

Serpentinization of peridotites from the southern Mariana forearc

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Received 28 February 2009; received in revised form 7 April 2009; accepted 20 April 2009

Abstract

A detailed petrologic and mineralogic study was carried out on serpentinized peridotites dredged from the southern landward slopes of the Mariana Trench, in order to reveal the serpentinization process of these unusual rocks and to identify the sole presence of the mineral lizardite. The constituent minerals of these southern Mariana forearc peridotites are olivine, amphibole and spinel, as well as serpentine, chlorite and talc. Compared with serpentinite seamounts, the serpentinized peridotites from the southern Mariana forearc are characterized by the absence of magnetite and brucite, and the common presence of talc; besides, the serpentine mineral variety is simplex, only lizardite. Combining mineral chemistry and mineral phase relationships, we conclude that (1) the absence of magnetite in the serpentinized peridotites is due to incomplete serpentinization, other than magnetite, the iron end-member in olivine forms Fe-rich brucite and Fe-rich serpentine; (2) brucite is not stable with high silica activity, reacting with later SiO₂-rich fluid and then forming lizardite, leading to a lack of brucite in these serpentinized peridotites; (3) the occurrence of talc is the result of later SiO₂-rich fluid reactions with lizardite; and (4) the reason for the sole occurrence of lizardite is that the temperature condition of our study area was not high enough for the formation of antigorite (which is stable at >500 °C). Despite the broad overlap of lizardite and chrysotile in growth temperature, differences in the modes of occurrence of lizardite and chrysotile, such as the scarcity of H₂O, low porosity and permeability, as well as the actual situation of initial serpentinization in the study area, result in the absolute prevalence of lizardite over chrysotile in the area.

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Keywords: Peridotite; Serpentinization; Mineral chemistry; Lizardite; Mariana

1. Introduction

Serpentinization is an important and ubiquitous process in subducted zones [1,2]. Besides causing changes of rheology and density of mantle rocks [3], serpentinization also influences other characteristic petrophysical properties such as magnetic susceptibility and seismic velocities [1,4]. Serpentinization also is believed to play an important role in geochemical budgets of the oceans [5,6] and may have important consequences for microbial processes [7,8]. Serpentinization is an important post-magmatic process, which is prevalent in the southern Mariana forearc peridotites.

Thus, a comprehensive and systemic understanding of the geologic processes that affect peridotites is needed to reveal the serpentinization process within the forearc mantle wedge. In addition, this information may help to elucidate the origin of the Mariana forearc serpentinite seamounts.

Serpentinized peridotites were dredged, drilled and sampled by submersibles at many locations in the Izu–Bonin–Mariana (IBM) arc system. The obtained samples were analyzed for serpentinite seamount petrography [9], trace elements [10], pore water [11] and serpentinization [12]. Peridotites from landward slopes of the trench are limited. Such analyses have only focused on petrography, mineralogy [13–15] and microstructures [16]. The peridotites from the landward slopes of the Mariana Trench have experienced some serpentinization. The character of this serpent-

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inization is obviously different from Mariana forearc serpentinite seamounts [12], in that they contain no magnetite and brucite, and lizardite is the only serpentine mineral within them. Until recently, however, research on the elementary character of serpentinization of peridotites from the landward slopes of the Mariana Trench was lacking. Furthermore, there was no clear understanding of either the serpentinization process or the reason for the formation of the particular mineral assemblage.

The present paper aims to reveal the elementary character of serpentinization of peridotites from landward slopes of the Mariana Trench, to illuminate the serpentinization process within the study area, and to elucidate the formation mechanism for the particular mineral assemblage in the serpentinized peridotites from the landward slopes of the Mariana Trench. Hence, this approach provides a comprehensive and systemic investigation of the serpentinization process of the southern Mariana forearc peridotites.

2. Geological outline and sample locations

The Izu–Bonin–Mariana (IBM) arc system can be divided into two segments based on its morphology (Fig. 1): the Izu–Bonin segment (north of 24°N) with linear shape and the Mariana segment (south of 24°N) with lunular shape [15]. The Mariana Trench marks the location where the Pacific Plate subducts beneath the eastern edge of the Philippine Sea Plate [16]. The subduction is thought to have begun about 43 Myr [17]. The Challenger Deep,

part of the southern Mariana Trench southwest of Guam, is the deepest oceanic trench in the world and is up to 2 km deeper than the average depth along the axis of the Mariana Trench [18–20]. The Kyushu–Palau Ridge and West Mariana Ridge are remnant arcs separated by the Parece Vela Basin. The active arc is separated from the West Mariana Ridge by an active back-arc basin, the Mariana Trough [13]. There is a well-developed forearc along the trench north of 13°N. The Mariana forearc comprises a region between the trench axis and the active volcanic arc (~200 km wide and 1500 km long). The Mariana Trench lacks an accreted sedimentary prism [21,22] and consists mainly of mafic and ultramafic igneous rocks that are typical of island arc ophiolites [23]. The central Mariana forearc (15°–20°N) has a chain of prominent bathymetric highs (seamounts) along the trench slope that are roughly conical and often slightly elongated subparallel to the trench [24,25].

Peridotite samples studied in the present paper were collected from a dredge haul (KH03-3-D8) from the research vessel (R/V) Hakuho of the University of Tokyo on the cruise KH03-3 in 2003 on the landward trench slope, near 11.8°N of the Mariana Trench (Fig. 1). The sampling depth was 4200–3500 m. In addition to the peridotites, basalts and pyroxenites also were dredged from station KH03-3-D8.

3. Petrography

The peridotite samples have experienced some serpentinization. In addition, the peridotites show marine weathering appearance. The main constituent minerals of these peridotites are olivine, amphibole and spinel, as well as serpentine, chlorite and talc. Olivine grains are generally partially replaced by serpentine minerals, leading to mesh texture with cores of relict olivine and rims of serpentine (Fig. 2a). The relict olivine cores were further replaced by serpentine minerals in some of the highly serpentinized samples. Spinel (herein spinel-group minerals) are commonly dark and opaque in these Mariana forearc peridotites. They usually have cracked textures, and some spinel grains are dispersed into small fine-grained assemblages (Fig. 2b). Chlorite often is found near spinel (Fig. 2c). In addition, fine spinel grains also occur in some veins (Fig. 2d). Amphibole can be divided into two types according to their crystalline morphology. One type is columnar-shaped, and serpentinization of amphibole often proceeds along the cleavage and fissure of the grain (Fig. 2e). The other type is needle-shaped, generally cuts through the olivine grain with mesh texture (Fig. 2f), which indicates that this amphibole is secondary (forms post-serpentinization). Serpentine has several kinds of occurrences such as occurring: (1) as rims of olivine in the mesh texture; (2) in the core of the mesh texture in some highly serpentinized samples (such as D8-5); (3) in the cleavage and fissure of amphibole grains; or (4) as serpentine veins. Chlorite often occurs around spinels (Fig. 2c), replacing serpentine

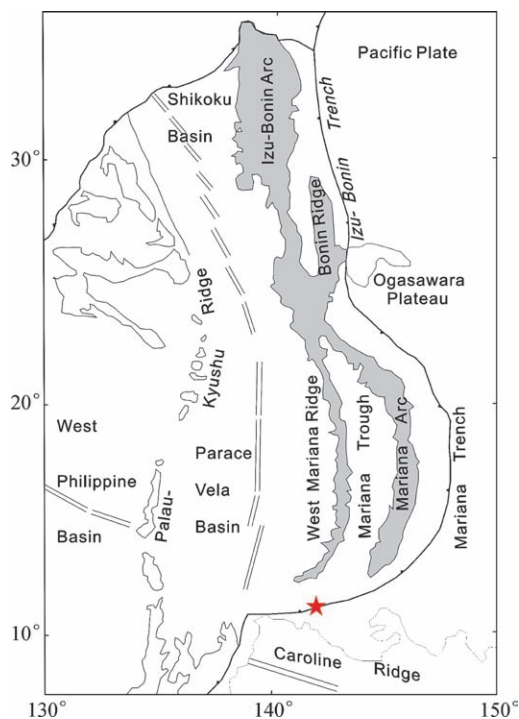


Fig. 1. Geologic sketch map of the Izu–Bonin–Mariana arc system, showing the distribution of major seafloor features. Revised from Stern et al. [17]. The red star refers to the sampling location.

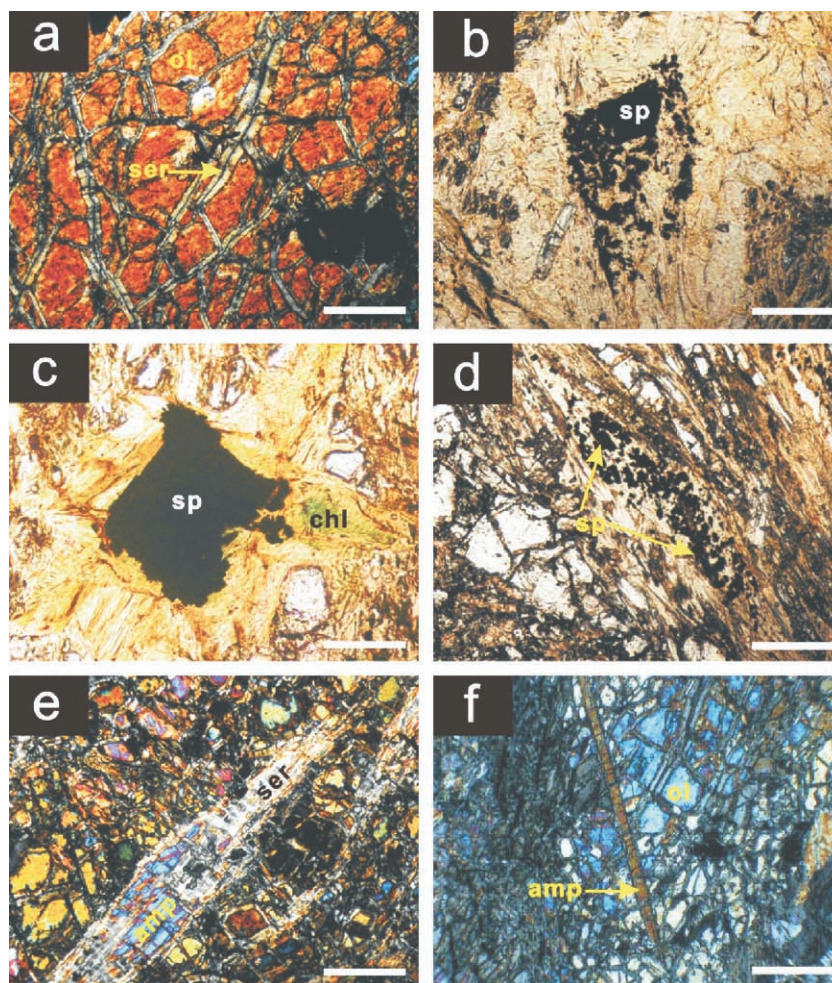


Fig. 2. Photomicrographs showing the main textures and minerals of serpentinized peridotites from the southern Mariana forearc. (a) Mesh texture with cores of relict olivine (ol) and rims of serpentine (ser); (b) dark spinel (sp) dispersed into small fine grains; (c) euhedral cubic spinel (sp) with chlorite (chl) nearby; (d) fine spinel (sp) grain assemblages occur in veins; (e) partially serpentinized amphibole (amp); and (f) needle-shaped amphibole (amp), cutting through the olivine (ol) grain with mesh texture. Scale bars = 0.2 mm.

and also is found as veins. Talc generally replaces serpentine, occurring in a mesh texture, and may be present as veins.

4. Mineral chemistry

Mineral chemical analyses were carried out using a JXA-8100 electron microprobe housed at the Institute of Geology and Geophysics, Chinese Academy of Sciences, operating at an accelerating voltage of 15 kV, beam current of 20 nA and using a 1- μ m beam. Representative analyses results are reported in Tables 1–3.

4.1. Olivine

Olivine showed mesh textures after alteration, and serpentine fills within the mesh vein. Representative analyses are reported in Table 1. Olivine in the southern Mariana forearc peridotites was forsterite with relatively uniform $Mg^{\#}$, between 0.91 and 0.92. MnO contents were less than 0.16 wt.%. MnO and FeO contents were generally posi-

tively correlated. NiO contents were 0.31–0.44 wt.%. All olivine analyzed were lacking in Ca, Cr and Al.

4.2. Amphibole

Three different kinds of amphibole were classified based on chemical composition (Table 1) and using nomenclature from Leake et al. [26]. Two kinds belong to Ca-rich amphibole, which has relatively high CaO content, and are defined as monoclinic amphiboles in which $(Ca + Na)_B > 1.00$ and $Na_B = 0.50$ –1.50. The value for Ca_B usually was >1.50 . According to the value of $(Na + K)_A$, Si in formula and $Mg^{\#}$, these minerals can further be divided into tremolite and magnesiohornblende. The third kind of amphibole was cummingtonite, in which $(Ca + Na)_B < 1.00$, $Mg^{\#} > 0.5$, and the mineral belongs to the monoclinic crystalline form, which shows inclined extinction under polarized light microscopy. The two former amphiboles are usually serpentinized, since serpentinization always proceeds along the cleavage and fissure of the amphibole grains. The third kind of amphibole formed post-serpenti-

Table 1
Representative electron microprobe chemical analyses of olivine, amphibole and spinel.

	Olivine		Amphibole			Cummingtonite			Spinel	
			Tremolite	Magnesiohornblende				Core	Rim	
SiO ₂	41.48	41.19	56.54	55.84	52.80	53.28	59.06	59.10	0.00	0.00
TiO ₂	0.00	0.01	0.03	0.05	0.01	0.00	0.00	0.01	0.10	0.30
Al ₂ O ₃	0.00	0.00	1.31	1.76	5.44	4.16	0.15	0.11	11.11	6.63
FeO	8.45	8.01	1.86	2.05	2.19	2.26	6.68	7.22	34.52	42.47
MnO	0.11	0.09	0.05	0.02	0.00	0.05	0.24	0.22	0.48	0.51
MgO	50.04	49.69	22.88	22.82	21.88	23.21	29.71	29.22	6.93	5.38
CaO	0.00	0.01	12.97	12.40	13.43	11.16	0.64	0.66	0.00	0.00
Na ₂ O	0.02	0.00	0.51	0.57	0.75	1.47	0.13	0.12	0.01	0.05
K ₂ O	0.00	0.00	0.00	0.03	0.00	0.00	0.01	0.00	0.00	0.00
Cr ₂ O ₃	0.00	0.00	0.18	0.32	0.87	0.35	0.00	0.03	45.15	41.70
NiO	0.30	0.44	0.04	0.08	0.00	0.03	0.06	0.13	0.12	0.24
Total	100.39	99.43	96.37	95.96	97.35	95.97	96.68	96.82	98.41	97.28
Oxygen atoms	O = 4	O = 4	O = 23	O = 23	O = 23	O = 23	O = 23	O = 23	O = 4	O = 4
Si	1.01	1.01	7.84	7.79	7.33	7.46	8.02	8.04	0.00	0.00
Ti	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.01
Al	0.00	0.00	0.21	0.29	0.89	0.69	0.02	0.02	0.44	0.28
Fe ²⁺	0.17	0.16	0.22	0.24	0.25	0.26	0.76	0.82	0.63	0.70
Fe ³⁺	–	–	–	–	–	–	–	–	0.34	0.55
Mn	0.00	0.00	0.01	0.00	0.00	0.01	0.03	0.03	0.01	0.02
Mg	1.81	1.81	4.73	4.74	4.53	4.84	6.02	5.92	0.35	0.28
Ca	0.00	0.00	1.93	1.85	2.00	1.67	0.09	0.10	0.00	0.00
Na	0.00	0.00	0.14	0.15	0.20	0.40	0.03	0.03	0.00	0.00
K	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Cr	0.00	0.00	0.02	0.04	0.10	0.04	0.00	0.00	1.21	1.16
Ni	0.01	0.01	0.00	0.01	0.00	0.00	0.01	0.01	0.00	0.01
Total cation	2.99	2.99	15.11	15.13	15.29	15.38	14.98	14.97	3.00	3.00
Mg [#]	0.91	0.92	0.96	0.95	0.95	0.95	0.89	0.88	0.36	0.29
Cr [#]	–	–	–	–	–	–	–	–	0.73	0.81

Mg[#] = Mg/(Mg + Fe²⁺) and Cr[#] = Cr/(Cr + Fe³⁺).

nization, and generally cuts through the olivine grain with mesh texture. There were obvious chemical composition differences between the two former amphiboles and the third amphibole. Tremolite and magnesiohornblende had relatively high CaO contents, up to 11–13.5 wt.%, while cummingtonite had relatively high FeO, MnO and MgO contents, which were 6.6–7.3 wt.%, 0.2–0.25 wt.% and 29–30 wt.%, respectively. In addition, Mg[#] in cummingtonite (0.88–0.89) was obviously lower than that of tremolite and magnesiohornblende (0.95–0.96).

4.3. Spinel

Table 1 lists the representative analysis results of the cores and rims of spinels. Compared with the spinel cores, the spinel rims were enriched in Fe but were deficient in Al, Mg and Cr.

4.4. Chlorite

Based on its character under polarized light, chlorite could be divided into three types: I occurred around spinels; II replaced serpentine and occurred in the vein of the mesh texture and III occurred as chlorite veins. The chemical compositions of these three different chlo-

rite occurrences were uniform, Mg[#] ranged between 0.92 and 0.95, and the FeO content was within 2.97–4.8 wt.%. The MgO content ranged between 31.1 and 32.39 wt.%. The range of Al₂O₃ content was 13.35–15.43 wt.%. The contents of Cr₂O₃ and NiO were 1.5–2.46 wt.% and 0.11–0.27 wt.%, respectively. The contents of TiO₂, MnO, CaO, Na₂O and K₂O were less than 0.07 wt.% (Table 2).

4.5. Serpentine

Based on X-ray powder diffraction (XRD) analyses, lizardite was the only serpentine mineral present in our serpentinized peridotites, which had the following occurrences: I in the mesh texture, replacing olivine; II replacing amphibole in the cleavage and fissures of the grains and III as serpentine veins. Mg[#] ranged between 0.85 and 0.94. The CaO (0.17–0.36 wt.%), Na₂O (0.29–0.41 wt.%) and Cr₂O₃ (0.11–0.15 wt.%) contents of serpentine type II were higher than those in the other type of serpentine. Such elements were probably supplied from breakdown of amphibole. The chemical compositions of type I and III serpentines were uniform, although the latter was more enriched in Si than the former (Table 3).

Table 2
Representative electron microprobe chemical analyses of chlorite.

	I		II		III	
SiO ₂	31.50	31.81	32.11	31.99	31.67	32.40
TiO ₂	0.02	0.02	0.04	0.03	0.02	0.00
Al ₂ O ₃	15.43	14.27	13.35	14.27	15.16	14.00
FeO	3.32	2.97	4.80	4.34	4.14	3.43
MnO	0.00	0.06	0.02	0.03	0.01	0.02
MgO	31.50	32.10	31.41	32.39	32.22	32.12
CaO	0.00	0.01	0.04	0.02	0.04	0.02
Na ₂ O	0.03	0.05	0.03	0.07	0.01	0.03
K ₂ O	0.00	0.00	0.00	0.01	0.01	0.01
Cr ₂ O ₃	1.87	2.40	2.46	1.50	2.23	2.13
NiO	0.27	0.15	0.11	0.21	0.12	0.19
Total	83.94	83.82	84.36	84.87	85.62	84.36
Oxygen atoms	O = 14	O = 14	O = 14	O = 14	O = 14	O = 14
Si	3.09	3.13	3.17	3.13	3.07	3.17
Ti	0.00	0.00	0.00	0.00	0.00	0.00
Al	1.79	1.65	1.55	1.64	1.73	1.61
Fe	0.27	0.24	0.40	0.36	0.34	0.28
Mn	0.00	0.00	0.00	0.00	0.00	0.00
Mg	4.61	4.71	4.62	4.72	4.65	4.69
Ca	0.00	0.00	0.00	0.00	0.00	0.00
Na	0.01	0.01	0.01	0.01	0.00	0.01
K	0.00	0.00	0.00	0.00	0.00	0.00
Cr	0.15	0.19	0.19	0.12	0.17	0.17
Ni	0.02	0.01	0.01	0.02	0.01	0.01
Total cation	9.94	9.95	9.96	10.00	9.98	9.94
Mg [#]	0.94	0.95	0.92	0.93	0.93	0.94

Mg[#] = Mg/(Mg + Fe²⁺) and Cr[#] = Cr/(Cr + Fe³⁺).

Table 3
Representative electron microprobe chemical analyses of serpentine.

	I		II		III	
SiO ₂	41.74	40.15	41.68	41.48	43.05	42.70
TiO ₂	0.00	0.01	0.01	0.00	0.02	0.00
Al ₂ O ₃	0.02	0.01	0.09	0.25	0.15	0.06
FeO	3.91	5.74	6.01	10.02	9.34	6.48
MnO	0.08	0.06	0.09	0.12	0.14	0.10
MgO	37.23	35.95	36.18	32.31	32.98	33.93
CaO	0.13	0.04	0.04	0.17	0.17	0.10
Na ₂ O	0.10	0.12	0.10	0.15	0.29	0.08
K ₂ O	0.08	0.02	0.05	0.03	0.04	0.01
Cr ₂ O ₃	0.01	0.06	0.06	0.03	0.11	0.03
NiO	0.30	0.23	0.18	0.39	0.20	0.18
Total	83.60	82.39	84.47	84.94	86.47	83.58
Oxygen atoms	O = 14	O = 14	O = 14	O = 14	O = 14	O = 14
Si	4.09	4.04	4.08	4.13	4.18	4.21
Ti	0.00	0.00	0.00	0.00	0.00	0.00
Al	0.00	0.00	0.01	0.03	0.02	0.01
Fe	0.32	0.48	0.49	0.83	0.76	0.53
Mn	0.01	0.01	0.01	0.01	0.01	0.01
Mg	5.44	5.39	5.28	4.79	4.77	4.99
Ca	0.01	0.00	0.00	0.02	0.02	0.01
Na	0.02	0.02	0.02	0.03	0.05	0.00
K	0.01	0.00	0.01	0.00	0.00	0.00
Cr	0.00	0.00	0.00	0.00	0.01	0.01
Ni	0.02	0.02	0.01	0.03	0.02	0.01
Total cation	9.92	9.97	9.92	9.87	9.84	9.79
Mg [#]	0.94	0.92	0.91	0.85	0.86	0.90

Mg[#] = Mg/(Mg + Fe²⁺) and Cr[#] = Cr/(Cr + Fe³⁺).

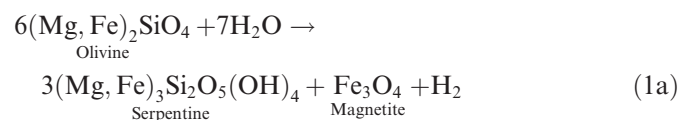
5. Discussion

5.1. Serpentinization process of southern Mariana forearc peridotite

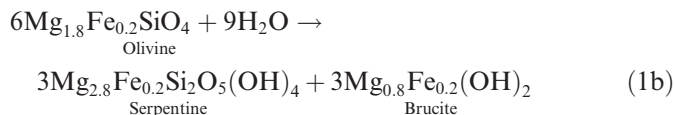
The southern Mariana forearc peridotites have experienced some serpentinization, and the main constituent minerals of the peridotites are olivine, amphibole and spinel, as well as serpentine, chlorite and talc. Magnetite and brucite, the common resultant minerals of serpentinization, are absent. Combining mineral chemistry with the observed relationship between mineral phases, the serpentinization process can be divided into the following stages (Fig. 3).

5.1.1. Stage I – alteration of olivine and amphibole

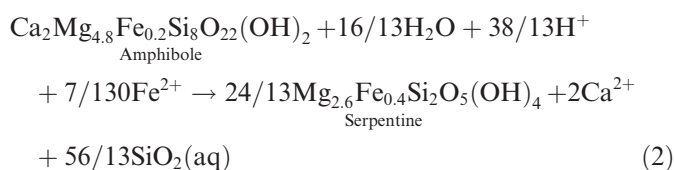
5.1.1.1. *Olivine.* Magnetite was ubiquitous in serpentinites and is the product of the serpentinization reaction of the iron end-member of olivine [27–29]. The commonly used reaction to describe the formation of magnetite is of Eq. (1a):



However, magnetite was absent in our peridotite samples. Toft et al. [30] suggested that Fe-bearing olivine produces Fe-rich brucite and Fe-rich serpentine at the initial serpentinization stage, and magnetite only occurs during the later serpentinization process. Bach et al. [31] studied serpentinized peridotites from the Atlantic and also suggested that magnetite is rare where serpentinization is incomplete. In the southern Mariana forearc peridotites, usually relic olivines are there in the core of mesh textures, indicating that serpentinization is incomplete. In addition, the serpentine that is produced by serpentinization of olivines usually has relatively high Fe content (Table 3). Thus, we infer that the absence of magnetite in the southern Mariana forearc peridotites is the result of incomplete serpentinization, where peridotites are still at the initial stage of serpentinization. Based on the chemical composition of olivine and serpentine (Tables 1 and 3), the reaction of olivine altered to serpentine can be described using Eq. (1b):



5.1.1.2. *Amphibole.* There is little research in the literature about amphibole serpentinization. Based on the chemical composition of amphibole, and its serpentinization resultant serpentine (Tables 1 and 3), we infer its reaction as Eq. (2), in which Fe^{2+} probably originates from olivine in proximity to amphibole. The alteration of amphibole releases Ca and SiO_2 .



5.1.2. Stage II – the further reaction of serpentine

In our samples, the formation of chlorite had a close association with serpentine. The further reaction of serpentine to form chlorite can be described by Eq. (3). Brucite that forms during serpentinization of olivine (see Eq. (1b)) further reacts with SiO_2 -rich fluid and then forms lizardite. This process can explain why brucite was lacking in the serpentinized peridotites. This process can be expressed using Eq. (4). The later SiO_2 -rich fluid reacts with serpentine, forming talc, following Eq. (5).

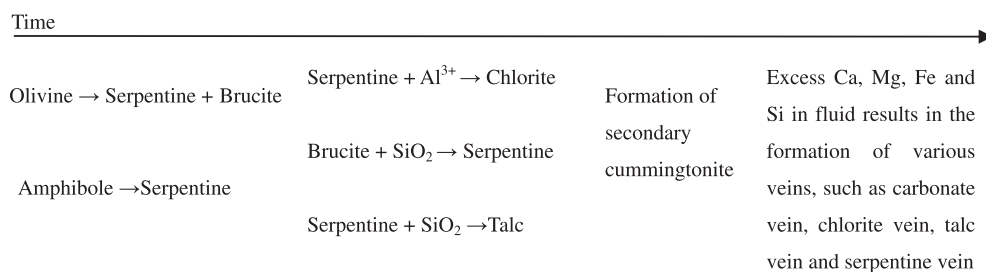
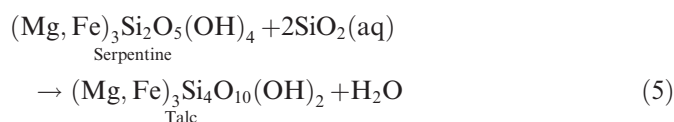
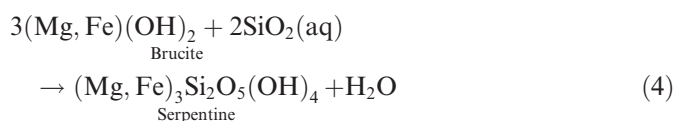
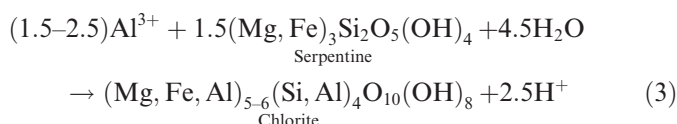


Fig. 3. Schematic of alteration process of the southern forearc Mariana peridotite.

5.1.3. Stage III – the formation of cummingtonite

We observed that cummingtonite grains cut through the olivine grains with mesh textures (Fig. 2f), indicating cummingtonite forms at the post-serpentinization stage. The formation of cummingtonite may indicate that the fluid is partially enriched in Fe and Mg.

5.1.4. Stage IV – the occurrence of later veins

There are four kinds of veins in the southern Mariana forearc serpentinized peridotites. They are chlorite, talc, serpentine and carbonate veins. The occurrence of the three former veins indicates that fluid is enriched in Mg, Fe and Si, and sometimes some fine chromite grains occur in these veins. The formation of carbonate veins is probably the result of later seawater infiltration.

5.2. Why lizardite is the only serpentine mineral present

X-ray powder diffraction (XRD) analyses showed that lizardite was the only serpentine mineral present in our samples (Fig. 4), without chrysotile and antigorite. Based on the experimental study of the MgO–SiO₂–H₂O system, it is generally thought that antigorite is stable at high temperatures (up to 500 °C) [32,33], while lizardite and chrysotile often form under relatively low temperature conditions (lower than 420 °C) [34]. Much work has been conducted to identify if and how temperature influences the formation of lizardite and chrysotile [34–40]. However, a conclusive answer has yet to be found.

The absence of antigorite in the southern Mariana serpentinized peridotite is the result of the low temperature (<500 °C) of serpentinization. While the growth temperature of lizardite and chrysotile broadly overlaps, it is difficult to explain why chrysotile is absent, while lizardite is present, based on temperature difference. Thus, we infer that temperature is not the reason for this disparity, but differences in modes of occurrence are responsible. The main reasons are as follows:

- (1) The serpentinization of the southern Mariana peridotites is at the initial stage, as indicated by the relic olivine and the mesh textures [34]. Such initial serpentinization is advantageous for the formation of lizardite. Chrysotile is believed to represent growth following the initial hydration [41], and chrysotile occurs preferentially in serpentinites that have undergone some degree of recrystallization, in which the serpentine minerals have begun to form interlocking textures [34].
- (2) One important characteristic in southern Mariana forearc peridotite is the coexistence of relict olivine and lizardite, which defines low values of water activity along crystal contacts [40,41]. Peridotite hydration commonly takes place sluggishly in a very dry or largely solid-state environment, and such a condition favors lizardite over chrysotile formation [34].
- (3) According to O'Hanley [42,43], the direct replacement of olivine in nature is to lizardite rather than to chrysotile. In her study of ophiolites from the ocean floor, Prichard [44] concluded that lizardite formed from olivine, and that chrysotile only grew after olivine was eliminated. Similar conclusions were reported by Laurent and Hébert [45] and Cogulu and Laurent [46] for the serpentinites of southeastern Quebec. In our samples, the relic olivine is ubiquitous, therefore, chrysotile cannot form.
- (4) The hydration reaction may be accompanied by volume expansion, on the order of 40–50% [47–50]. This will tend to seal up pathways of infiltration and diffusion at or close to the reaction site itself, resulting in an extremely low porosity and permeability rock-dominant environment [34]. Such a dry environment favors the formation of lizardite over chrysotile [34].

For the above reasons, we infer that the prevalence of lizardite over chrysotile in the southern Mariana forearc peridotite is not related to temperature, but is due to the difference of occurrence of lizardite and chrysotile. When the advantages for lizardite formation are not present, such as in fluid-filled pores and cracks, the predominant form of the serpentine mineral at low temperatures will become chrysotile.

6. Conclusions

The peridotites from the southern Mariana forearc have experienced some extent of serpentinization. The main minerals of these serpentinized peridotites are olivine, amphibole and spinel, as well as serpentine, chlorite and talc. Combining mineral chemistry with the observed mineral phase relationships, the alteration process of the southern Mariana forearc peridotites can be divided into four stages. It is worth noting that we have observed the serpentinization of amphibole, which is characteristic of the Mariana peridotites. This is the first report of this process in this area. The absence of magnetite is the result of the

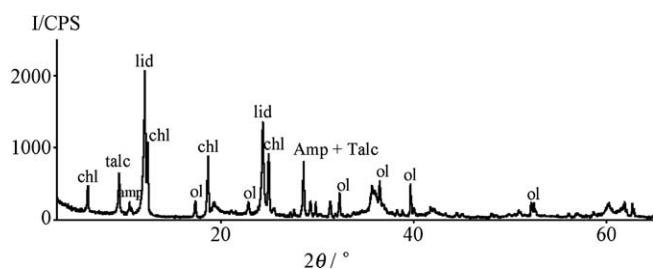


Fig. 4. X-ray powder diffraction patterns of serpentinized peridotite from the southern Mariana forearc. The spectrum was obtained using an X-ray diffractometer D/max 2400 at room temperature, using a rotating Cu target with a voltage of 40 kV and a current of 40 mA. The scan range (2θ) was 2–65° with a step size of 0.02°. chl = chlorite; amp = amphibole; lid = lizardite; and ol = olivine.

incomplete serpentinization of Mariana forearc peridotites. Under such conditions, the serpentinization of the iron end-member of olivine forms Fe-rich brucite and Fe-rich serpentine, instead of magnetite. Brucite that forms during early serpentinization of olivine further reacts with later SiO₂-rich fluids and forms lizardite, leading to the lack of brucite in these serpentinized peridotites. The occurrence of talc is the result of later SiO₂-rich fluids reacting with lizardite. Lizardite is the only serpentine mineral present in the southern Mariana forearc peridotites. For the temperature condition of our study area is not enough for the formation of antigorite as it is stable at >500 °C; in addition, the differences in the modes of occurrence of lizardite and chrysotile, leads to the absolute prevalence of lizardite over chrysotile.

Acknowledgements

This work was supported in part by the Pilot Project of the Knowledge Innovation Project, Chinese Academy of Sciences (Grant Nos. KZCX2-YW-211, KZCX3-SW-223), National Natural Science Foundation of China (Grant No. 40830849), and the Special Foundation for the Eleventh Five Plan of COMRA (Grant No. DYXM-115-02-1-03). The authors thank the tremendous efforts of the entire crew during cruise KH03-3. We also thank Li Yibing and Ishii Teruaki from the University of Tokyo for providing samples and making this study possible. Special thanks are extended to the anonymous referee for the valuable comments which improved the manuscript.

References

- [1] Ranero CR, Morgan JP, McIntosh K, et al. Bending-related faulting and mantle serpentinization at the Middle America trench. *Nature* 2003;425:367–73.
- [2] Ewans J, Hawkins J. Petrology of seamounts on the trench slope break. *EOS* 1979;60:968.
- [3] Escartín J, Hirth G, Evans B. Effects of serpentinization on the lithospheric strength and the style of normal faulting at slow-spreading ridges. *Earth Planet Sci Lett* 1997;151:181–9.
- [4] Bach W, Paulick H, Garrido CJ, et al. Unraveling the sequence of serpentinization reactions: petrography, mineral chemistry, and petrophysics of serpentinites from MAR 15°N (ODP Leg 209, Site 1274). *Geophys Res Lett* 2006;33:L13306. doi:10.1029/2006GL02568.
- [5] Thompson G, Melson WG. Boron contents of serpentinites and metabasalts in the oceanic crust: implications for the boron cycle in the oceans. *Earth Planet Sci Lett* 1970;8:61–5.
- [6] Snow JE, Dick HJB. Pervasive magnesium loss by marine weathering of peridotite. *Geochim Cosmochim Acta* 1995;59:4219–35.
- [7] Kelley DS, Karson JA, Blackman KD, et al. An off-axis hydrothermal vent field near the Mid-Atlantic Ridge at 30°N. *Nature* 2001;412:145–9.
- [8] Holm NG, Charlou JL. Initial indications of abiogenic formation of hydrocarbons in the Rainbow ultramafic hydrothermal system, Mid-Atlantic Ridge. *Earth Planet Sci Lett* 2001;191:1–8.
- [9] Ishii T, Robinson PT, Maekawa H, et al. Petrological studies of peridotites from diapiric serpentinite seamounts in the Izu–Ogasawara–Mariana forearc, Leg 125. In: Proceedings of the Ocean Drilling Program: scientific results, vol. 125; 1992. p. 445–85.
- [10] Parkinson IJ, Pearce JA, Thirlwall MF, et al. Trace element geochemistry of peridotites from the Izu–Bonin–Mariana forearc, Leg 125. In: Proceedings of the Ocean Drilling Program: scientific results, vol. 125; 1992. p. 487–506.
- [11] Michael JM. Pore water from serpentinite seamounts in the Mariana and Izu–Bonin forearc, Leg 125: evidence for volatiles from the subducting slab. In: Proceedings of the Ocean Drilling Program: scientific results; 1992. p. 373–85.
- [12] D’Antonio M, Kristensen MB. Serpentine and brucite of ultramafic clasts from the South Chamorro Seamount (Ocean Drilling Program Leg 195, Site 1200): inferences for the serpentinization of the Mariana forearc mantle. *Mineral Mag* 2004;68(6):887–904.
- [13] Ohara Y, Ishii T. Peridotites from the southern Mariana forearc: heterogeneous fluid supply in mantle wedge. *Island Arc* 1998;7(3):541–58.
- [14] Chen JB, Zeng ZG. Metasomatism of the peridotites from southern Mariana fore-arc: trace element characteristics of clinopyroxene and amphibole. *Sci Chin D* 2007;50(7):1005–12.
- [15] Chen JB, Zeng ZG. Petrology and mineralogy of peridotites from the southern Mariana forearc: implication for the metasomatism of the mantle wedge under Mariana arc. *Marine Geol Quaternary Geol* 2007;27(1):53–9, [in Chinese].
- [16] Michibayashi K, Tasaka M, Ohara Y, et al. Variable microstructure of peridotite samples from the southern Mariana Trench: evidence of a complex tectonic evolution. *Tectonophysics* 2007;444(1–4):111–8.
- [17] Stern RJ, Fouch MJ, Klempner SL. An overview of the Izu–Bonin–Mariana subduction factory. In: Inside the subduction factory. Washington, DC: American Geophysical Union; 2004.
- [18] Fujioka K, Okino K, Kanamatsu T, et al. Morphology and origin of the Challenger Deep in the Southern Mariana Trench. *Geophys Res Lett* 2002;29. doi:10.1029/2001GL01359.
- [19] Fryer P, Becker N, Appelgate B, et al. Why is the Challenger Deep so deep? *Earth Planet Sci Lett* 2003;211:259–69.
- [20] Gvirtzman Z, Stern RJ. Bathymetry of Mariana Trench–arc system and formation of the Challenger Deep as a consequence of weak plate coupling. *Tectonics* 2004;23:TC2011. doi:10.1029/2003TC00158.
- [21] Ishii T. Dredged samples from the Ogasawara fore-arc seamount or Ogasawara paleoland-fore-arc ophiolite. Formation of Active Ocean Margins. Tokyo: Terra Scientific Publishing Company; 1985, p. 307–42.
- [22] Bloomer SH, Fisher RL. Petrology and geochemistry of igneous rocks from the Tonga Trench – a nonaccreting plate boundary. *J Geol* 1987;95:469–95.
- [23] Natland JH, Tarney J. Petrologic evolution of the Mariana arc and back-arc basin system: a synthesis of drilling results in the south Philippine Sea. Initial Rep Deep Sea Drilling Proj 1982;60:877–908.
- [24] Fryer P, Ambos EL, Hussong DM. Origin and emplacement of Mariana forearc seamounts. *Geology* 1985;13(11):774–7.
- [25] Fryer P, Saboda KL, Johnson LE, et al. Conical seamount: SeaMARC II, Alvin submersible, and seismic-reflection studies. In: Proceedings of the Ocean Drilling Program: Scientific Results, vol. 125; 1990. p. 69–80.
- [26] Leake BE, Woolley AR, Birch WD, et al. Nomenclature of amphiboles: Report of the subcommittee on amphiboles of the International Mineralogical Association Commission on new minerals and mineral names. *Mineral Mag* 1997;61:295–321.
- [27] Mével G. Serpentinization of abyssal peridotites at mid-ocean ridges. *Geoscience* 2003;335:825–52.
- [28] Gahlan HA, Arai S, Ahmed AH, et al. Origin of magnetite veins in serpentinite from the Late Proterozoic Bou-Azzer ophiolite, Anti-Atlas, Morocco: an implication for mobility of iron during serpentinization. *J Afr Earth Sci* 2006;46:318–30.
- [29] Iyer K, Austrheim H, John T, et al. Serpentinization of the oceanic lithosphere and some geochemical consequences: constraints from the Leka ophiolite complex, Norway. *Chem Geol* 2008;249:66–90.
- [30] Toft PB, Hamed JA, Haggerty SE. The effects of serpentinization on density and magnetic susceptibility: a petrophysical model. *Phys Earth Planet Interiors* 1990(1–2):137–57.

- [31] Bach W, Garrido CJ, Paulick H, et al. Seawater-peridotite interactions: first insights from ODP Leg 209, MAR 15°N. *Geochem Geophys Geosyst* 2004;5(9):Q09F26.
- [32] Evans BW, Johannes W, Oterdoom H, et al. Stability of chrysotile and antigorite in the serpentine multisystem. *Schweiz Mineral Petrogr Mitt* 1976;56:79–93.
- [33] Moody JB. Serpentinization: a review. *Lithos* 1976;9:125–38.
- [34] Evans BW. The serpentinite multisystem revisited: chrysotile is metastable. *Int Geol Rev* 2004;46:479–506.
- [35] Normand C, Williams-Jones AE, Martin RF, et al. Hydrothermal alteration of olivine in a flow-through autoclave: nucleation and growth of serpentine phases. *Am Mineral* 2002;87:1699–709.
- [36] Chernosky JV. Aggregate refractive indices and unit cell parameters of synthetic serpentine in the system MgO–Al₂O₃–SiO₂–H₂O. *Am Mineral* 1975;60(3–4):200–8.
- [37] O’Hanley DS, Wicks FJ. Conditions of formation of lizardite, chrysotile and antigorite, Cassiar, British Columbia. *Can Mineral* 1995;33:753–73.
- [38] Wenner DB, Taylor HP. Temperatures of serpentinization of ultramafic rocks based on ¹⁸O/¹⁶O fractionation between coexisting serpentine and magnetite. *Contrib Mineral Petrol* 1971;32:165–85.
- [39] Caruzo L, Chernosky JV. The stability of lizardite. *Can Mineral* 1979;17:757–69.
- [40] O’Hanley DS, Chernosky JV, Wicks FJ. The stability of lizardite and chrysotile. *Can Mineral* 1989;27:483–93.
- [41] Sanford RF. Mineralogical and chemical effects of hydration reactions and applications to serpentinization. *Am Mineral* 1981;66:290–7.
- [42] O’Hanley DS. Fault-related phenomena associated with hydration and serpentine recrystallization during serpentinization. *Can Mineral* 1991;29:21–35.
- [43] O’Hanley DS. Serpentinites: records of tectonic and petrologic history. Oxford: Oxford University Press; 1996, p. 277.
- [44] Prichard HM. A petrographic study of the process of serpentinization in ophiolites and the ocean crust. *Contrib Mineral Petrol* 1979;68:231–41.
- [45] Laurent R, Hébert Y. Paragenesis of serpentine assemblages in harzburgite tectonite and dunite cumulate from the Quebec Appalachians. *Can Mineral* 1979;17(4):857–69.
- [46] Cogulu E, Laurent R. Mineralogical and chemical variations in chrysotile veins and peridotite host-rocks from the asbestos belt of southern Quebec. *Can Mineral* 1984;22(1):173–83.
- [47] Hostetler PB, Coleman RG, Mumpton FA, et al. Brucite in alpine serpentinites. *Am Mineral* 1966;51:75–98.
- [48] Bogolepov VG. Problem of serpentinization of ultrabasic rocks. *Int Geol Rev* 1970;12:421–32.
- [49] Coleman RG, Keith TE. A chemical study of Serpentinization-Burro Mountain, California. *J Petrol* 1971;12:311–28.
- [50] O’Hanley DS. Solution to the volume problem in serpentinization. *Geology* 1992;20:705–8.