行政院國家科學委員會專題研究計畫 成果報告

中國大陸蘇魯與柴北緣地區超高壓榴輝岩之原岩探討與其
在地球內部元素分化之應用

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計畫主持人：楊懷仁

計畫參與人員：黃麗雲 郭春滿 賴逸真 蘇同新

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PI: Huai-Jen Yang
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Goals and Proposed Approaches

The goal of the proposed project is to constrain the petrogenesis of eclogites from the Sulu ultra-high pressure (UHP) metamorphic terrane at eastern China and those from north Qaidam at central China, using the compositional and Sr-Nd isotopic variations of these rocks. For Sulu samples, we only focus on high-Ti eclogites for their potential of being mined for titanium. In contrast, we carried out a survey study for the Qaidam eclogites, for which the basic petrographic and geochemical classifications are unavailable.

Results and Discussions

Our results have been presented in the AGU fall meeting of 2004 and the 7th International Eclogite Conference (IEC). A manuscript entitled “Compositions of high Fe-Ti eclogites from the Sulu UHP terrane, China: controls of element distributions during protolith formation and metamorphism” has been submitted to “Chemical Geology”. In addition, a master thesis by C.-M. Ker has been synthesized from the results of Qaidam eclogites. The contexts of the submitted manuscript and master thesis are summarized as followings.

Petrogenesis of the high-Ti eclogites from the Sulu UHP terrane

Combining our results and the published CCSD data, we constrain (1) the roles of protolith compositions, metamorphic differentiation, and metasomatism in controlling the compositional variations of high-Fe-Ti eclogites, and (2) the mechanism causing Ti-enrichment and decoupling of Ti from other high-field-strength elements.

The compositions of the studied eclogites sampled from Maobei in the Sulu metamorphic terrane in eastern China mainly reflect protolith characteristics, although the effects of metamorphic differentiation and fluid infiltration can be detected. The important compositional features and associated implications include the followings.

(1) The negative SiO₂-Al₂O₃ correlation trend deviates from the field defined by Skaergaard gabbros with the low SiO₂ end extending toward the composition of constituting garnet, providing evidence for concentrating garnet by metamorphic
differentiation.

(2) One of the two low-SiO$_2$ samples has low LREE concentrations approaching the values of garnetite, consistent with garnet enrichment during metamorphism. In contrast, another low-SiO$_2$ sample contains the highest LREE and Sr abundances among the analyzed eclogites. Its concaved-up REE pattern is attributed to interaction with fluid during metamorphism.

(3) The trace element abundances of the eclogite samples are lower than those of basalts but comparable to those of gabbros indicating gabbroic protoliths. Mass balance using major oxides further constrains the mineral proportions in the cumulates to be plagioclase : clinopyroxene : olivine : Fe-Ti oxides = 41: 39:8:12. The ratio of plagioclase/clinopyroxen is consistent with crystallization at 2–8 kbar.

(4) The HFSE in the analyzed eclogites are decoupled; specifically, Ti enrichment is accompanied by Nb-Ta-Zr-Hf depletions. Similar features are also observed for the eclogites cored by CCSD at 530–600 meters (subunit 8) and can be explained as the characteristics of titanomagnetite-bearing gabbros in equilibrium with melts strongly depleted in Nb, Ta, Zr and Hf with Ti/Eu ratios close or slightly lower than the chondritic values. Such melt compositions were found in the CCSD eclogites cored at 318–380 and 420–470 meters (subunits 4 and 6). Therefore, it is concluded that the eclogites from CCSD subunit 8 are related to some subunits 4 and 6 eclogites by crystal-melt association.

(5) Some of the CCSD subunits 4 and 6 eclogites contain > 5% TiO$_2$, which cannot be explained by differentiation of basalts; therefore, must result from metamorphic enrichment of rutile.

**Tectonic implications of the systematic spatial distributions of the protoliths of northern Qaidam Eclogites**

The north Qaidam eclogites are distributed at three localities; the western Lu-Liang-Shan, central Xi-Tie-Shan, and eastern Dulan. Their chemical and Sr-Nd isotopic compositions mainly reflect protolith characteristics, which show systematic spatial variation. Specifically, western Lu-Liang-Shan eclogites were metamorphosed from both N-MORB and E-MORB protoliths whereas the latter dominates central Xi-Tie-Shan eclogites with the exception of two samples showing arc signatures, which are enhanced in eclogites from eastern Dulan. Two models are proposed to explain such a systematic spatial distribution. The first model involves two subduction events. The arc protoliths metamorphosed to the Dulan eclogites might be resulted from the eastward collision between the paleo-Qilian ocean and its near-by continent. Then, the subsequent northward subduction of the paleo-Qilian ocean and the associated eastern arcs completely consumed this ocean-arc system leading to the formation of north...
Qaidam eclogites. Alternatively, the relative proportions of ocean and arc protoliths might reflect the size of the consumed ocean with high proportions of arc-related protoliths corresponding to a smaller ocean.

**Significance of the geochemical variations of Xi-Tie-Shan and Lu-Liang-Shan eclogites**

In addition to the regional spatial differences, the chemical compositions as well as Sr and Nd isotopic ratios of eclogites from each sampling location also vary systematically providing constraints on the petrogenesis of these eclogites.

**Xi-Tie-Shan eclogites**

Among the three sampling locations, eclogites from Xi-Tie-Shan show the best correlations between MgO and other major oxide contents. In previous studies, these correlations were attributed to the effects of crystal fractionation during the formation of their protoliths. Such model proposed that the protoliths of Xi-Tie eclogites were basalts derived from a common parental melts by crystal fractionation. However, our model, on the basis of trace element variations, shows the Xi-Tie eclogites were metamorphosed from three types of protoliths including (1) EMORB, (2) gabbro in equilibrium with EMORB, and (3) arc lavas with the dominance of EMORB protoliths.

**Lu-Liang-Shan eclogites**

It has long been argued whether the compositions of eclogites completely reflect that of their protoliths or control by metamorphic and metasomatic processes. The \( \varepsilon_{Nd}^{147}Sm/^{143}Nd \) systematic of Lu-Liang-Shan eclogites provides insight into the consequence of these processes. In detail, the \( \varepsilon_{Nd} \) values of the Lu-Liang–Shan eclogites, after being corrected for the metamorphic age of 450 Ma, can be divided into two groups, greater and less than 9. Those with \( \varepsilon_{Nd_{(450 \text{ Ma})}} < 9 \) (Group I) also have trace element abundances comparable to EMORB. In contrast, eclogites with \( \varepsilon_{Nd_{(450 \text{ Ma})}} > 9 \) (Group II) are also characterized by \( ^{147}Sm/^{143}Nd \) ratios high than trace element depleted N-MORB (> 16 versus ~10). More significantly, the \( \varepsilon_{Nd_{(450 \text{ Ma})}} \) values are negatively correlated with \( ^{147}Sm/^{143}Nd \) ratios, while the \( \varepsilon_{Nd} \) values vary in a small range of (16.5-18.8). The \( \varepsilon_{Nd}^{147}Sm/^{143}Nd \) and \( \varepsilon_{Nd_{(450 \text{ Ma})}}^{147}Sm/^{143}Nd \) relationships exert the following critical constraints on the petrogenesis of Group II Lu-Liang-Shan eclogites.

1. The absence of correlation between the \( \varepsilon_{Nd} \) values and \( ^{147}Sm/^{143}Nd \) ratios implying in-situ radioactive decay was not responsible for their high \( \varepsilon_{Nd} \) values.

2. The negative \( \varepsilon_{Nd_{(450 \text{ Ma})}}^{147}Sm/^{143}Nd \) correlation can be explained by two-component mixing during the formation of the protoliths of Group II eclogites. However, one of the mixing component must have a \( ^{147}Sm/^{143}Nd \) ratio similar to N-MORB with a \( \varepsilon_{Nd_{(450 \text{ Ma})}} \) value higher than N-MORB. However, such
geochemical characteristics are not observed in the terrestrial materials arguing against this two-component mixing model.

(3) The high $\varepsilon$Nd$_{(450 \text{ Ma})}$ values of $> 13$ might result from insufficient age correction owing to the modification of Sm/Nd ratios by post-metamorphism metasomatism. If the metasomatism occurred not too long after metamorphism, $\varepsilon$Nd values should be correlated with Sm/Nd ratios, inconsistent with what observed. Alternatively, recent metasomatism could lead to variation in Sm/Nd ratio with insignificant effects on the $\varepsilon$Nd values. In this model, the sample with highest Sm/Nd ratio were least affect by metasomatism because its $\varepsilon$Nd$_{(450 \text{ Ma})}$ value is comparable to that of the MORB. The high Sm/Nd ratio of this sample is consistent with concentrating garnet by metamorphic differentiation. In-growth of radioactive $^{147}$Sm resulted in the observed high $\varepsilon$Nd values of $>16$. Recent metasomatism lowered the $^{147}$Sm/$^{144}$Nd ratios. This model is favored as it satisfactorily explained the $^{147}$Sm/$^{144}$Nd, $\varepsilon$Nd, $\varepsilon$Nd$_{(450 \text{ Ma})}$ values, and the relationships of these parameters.

In summary, the $^{147}$Sm/$^{144}$Nd-$\varepsilon$Nd systematic of the Lu-Liang-Shan eclogites reflect the combined effects of two processes; first, concentrating garnet by metamorphic differentiation, then, fluid or melt-infiltration to lower the $^{147}$Sm/$^{144}$Nd ratios resulting in under-correction for the $\varepsilon$Nd$_{(450 \text{ Ma})}$ values. We plan to synthesis two manuscripts from the results from Qaidam eclogites.