受け入れ教官：基礎宇宙化学部門：中村栄三

Secular change of the Composition and Temperature of the upper mantle

（上部マントルの温度・組成の経年変化）

Tsuyoshi Komiya (小宮　剛), Tokyo Institute of Technology(東京工業大学)

Understanding the thermal and compositional evolution of the mantle is the essential to decoding the whole history of the Earth, because the Earth consists of mantle over 85 % of the whole. However, the estimate of composition and temperature of the Archean (upper) mantle has been still controversial because fertile mantle xenoliths have not been discovered yet in the Archean. The procedures of estimate of the Archean mantle composition are classified into three types. The first is the estimate from composition of spinifex textured peridotitic komatiites (e.g. Bickle et al., 1976). The second is the estimate from relatively primitive modern peridotites, assuming that the primitive peridotites have survived since the Archean (e.g. Jagoutz et al., 1979). The third is the estimate from comparison of primitive basalts with experimental melts from natural peridotites (Ohta et al., 1996). However, the first method, recently, lost the validity because peridotitic komatiite does not represent magma at high degree of melting of peridotite at low pressure. In addition, recent works consider komatiite as plume-derived magma. The second approach may be also invalid, because mantle had already differentiated even in the Archean.

The estimate of temperature of the Archean mantle is more ambiguous, and draws on thermal calculation (e.g. Breuer & Spohn, 1995), except for some pioneering works (Takahashi, 1990; Nisbet et al., 1993). Even the pioneering works estimated the temperature from peridotitic komatiites. Recently, Ohta and others (1996) estimated the temperature of the upper mantle from mid-Archean MORB in Cleaverville region.

It is critical to determine the tectonic setting of mafic/ultramafic volcanism for estimate the composition and temperature of the source mantle, because it is known well that the geochemical characters of modern volcanic rocks are strongly dependent on tectonic setting such as MORB, OIB and IAB. However, tectonic setting of Archean mafic magmatism is still ambiguous. Previous works tried to classify the greenstones based on the discrimination diagrams defined by the geochemistry of the modern basalts (e.g. Condie, 1989). However, the discrimination diagrams for modern basalts are not necessarily applicable to Archean greenstones, because Archean mantle was different from the modern mantle in composition (e.g. Ohta et al., 1996). Recent geological investigation of some greenstone belts such as the Isua Supracrustal Belt (Komiya et al., 1999), the Cleaverville area (Ohta et al., 1996) and North Pole area (Maruyama et al., 1991) revealed that they were the accretionary complexes in the Archean. In addition, application of accretionary geology to the greenstone belt allows us to deduce the tectonic setting of Archean mafic volcanism.

The elimination of post-magmatic alteration is the most difficult and inevitable problem in many petrochemical studies on the Archean greenstone. However, relict igneous clinopyroxenes (Cpx) in Archean greenstones area allow us to estimate original composition of the host magmas. We analyzed major and rare earth elements with electron probe microanalyzer (JEOL-JXA-8800) and Cameca Ims-3f (secondary ion mass spectrometer SIMS) at Tokyo Institute of Technology. In addition, we selected 861 greenstone samples for whole-rock analyses through comprehensive investigation, including geology, carefully sampling of over 6,000 apparently fresh greenstone samples, metamorphic petrology and petrographic observation.

This paper presents the geology of five differently aged greenstone belts (the 3.8 Ga Isua supracrustal belt (ISB); the 3.5 Ga North Pole (NP), the 3.3 Ga Cleaverville (CLB), the 2.5 Ga Beasley River (BR), Pilbara and the 1.6 Ga Glengarry Basin (KLR), Yilgarn), together with the field occurrence and geochemistry of the greenstones and the relict igneous Cpx. I estimated the secular variation of temperature and composition of the MORB-source mantle, namely upper mantle, from the geochemistry of the MORB-origin greenstones.

The tectonic setting of the basaltic volcanism was determined based on comparison between occurrence of greenstones within modern and ancient accretionary complexes (e.g. Komiya et al. 1999). Namely, the greenstones overlain by thick-bedded chert are the mid-ocean ridge basalt (MORB), while those conformably alternating with thin bedded chert or intruding thick bedded chert are ocean island basalt (OIB). 1: 5,000 scale mapping of the 3.8 Ga Isua supracrustal belt, the 3.5 Ga North Pole area and the 3.3 Ga Cleaverville area shows that duplex structure composed of several horses is widespread in each greenstone belt. The duplexes vary in size from a few meters to several kilometers. The reconstructed lithostratigraphy of each horse reveals a simple pattern, in ascending order from greenstone with basaltic composition to chert/BIF. Turbidite layers cover the thick cherts in some places. The cherts and the underlying low-K tholeiites contain no continent- or arc-derived materials. The lithostratigraphy is quite similar to the Phanerozoic "oceanic plate stratigraphy." The line of evidence of duplex structure and "oceanic plate stratigraphy" indicates that these greenstone belts were formed as accretionary complexes. The dominantly mafic composition of the turbidites suggests that the accretionary complexes were formed in the intra-oceanic environment, comparable to the present-day western Pacific Ocean. Two types of greenstones occur in the Isua supracrustal belt. The first is pillow and massive lavas conformably overlain by thick, bedded chert layers (MORB). The others are basaltic dikes, which intrude thick chert layers (OIB) (Komiya et al. 1999). Two modes of occurrence of greenstones are present in the North Pole area; greenstones overlain by thick, bedded chert (MORB) and those conformably alternating with thin, bedded chert (OIB) (Maruyama et al. 1991). In the Cleaverville area, the greenstones overlain by the thick, bedded chert were derived from mid-ocean ridge volcanism (Ohta et al. 1996).

Geological mapping on a 1: 5,000 scale was similarly undertaken in the Beasley River area of the Hamersley Group, and in the Kilara and Peak Hill areas of the Glengarry Basin. The former is divisible into six subunits based on the lithologies: the Lower lava flow, the Lower BIF, the Middle BIF, the Upper lava flow, the Rhyolite, the Upper BIF, and the Uppermost sedimentary Unit in ascending order. In the Lower lava flow Unit, no shales or terrigenous sediments are interleaved with pillow/massive lava flows, while there are shales, sandstones, and even conglomerates at the top of the Lower BIF Unit, and in the Upper sedimentary Unit. Despite that the lithostratigraphy is similar to "oceanic plate stratigraphy," the absence of thrusts, which define duplex structure, does not indicate an accretionary complex, but a sedimentary basin in a closing rift valley. Pillow/massive lavas in the Lower lava flow Unit were derived from mid-ocean ridge volcanism in a mature rifting system equivalent to the Red Sea in the Phanerozoic. Despite the poor exposure, the geology of the Kilara/Peak Hill area appears to be similar to that of the Beasley River area, implying the greenstone were produced by mid-ocean ridge volcanism in a mature rift system.

861 greenstone samples, defined as the least altered samples from the field and microscopic observations, were selected from ca. 6,000 samples for major and trace element analyses. Moreover, rare earth elements (REE) were also analyzed on some of them. The greenstones are defined as low-K tholeiite, and are distinctly enriched in FeO* at high MgO content, compared with modern MORB. The liquid lines of descent indicate the fractional crystallization of Ol-Pl-Cpx for MORBs in ISB, NP, CLB and KLR, or Ol-Cpx-Pl for that in BR. MORBs in ISB and NP are characterized by slightly LREE-depleted patterns, whereas those in CLB, BR and KLR are flat- or slightly LREE-enriched, respectively. OIBs in ISB and NP have flat- or slightly LREE-enriched patterns. The differences of the field occurrence and geochemical characteristics between MORB and OIB in ISB and NP indicate that mantle had already differentiated into at least two components. The geochemistry of Archean MORBs indicates that the presence of depleted mantle in the Archean, but that the relatively weak depletion is consistent to moderate depletion of the Early Archean mantle, rather than the extreme depletion deduced from whole-rock Nd isotopic composition (Bennett et al., 1993).

Microprobe analyses of relict clinopyroxenes within MORBs in ISB, NP, CLB, BR, and KLR show that the composition of clinopyroxenes is similar to those in modern MORB on the Lindsley quadrilaterals. They have lower Ti, Al and Na contents, compared with those in modern MORB. In addition, obvious compositional differences exist between Cpx in MORB and in OIB in the NP. The Cpx of NP OIB have higher Ti/Al ratio at high Mg#, and have higher La/Lu ratio relative to those of NP MORB. The relationships are similar to those between modern OIB and MORB. Moreover, the calculated partition coefficients of TiO_2, Al_2O_3, Na_2O, REE and the MgO/FeO ratio between the Cpx and whole rock analyses, range within the variations of experimental data, suggesting that secondary alteration was insignificant in the oxides.

The potential temperature and FeO content of source mantles were estimated by comparison of the most primitive MORBs in each area with recent melting experimental compilations. The results indicate that the source mantles of the ancient MORBs were highly enriched in FeO, and contain 10 wt % in FeO (c.f. 85-87 in $Mg^{\#}$), but that the FeO content was constant until early Proterozoic, and then decreased. The potential mantle temperature of each ancient MORB is also higher than that of modern MORB, and was about 1480 °C. The fact indicates that the mantle even in the Early Archean was hotter by at most *ca.* 150 to 200 °C than the modern mantle, contrast to the estimate from peridotitic komatiites (Takahashi, 1990; Nisbet et al., 1993). It changed, concomitant with the change of the FeO content.

Recent ultra-high-pressure experiment implies that some of Fe^{2+} ions transformed into Fe+Fe^{3+} during slab penetration into lower mantle because aluminous Mg-perovskite contains $Al^{3+}Fe^{3+}$ instead of $Mg^{2+}Si^{4+}$ (Wood & Rubie, 1996). The formation of the metallic iron may decrease the FeO content of the upper mantle. Recent geological (Komiya et al., 1999) and metamorphic petrological investigations (Hayashi et al., 2000) indicate that plate tectonics was in operation even in the Early Archean. In addition, phase relation of mantle peridotite (Herzberg & Zhang, 1996), 200 °C higher potential mantle temperature (this work) and high geothermal gradient at subduction zone by 200 °C (Hayashi et al., 2000) suggest high possibility of slab penetration even in the Early Archean. Assuming that the production rate of metallic iron is equivalent to that of Fe^{3+} in the formation of Mg-perovskite, it takes 3.1 and 5.0 billion years for the whole mantle to decrease from 10 to 8 wt % in FeO and from 29 to 21 ppm in P_2O_5 at the production rate of MORB in the Archean. The extraction of metallic iron from the mantle may be also consistent to high ratio of Ce/Pb of modern MORB and OIB relative to that of primitive mantle (Hofmann et al., 1986).