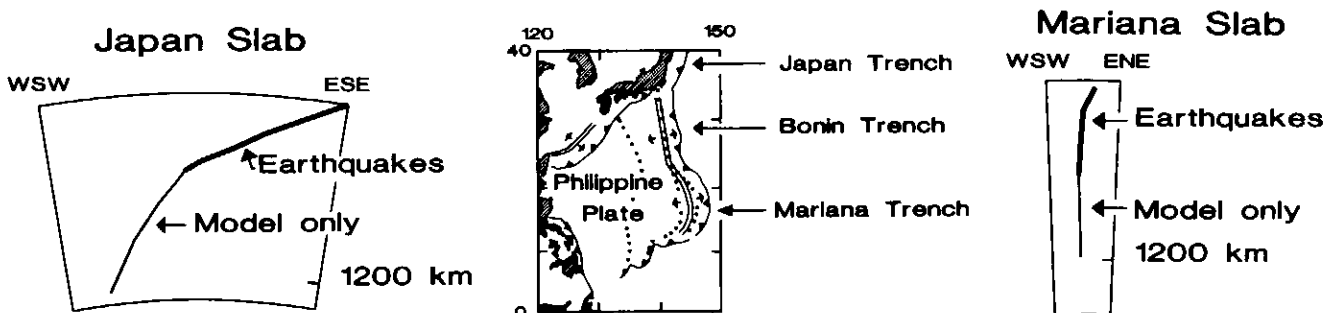


Figure 4 The Mariana and the Bonin Trenches are the eastern boundaries to the Philippine Plate. The centre panel shows the major tectonic elements: underthrusting and trench axes - solid lines with barbs; spreading axes - double lines and arrows; ridges - dots. (This has been re-drawn, greatly simplified, from Karig and Rankin, 1983, fig. 1). The left and right panels show the difference between the down-going slabs of the Japan and Mariana convergences — the Mariana slab dips nearly vertically. Note that there is no vertical exaggeration. The upper part of the down-going slabs, shown in heavy line, are well-defined by earthquakes; the lower part of the slabs, shown as lighter line, are interpretations from travel-time residuals (Creager and Jordan, 1986). Note the discussion concerning this - it bears on mantle convection (Frohlich, 1989). (These panels have been re-drawn, greatly simplified, from Creager and Jordan, 1986, fig. 5).

the sediments of the ocean floors, and in hydrated products of igneous rocks of the ocean crust — such as serpentinites. It will be released with de-watering at island-arcs, as a result of the compaction of sediments and the heating of hydrous minerals such as serpentinites. We see this at Barbados (Leg 110), and at the Marianas (Leg 125).

Leg 110 of the Ocean Drilling Program drilled sites in the Lesser Antilles Forearc (Figures 1 and 7). This work suggested that within modern subduction settings fluids are transported from greater than 25 km down the décollement surface (Moore *et al.*, 1987). Within the Barbados accretionary prism fluid sources from sediment consolidation are initially small on account of very low matrix permeabilities; only after the formation of faults and the concomitant increase in fracture permeability as the accretionary process evolves do sediments significantly de-water and supply fluids to the system (see Brown and Westbrook, 1988; Moore, 1989). The pore waters collected in Leg 125 from the serpentine seamounts are chemically different from normal seawater too (Fryer *et al.*, 1989a,b). Consequently it seems that at subduction settings fluids may

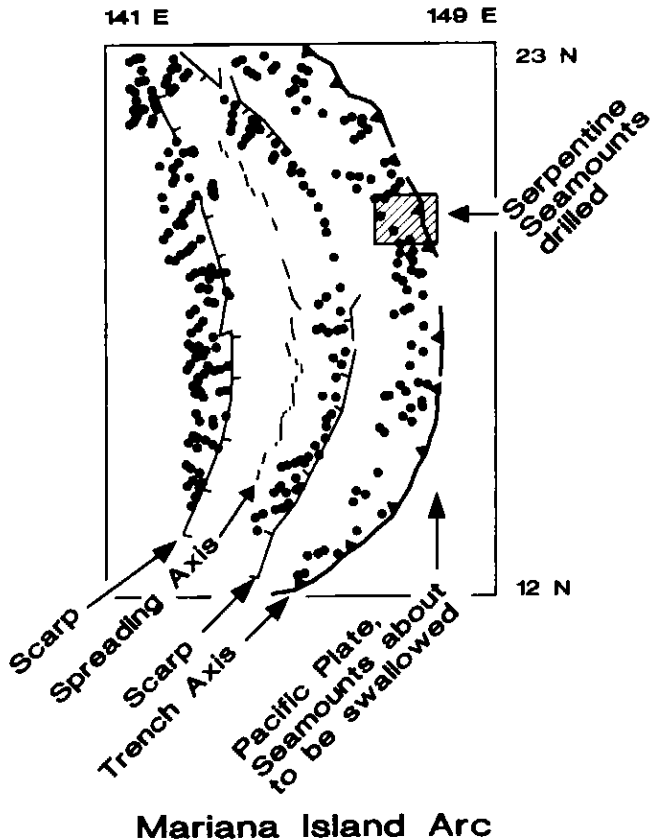


Figure 5 Major features of the outer part of the Mariana Island Arc. The dots represent seamounts and islands within the Arc itself. Seamounts on the Pacific Plate to the east are not shown. The area of Figure 6 is shown inset. (Re-drawn, greatly simplified, from Fryer *et al.*, 1985, fig. 1).

Box 3 Serpentinites and the Ocean Drilling Program — Mariana and Izu-Bonin Trenches

“Within serpentinites we observed pebbly serpentinite muds with and without convolute lamination and serpentinite breccias. Many of these layers bear larger blocks, mostly of serpentinite; Overlying claystones have de-watering structures.

“The principal results can be summarized as: the confirmation that forearc seamounts can be constructed from serpentinite flows emanating from a central diapir; the evidence from clasts that low to medium-grade metamorphism characterizes the source region of the serpentinite diapirs; and the evidence from water chemistry that dehydration of the subducted lithosphere may have played an important role in the serpentinization of the source region of the serpentinite diapirs.”

Lynn Johnson, Hawaii Institute of Geophysics
Leg 125, Ocean Drilling Program

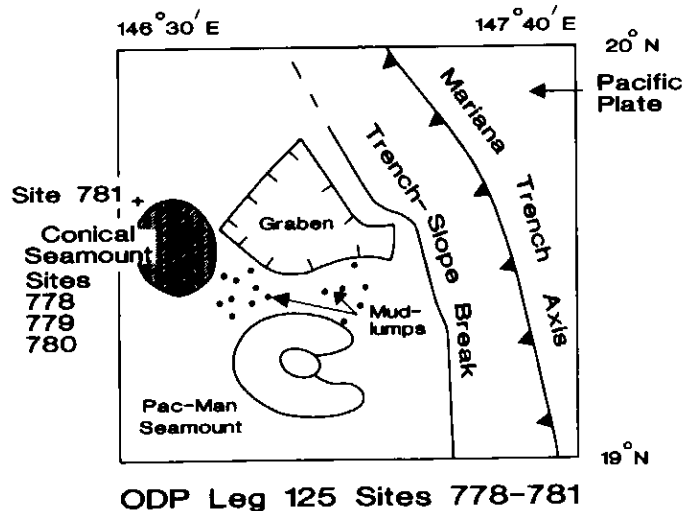


Figure 6 Drilling by Leg 125 on and near Conical Seamount, west of the trench-slope break of the Mariana Arc (Re-drawn - simplified and with additions - from Fryer and Fryer, 1987, fig. 3)

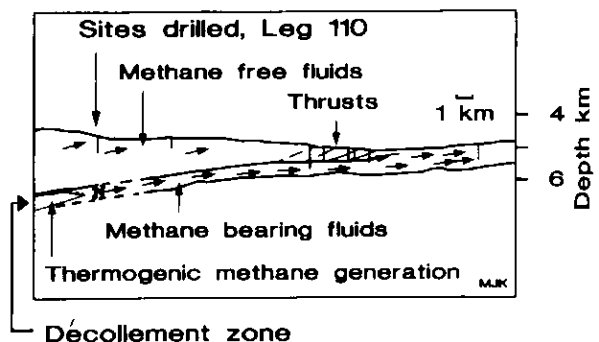


Figure 7 Fluids and the Barbados Subduction Zone the hydrogeological framework of the Leg 110 area. Arrows show the directions of fluid flow (Re-drawn, simplified, from Moore *et al.*, 1987, fig. 2b)

migrate upward from deep sources and contribute to diapiric formation — like the mud volcanos at Barbados, and the serpentinite seamounts at the Mariana Arc. Free pore waters blocked by impermeable barriers may form seismically reflective zones — as R.D. Hyndman has suggested that we observe in the deep seismic studies of LITHOPROBE beneath Vancouver Island (Hyndman, 1988).

These serpentinite seamounts appear to be part of a larger global water cycle. Seawater is incorporated in the ocean crust beneath mid-ocean ridges, where it penetrates to depths of many kilometres, and serpentinites are among the many hydration products (see MacDonald and Fyfe, 1985; Muelenbachs and Clayton, 1976; Wenner and Taylor, 1973). Seawater is also incorporated into the sediments of the ocean floor. Some of this water, at least, is returned to the atmosphere and oceans at subduction zones by de-watering, and some must descend into the mantle with the down-going slab. Muelenbachs and Clayton (1976) suggested that the present volume of the oceans might cycle through the mantle in about 1 billion years.

The ascent of the serpentinite diapirs

The down-going slab releases water as any sediments subducted are squeezed and as the hydrous minerals of the igneous complex are heated (see Hyndman, 1988). The rising water hydrates the overlying mantle wedge if the temperature is right and if permeability allows, and serpentinitized blobs rise diapirically.

The concept is very much like Hess' original idea, only at a subduction zone, not at a mid-ocean ridge. Fryer *et al.* (1985) suggested that the serpentinitization takes place within 70 to 150 km of the trench axis, toward the arc. Temperatures in the forearc wedge will be too cool outside that region, toward the trench, and too hot outside the region, toward the arc. The process cannot be simple — Saboda *et al.* (1987) point out that the ultramafic rocks of the seamounts reflect "a history of multiple metamorphic events", and Fryer *et al.* (1988a) tell us that both seawater and a deep source of water can be distinguished in the Mariana serpentinite seamounts.

Serpentinite seamounts and Appalachian ophiolites

Many of the Appalachians' ophiolites may have formed as parts of island-arc complexes with the convergence of ancient plates (see e.g., Williams and Talkington, 1977). The setting of the Troodos ophiolite in Cyprus appears to be similar to the Mariana and Bonin Arcs of today (Gibson *et al.*, 1987; Mehegan, 1988; Robinson *et al.*, 1983). What would the remnants of serpentinite seamounts of modern ocean basins look like in an ophiolite? Would they become the mélanges of western Newfoundland?

Box 4 Serpentine and Quebec's Quiet Revolution

"The mining of asbestos in the Eastern townships of Quebec commenced in 1876 ... The asbestos occurs in certain serpentine masses, usually of small area ... The serpentine ... has been derived from the alteration of peridotites that, with possibly one exception, appear to be of Ordovician age ... The asbestos is of the chrysotile variety, and occurs in gash veins ... The fibres of the mineral usually stand at right angles to the side walls of the veins, and sometimes extend completely across, but often there is, towards the centre, a film of chromite or magnetite. ... The asbestos veins are invariably accompanied on both sides by bands of pure serpentine that grade into less altered peridotite."

(Young, 1909)

"Asbestos ... The Romans used asbestos cloth for wrapping the dead for cremation over 2000 years ago ... Canada, the world's second-largest producer of asbestos, accounted in 1980 for about 25% of world production ... Past high-level exposure to airborne asbestos dust in the work place has been a health hazard ..."

(Dubois and Mailhot, 1985)

"Asbestos strike began 14 February 1949 and for the next 4 months paralysed major asbestos mines in Québec ... The strike became a historical and political event of symbolic import that ... presaged the QUIET REVOLUTION."

(David, 1985)

"Where was Pierre Trudeau, this 14 February? Somewhere in the world, in Europe or in Asia. Anyway, a long way off. He will come back only in the spring. He will visit the striking workers on the picket line at Asbestos with us. He will say some words to the miners. He will meet Jean Marchand. We will both be arrested by the Québec Sûreté, which will lead to wild scenes ..."

(Pelletier, 1983, p. 33)

All this because of a hydrous magnesium silicate, of a dull green colour with markings resembling those of a serpent's skin.

All because of — serpentine.

J.P. Lockwood forecast serpentinite seamounts in his studies of "alpine type" ultramafic rocks. "The sources of [this] serpentinite debris are postulated to be upward-migrating serpentinite intrusions which penetrate the sea floor or Earth's surface ..." (Lockwood, 1971, p. 919). Serpentinization within the ophiolites now found on land appears to be a different event from serpentinization within ocean crust. Meteoric water — crustal water — appears to have caused the former, and seawater the latter (Muelenbachs and Clayton, 1976; Wenner and Taylor, 1973). Consequently, if the serpentinite-rich sediments associated with ophiolites were shed from the serpentinite seamounts of the time, perhaps focussed geological or isotopic studies could differentiate between the sources of water in these serpentinite-rich sediments and those of the ultramafic bodies of the ophiolites themselves.

Serpentines of Appalachian ophiolites provide the chrysotile for the asbestos mines of the Eastern Townships of Quebec and of Newfoundland (Box 1). Miners struck the mines of Quebec in 1949 — "La Grève des Amiantes" — (Box 4), and so serpentine played an unwitting role in our Canadian political evolution. Jean Marchand, Gérard Pelletier and Pierre Elliott Trudeau were all three occupied in La Grève des Amiantes in 1949, one of the ushers to Quebec's Quiet Revolution.

Acknowledgements

We really appreciate the helpful comments of Kate Moran and Roy Hyndman, Geological Survey of Canada, Rebecca Jamieson and Sean Willett, Dalhousie University, Fred Wicks and Dave O'Hanley, Royal Ontario Museum, Karl Muelenbachs, University of Alberta, Ward Neale, Calgary, and Bill Fyfe, University of Western Ontario.

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Accepted, as revised, 15 June 1989.