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(Communicated by Ikuo KUSHIRO, M. J. A.)

Abstract: Dunite and related rocks from the Moho transition zone of the East Pacific Rise (EPR) and the Mid-Cayman Trough (MCT) are examined to know the spreading-rate dependence of their compositions. The rocks from both ridges are basically a reaction product between peridotite and primitive MORB. Despite the large difference of prevalent peridotite chemistry, depleted harzburgite for EPR and lherzolite for MCT, the dunite has less different compositional ranges. The Al_2O_3 content of spinel differs only by 5 wt%, which may be equivalent to the difference of about 1 wt% of Al_2O_3 in the melt. This is almost equal to the possible spreading-rate dependent compositional difference of observed Mg-rich MORB. The relatively unfractionated MORBs erupted are in equilibrium with the oceanic dunite of which composition is independent of or only slightly dependent on spreading rate. Dunite is calculated to be about half of the total oceanic mafic crust by weight. The dunite is concentrated as the Moho transition zone, and is sparsely distributed as small lenses within the uppermost mantle peridotite.

Key words: MORB; dunite; olivine; chromian spinel; upper mantle; interaction; mid-ocean ridge.

Introduction. Abyssal mantle peridotite is variable in chemistry, approximately depending on spreading rate of the mid ocean ridge[1),2)]; i.e., the extent of partial melting apparently increases with increasing spreading rate.[2)] The primary MORB composition, therefore, should be highly changeable in accordance to the spreading rate.[3)] This is not the case, however; the spreading-rate dependence of the MORB composition is very slight.[2)] I try to compare the petrological characteristics of dunite and related rocks (troctolite and olivine gabbro) possibly forming the Moho transition zone derived from two contrasting ocean ridge systems, the East Pacific Rise (EPR) and the Mid-Cayman Trough (MCT) to examine their spreading-rate dependence. The former is a fast-spreading ridge with a full spreading rate of 13 cm/y[4)] and the latter, a slow-spreading ridge with a full spreading rate of 1.5 to 2 cm/y.[5)] I further discuss the role of dunite for the genesis of primitive MORB.

Sample descriptions. Ultramafic and related mafic plutonic rocks from Hess Deep, equatorial Pacific, represent the uppermost mantle to the Moho transition zone beneath the East Pacific Rise (EPR).[6),7)] The mantle peridotite is moderately depleted harzburgite with or without modal clinopyroxene, which is continuous in lithology to olivine gabbro through dunite and troctolite in short intervals (< 1 m) in the drill cores of ODP Leg 147.[6),7)] Dunite and troctolite are frequently rich in chromian spinel.[7),8)] Plagioclase and clinopyroxene are interstitial to olivine and chromian spinel in dunite and troctolite.

Ultramafic-mafic plutonic rocks were dredged during the Cruise 4 of R/V Akademik Nikolay Strakhov from the spreading center of the Mid-Cayman Trough (MCT).[9)] The mantle peridotite from MCT is lherzolite,[1),9)] and is associated with dunite, troctolite and olivine gabbro. Harzburgite has not been found. The rock suite, despite its strongly fragmentary nature, is essentially the same in appearance to the drilled one from Hess Deep. Difference of the mantle peridotite, harzburgite for EPR (Hess Deep) and lherzolite for MCT, is consistent with the spreading-rate dependence shown by Niu and Hékinian.[2)]

Both Hess Deep and the dredging sites of MCT are not associated with transform faults,[10),11)] and the transform effect on the rocks discussed here will be minimized.

Petrology and origin of the dunite-troctolite-

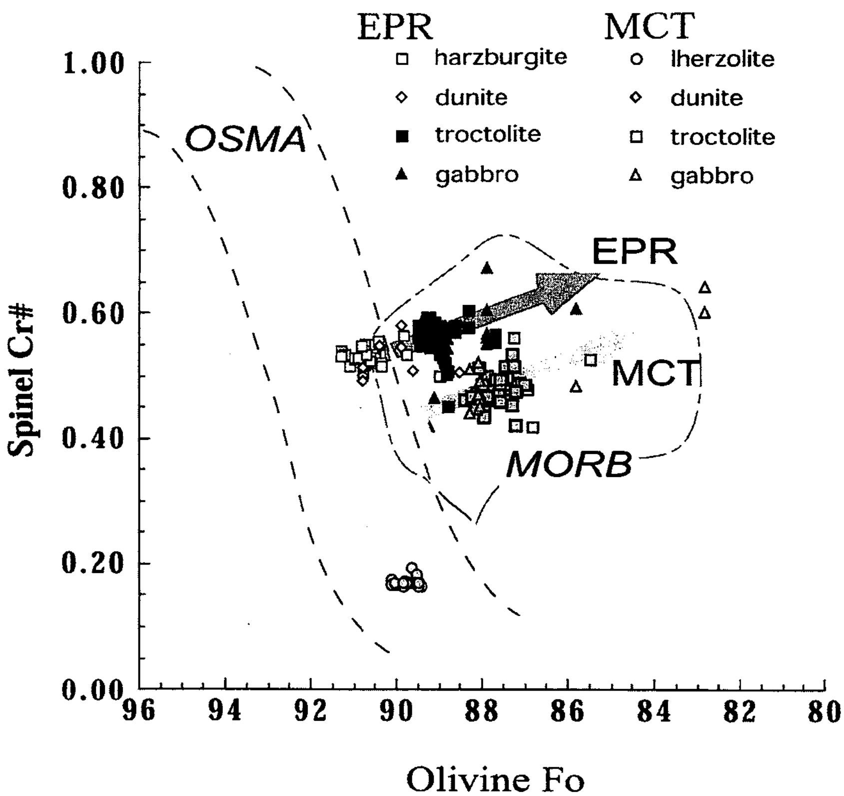

Fig. 1. Relationship between the Cr# (= Cr/(Cr + Al) atomic ratio) of spinel and Fo content of olivine in rocks. Data for East Pacific Rise (Hess Deep) are partly from Arai and Matsukage.[7] OSMA, the olivine-spinel mantle array, a spinel peridotite mantle restite trend of Arai.[23] MORB field is after Arai.[17] Note the olivine-spinel trends for dunite-troctolite-gabbro from EPR and MCT are within the MORB area.

gabbro complex. Origin of dunite replacing peridotite is due to a reaction between the peridotite and invading melt.[12),13)] The reaction is a combined process of olivine accumulation from the melt and partial melting of the peridotite. The dunite and troctolite (and possibly some olivine gabbro) from EPR are most probably the reaction product between mantle peridotite (harzburgite) and MORB,[7),8)] because (1) the harzburgite is continuous in lithology to olivine gabbro through dunite and troctolite, (2) the dunite and related rocks are frequently very heterogeneous and are always free of any layering and other structures indicative of cumulus origin, and (3) chemical compositions of minerals indicate an interaction origin: the Cr_2O_3 content and Mg# (= Mg/[Mg + total Fe] atomic ratio) in clinopyroxene are almost constant or very slightly changed with an increase of the TiO_2 content.[7),9)] Troctolite and olivine gabbro are essentially the mixture of residual or cumulus olivine and various proportions of interstitial melt.[7)]

The MCT rocks are essentially similar to the EPR ones: their clinopyroxene has a similar variation trend.[9)] The dunite, troctolite and olivine gabbro from MCT are also the reaction product between mantle peridotite (lherzolite) and a primary MORB.

In the dunite-troctolite, the Cr# (= Cr/[Cr + Al] atomic ratio) of chromian spinel only slightly increases with a decrease of the Fo (= 100Mg#) of olivine, ranging from 0.5 to 0.6 for the EPR and from 0.4 to 0.6 for the MCT[9)] (Fig. 1). The Al_2O_3 content of chromian spinel is slightly but distinctively lower in the EPR rocks than in the MCT rocks (Fig. 2). It is noteworthy that the difference of Cr# or Al_2O_3 of spinel in the dunite-troctolite is small between the two ridges relative to the large difference of the same value for the mantle peridotite, ca. 0.5 or 25 wt% for the EPR against ca. 0.2 or 52 wt% for MCT.[7),9)]

Spreading-rate dependent chemical variations for mantle restite and MORB. The abyssal peridotite demonstrates a lithological and chemical variation strongly dependent on spreading rate of the involved ridges.[1),2)] This has been ascribed to the

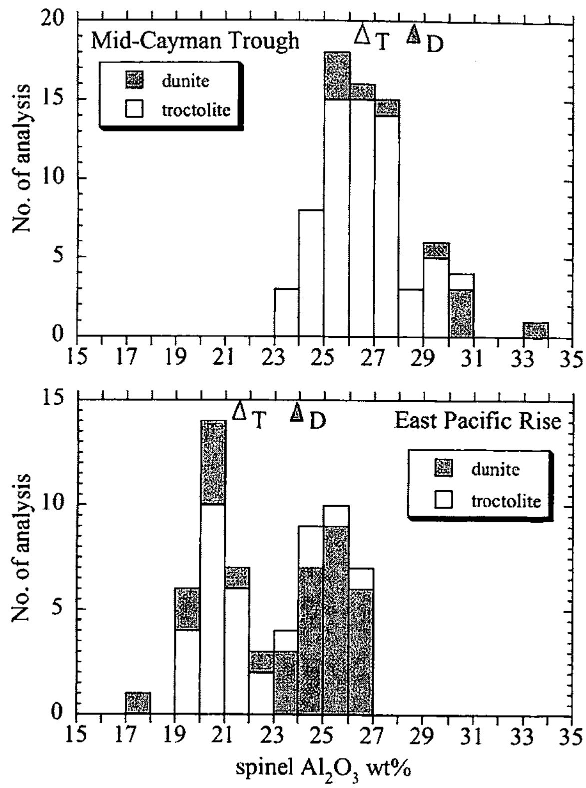

Fig. 2. Frequency histograms of Al_2O_3 content (wt%) of spinel in dunite and troctolite from EPR and MCT. Triangles are averages for dunite (D) and troctolite (T). Data are from Arai and Matsukage[7] and Isobe.[28]

spreading-rate dependence of the extent of partial melting of the mantle.[2] In contrast the compositions of relatively Mg-rich or hypothetical primitive MORB with a correction of fractionation effects are almost constant irrespective of spreading rate (for > 2 cm/y full rate)[14] or are very slightly dependent on the spreading rate.[2] Niu and Hékinian[2] demonstrate that A8 (Al_2O_3 wt% normalized to 8 wt% of MgO) decreases from 16 to 15 with a decrease of the full spreading rate from 15 to 1 cm/y, eliminating effects of plume and mantle heterogeneity. This composition is, however, too low in Mg# to be in equilibrium with the mantle peridotite.

The Cr# of spinel and Al_2O_3 content of orthopyroxene in peridotite are closely related with the extent of melting of peridotite.[3] The Al_2O_3 content of the initial melt in equilibrium with abyssal peridotite can be predicted to vary by about 5 wt% depending on the extent of partial melting,[3),15] even though we consider the temperature difference between the experiments and natural peridotite equilibration.[16] This difference of Al_2O_3 content of partial melts is much larger than the A8 range, from 16 to 15, actually expected for relatively primitive MORB.[2] The Cr# of chromian spinel coexisting with magnesian olivine (> Fo_{85}) in MORB is almost within a narrow range from 0.4 to 0.6[17] (Fig. 1), which is consistent with the narrow range of A8. The narrow range for A8 is hardly due to fractional crystallization from the initially different compositions (e.g., by 5 wt% for Al_2O_3) because no cumulates with different compositions depending on the spreading rate have been found from the ocean floor.

Discussion. The petrological nature of the dunite-troctolite derived from the oceanic Moho transition zone well explains the uniform but slightly spreading-rate dependent compositions of MORB.[2,14] It is highly possible that the MORB is not in equilibrium with abyssal peridotite[18] but with the transition-zone dunite and troctolite in terms both of REE distribution[19] and of Fo(olivine)-Cr#(spinel) relationship (Fig. 1). The narrow range of Cr# of MORB spinel in equilibrium with Mg-rich olivine, mostly from 0.4 to 0.6,[17] may indicate a narrow range of Cr# of residual counterpart of MORB in deep parts. This is contradictory to the rather widespread Cr# range for the abyssal peridotite, from 0.1 to 0.6,[1,2] and indicates that the observed Mg-rich MORB cannot be in equilibrium with the abyssal peridotite. The range of Cr# of spinel in the transition-zone dunite and troctolite, on the other hand, is actually narrow and is consistent with the range in the erupted MORBs (Fig. 1). Fig. 2 demonstrates a possible spreading-rate dependent composition of the transition zone dunite and troctolite: their chromian spinels are more Al-rich for the MCT rocks than for the EPR ones. This difference, ca. 5 wt% of Al_2O_3, is roughly equivalent to 1 wt% of Al_2O_3 in the melt in equilibrium with the spinel. The melt in equilibrium with the dunite spinel may have 15 and 16 wt% of Al_2O_3 from EPR and MCT according to the empirical distribution relationship.[20] This variation is consistent with the spreading-rate dependent variation of A8 in MORB, which slightly decreases with increasing spreading rate.[2] It is highly possible that the low-pressure Mg-rich MORB compositions observed are constrained by equilibration with the oceanic dunite, a reaction product between peridotite (harzburgite to lherzolite dependent on the spreading rate) and more primitive high-pressure MORB.

Fig. 3 demonstrates a simplified compositional relation between the high-pressure primary MORB, observed Mg-rich MORB (low-pressure MORB), mantle peridotite and dunite beneath spreading ridges. The

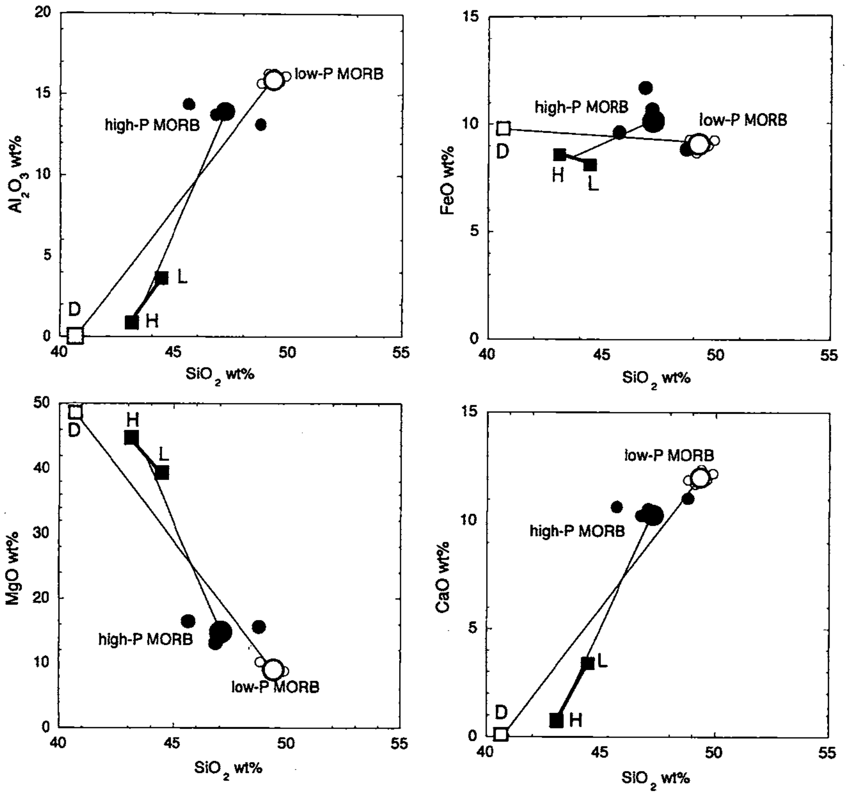

Fig. 3. Possible compositional relations between high-pressure and low-pressure MORBs, residual peridotite (lherzolite, L, to harzburgite, H), and dunite (D). The high-pressure primary MORB composition is an average (large closed circle) of experimental melts (small closed circle), Nos. 22 (2.5 GPa, 1425 °C) & 25 (3 GPa, 1500 °C) of KLB-1, and Nos. 9 (2 GPa, 1425 °C) & 10 (2.5 GPa, 1425 °C), of Hirose and Kushiro.[21] The low-pressure MORB is an average (large open circle) of erupted high-Mg MORBs (small open circle).[29),30] The compositions of residual peridotite were estimated by averaged mineral chemistry and mode of harzburgite and lherzolite from EPR (Hess Deep)[7] and MCT,[28] respectively. See text for more detail.

reaction, high-pressure MORB + peridotite = low-pressure MORB + dunite, is essential for both slow- and fast-spreading ridges (Figs. 3 & 4a). I adopted an averaged composition of some melts experimentally determined by Hirose and Kushiro[21] as the primary high-pressure MORB (Fig. 3). The melts are in equilibrium with lherzolite (ol + opx + cpx) at 2.5 GPa and with harzburgite (ol + opx) at 2.0 GPa from two starting materials (HK-66 and KLB-1).[21] The melt compositions of Hirose and Kushiro[21] were determined using diamond-aggregate method, and are most reliable. This pressure range is highly possible for the depth of release of primary MORB from its restite.[22] HK-66 (Fo_{86}) and KLB-1 (Fo_{89}) may be slightly too fertile and too refractory, respectively, for the MORB source; harzburgitic restite from HK-66[21] has olivine with Fo_{87} and KLB-1 is rather close in composition to the most fertile abyssal peridotite, which may be a restite itself.[23] The composition of a low-pressure relatively unevolved MORB is easily defined as in Fig. 3. The average melt composition of Hirose and Kushiro[21] above is appropriate for the primary high-pressure MORB that reacts with peridotite (lherzolite to harzburgite) to form the low-pressure MORB and dunite (Fig. 3). The average proportion of dunite to the low-pressure MORB that may produce the mafic oceanic crust is about half by weight (Fig. 3).

Combined the result above with the observation on ophiolites, most of which are of fast-spreading ridge origin,[24] I construct a petrological model of the sub-oceanic upper mantle, especially for the fast-spreading ridge system (Fig. 4). The Moho transition zone is actually 0.5 km at the thickest as observed at the Oman ophiolite,[24),25] and is far insufficient for the amount of the dunite. It is, therefore, highly possible that dunite has

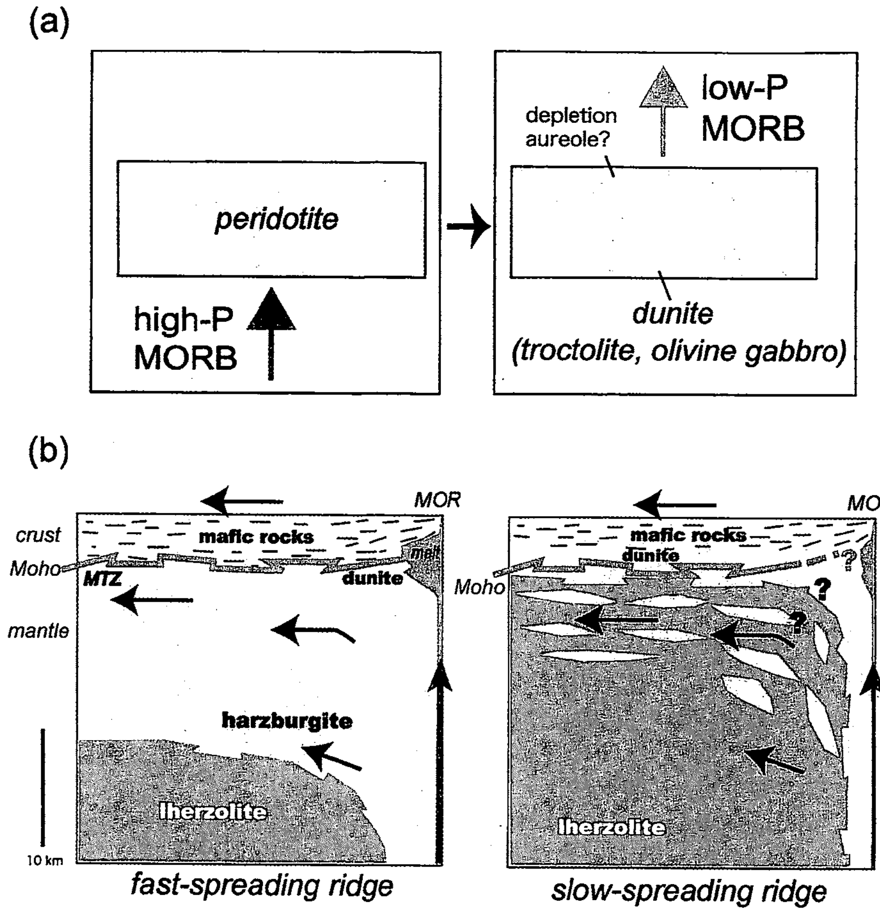

Fig. 4. Formation of dunite in generation of primitive MORB within the upper mantle. (a) A simplified illustration for the MORB genesis, high-pressure MORB + peridotite = low-pressure MORB + dunite (troctolite, olivine gabbro depending on the degree of melt extraction[7]). The dunite may have depletion aureole. (b) A petrological model (an across-ridge cross-section) of the oceanic upper mantle to show the distribution of dunite. The harzburgite layer may be thin at the slow-spreading ridge.[31),32)] The distribution of lherzolite in the mantle beneath a fast-spreading ridge is suggested by that in the Oman ophiolite.[33)] Note that the Moho may be the boundary between the mafic crust and dunite for the fast spreading ridge, and may be the serpentinization front within the ultramafic part for the slow spreading ridge.[31),34)] The Moho transition zone is exaggerated here. MOR, mid-ocean ridge. MTZ, Moho transition zone. Black arrow, spreading of the ocean floor.

been produced after the final release from residual peridotite at depths.[19)] If the depth of the final release is 45 km or 60 km and the oceanic mafic crust is 6 to 7 km thick, the dunite occupies several to ten % of the overlying upper mantle (Fig. 4b). This proportion of dunite to mantle peridotite is reasonable as observed in the ophiolitic harzburgite complex[26)] possibly derived from the oceanic mantle of fast-spreading ridge origin. For the upper mantle of slow-spreading ridge system, the harzburgite layer is relatively thin, if any, and dunite lenses may have depletion aureole of harzburgite within the lherzolitic mantle (Fig. 4b).

Excess olivine in peridotites may be another possibility for the olivine accumulation instead of forming discrete dunite.[27)] This is less possible, however, because the actual abyssal peridotites that could have excess olivine are hardly in equilibrium with MORB. The usual discordance for the Cr# of spinel and the disequilibrium for REE distribution between abyssal peridotite and MORB may contradict the excess olivine formation associated with chemical modification of peridotite as a main process for the MORB formation. The reaction between peridotite and melt to leave dunite can be widely observed within the Moho transition zone and the upper mantle in ophiolite as well as from the ocean floor. This is the essential process to determine the composition of the low-pressure MORB that ultimately leaves the upper mantle upward. This study indicates that the assemblages olivine + spinel + melt with similar or slightly spreading-rate depending compositions are stable at the oceanic uppermost mantle just beneath mid-oceanic ridges. This may mean that the thermal regime is almost the same there, slightly or hardly depending on the spreading rate.

Acknowledgements. I express my hearty appreciations to Prof. I. Kushiro, M. J. A., for his comments and discussion. I am grateful to Dr. K. Matsukage for discussion and to Mr. E. Isobe and Dr. S. Vysotskiy for collaboration for the MCT rocks. I am very much indebted to ODP Japan for arrangement of my participation to the ODP cruise of Leg 147 on Hess Deep. Dr. K. Kadoshima and Ms. M. Kida assisted me in preparation of the manuscript.

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(Received Dec. 20, 2004; accepted Jan. 12, 2005)