Dating of zircon from Ti-clinohumite–bearing garnet peridotite: Implication for timing of mantle metasomatism

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ABSTRACT

Garnet peridotites from the Kokchetav ultrahigh-pressure (UHP) massif contain abundant volatile and high field strength element (HFSE) bearing minerals, such as Ti-clinohumite and zircon. These characteristics are interpreted to be related to fluid-infiltrated mantle metasomatism from the oceanic lithosphere that had been subducted below the area. The zircons from the peridotites were dated by using sensitive high-resolution ion microprobe (SHRIMP) and yielded apparent U-Pb ages of 554–494 Ma (weighted mean age, 528 Ma) that are mostly consistent with the timing of UHP metamorphism deduced from diamond-bearing country rocks in this massif. These zircons have an almost flat rare earth element (REE) pattern and very low REE concentrations; these characteristics are similar to those observed in kimberlitic zircons. Inherited zircon cores, although only rarely preserved, yielded apparently Proterozoic ages and have different trace element characteristics compared to the overgrowth rims. These features indicate that the mantle metasomatic events and the recrystallization of Ti-clinohumite and zircon were due to HFSE-enriched fluid infiltration during the UHP metamorphism at great depths. The metasomatized mantle may have been transported farther into the deep upper mantle and contributed to the source of intraplate magmas such as kimberlites and alkali basalts, because these rocks have characteristically high volatile and HFSE concentrations such as those of the Ti-clinohumite–bearing garnet peridotites.

Keywords: mantle metasomatism, Ti-clinohumite, zircon, U-Pb geochronology, ultrahigh-pressure metamorphism.

INTRODUCTION

Orogenic peridotites play a fundamental role in the understanding of the composition, the geophysical properties, and the geodynamic processes of Earth's upper mantle, and have therefore been intensively studied in many orogenic belts (for review, see Medaris, 1999). Peridotite bodies that locally contain garnet-bearing assemblages are widespread but minor constitutes of many ultrahigh-pressure (UHP) metamorphic terranes; most have yielded the highest pressures of metamorphic conditions for the UHP terranes, including the Dabie-Sulu terrane in central China (Zhang et al., 2002), the Western Gneiss region of Norway (van Roermund et al., 2000), and the Alpe Arami in the Austrian Alps (Dobrzhinetskaya et al., 1996). These rocks have been considered to have originated in the mantle and to have been tectonically emplaced into crustal sequences (e.g., Carswell and Gibb, 1980), or to be fragments of mantle wedge incorporated into a subducted continental slab during subduction and then subjected to UHP-HP metamorphism (e.g., Brueckner, 1998; Zhang et al., 2000). However, some ultramafic rocks were tectonically intruded into the crust prior to subduction and later subducted together with continental plate material (Yang and Jahn, 2000; Zhang et al., 2000). These garnet peridotites provide important information on the processes of slab-mantle interaction and mantle metasomatism in a deep subduction zone.

Minor garnet-bearing ultramafic rocks are associated with diamond-grade eclogite and diamondiferous gneiss and marble in the Kokchetav massif (Udovkina, 1985; Zhang et al., 1997; Okamoto et al., 2000; Muko et al., 2002). They contain abundant Ti-clinohumite coexisting with olivine and garnet; fine-grained zircons are ubiquitous as inclusions in garnet. The abundance of high field strength elements (HFSEs), such as Ti and Zr, and volatiles in the ultramafic rocks may have resulted from fluid infiltration released from downgoing oceanic lithosphere. The same characteristics of HFSE and volatile enrichment have been observed in the intraplate magmas including kimberlite and alkali basalts (e.g., Dawson, 1971) and have been considered to derive from partial melting of metasomatized mantle at great depths (e.g., Ringwood et al., 1992; Iizuka and Nakamura, 1995).

Determining the geochronologic framework is a key to constraining the origin and timing of the mantle metasomatism. From several Ti-clinohumite–bearing garnet peridotites, we extracted zircons and analyzed them with a sensitive high-resolution ion microprobe (SHRIMP) for Th-U-Pb isotopes and with laser-ablation inductively coupled plasma–mass spectrometry (ICP-MS) for rare earth element (REE) characteristics.

GEOLOGIC OUTLINE AND SAMPLE DESCRIPTION

The Kokchetav massif is in the central domain of the composite Eurasian craton (53°N, 69°E) and was formed during Cambrian collisional orogenic events (Dobretsov et al., 1995). A thin (1–2 km), coherent, subhorizontal UHP-HP metamorphic sheet is structurally bounded by low-grade metamorphic units (Kaneko et al., 2000). The UHP-HP unit mainly consists of paragneiss, orthogneiss, marble, eclogite, and amphibolite. Eclogites occur as lenticular masses within diamond-bearing gneiss and marble and yield pressure-temperature (*P-T*) conditions of >40 kbar, 780–1000 °C on the basis of existence of quartz pseudomorphs after coesite and Fe-Mg partitioning between clinopyroxene and garnet (Shatsky et al., 1995; Zhang et al., 1997). However, some eclogites yielded higher pressures (>60 kbar) and temperatures (>1000 °C) according to the K_2O-in-augite geobarometer (Okamoto et al., 2000). Metamorphic diamonds have been identified in pelitic gneisses, marbles, and garnet pyroxenites from the Kumdy-Kol region (Sobolev and Shatsky, 1990; Zhang et al., 1997; Ogasawara et al., 2000; Katayama et al., 2000).

Minor Ti-clinohumite–bearing garnet peridotites are restricted to the diamond-bearing Kumdy-Kol region (Udovkina, 1985; Zhang et al., 1997; Okamoto et al., 2000; Muko et al., 2002). They show net-

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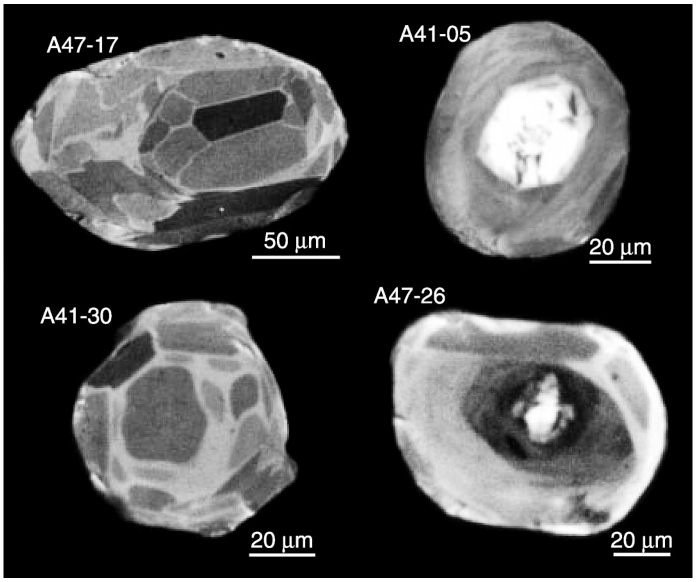

Figure 1. Cathodoluminescence image of zircons from Ti-clinohumite–bearing garnet peridotite. Some zircons contain inherited core with bright luminescence.

erogranular and granoblastic texture and are composed of garnet, Ti-clinohumite, olivine, spinel, and ilmenite with accessory minerals of apatite and zircon. Abundant Ti-clinohumite crystals, ranging from 5 to >30 vol%, occur as both a matrix phase and inclusions in garnet. Most grains contain tiny lamellae of ilmenite or blebs of ilmenite and olivine. They are relatively homogeneous in composition and contain 3.4–4.0 wt% TiO_2 and 0.7–0.8 wt% F with X_{Mg} of 0.74–0.87. Idiomorphic, coarse-grained garnets (0.1–2.0 mm in size) contain numerous inclusions of ilmenite, Ti-clinohumite, clinopyroxene, phlogopite, chlorite, amphibole, apatite, and zircon. Compositions of analyzed garnets are homogeneous and rich in pyrope component (to 63 mol%). Olivine closely associated with Ti-clinohumite commonly contains ilmenite blebs and is partly replaced by serpentine. Most green spinels rimmed by magnetite occur as interstitial phases separated from garnet by serpentine or chlorite. In a few cases, garnet is surrounded by secondary spinel.

The Ti-clinohumite–bearing garnet peridotites contain considerable amounts of zircons; most zircons are anhedral to subhedral crystals 10–50 µm in size, and some lie along specifically oriented planes within garnet and Ti-clinohumite. Zircon separates from these rocks contain very minor inclusions of garnet and apatite, which were examined by laser Raman spectroscopy. Cathodoluminescence (CL) imaging revealed that most zircons are homogeneous with stubby texture (Fig. 1), similar to zircons from granulite facies rocks (Vavra et al., 1999). Some zircon grains contain small bright inherited cores (Fig. 1). The boundary between the inherited core and stubby-shaped overgrowth is irregular and partly corroded by the rims.

ANALYTICAL METHODS

The zircon grains mounted on epoxy discs were used for U-Th-Pb dating by SHRIMP II at Hiroshima University, Japan. Instrumental conditions and measurement procedures were described in Sano et al. (2000). The spot size of the ion beam was ~20 µm; seven scans through the critical mass range were made for data collection. The $^{206}Pb/^{238}U$ ratio in the samples was calibrated by using an empirical relationship of Claoue-Long et al. (1995) and corrected by using reference zircon SL13 from Sri Lanka (572 Ma). The common-Pb correction used the $^{206}Pb/^{204}Pb$ ratio and assumed a two-stage evolution model (Stacey and Kramers, 1975).

Trace element analysis of the zircons was performed on the laser-ablation ICP-MS at the Tokyo Institute of Technology (Iizuka and Hirata, 2002). Ablation was done with a pulsed 193 nm Ar Excimer laser with 140 mJ energy at a repetition rate of 5 Hz and pit size of 20 µm. A helium stream was used to transport the sample effectively and reduce deposition at the ablation site (Eggins et al., 1998). Detection limits were ~<0.05 ppm for most REEs.

RESULTS AND DISCUSSION

The ion-microprobe data and trace element concentrations of the analyzed zircons are summarized in Tables 1 and DR1[1] and graphically presented on Tera-Wasserburg diagrams with 1σ errors (Fig. 2) and spider diagrams normalized to chondrites (Fig. 3). The two different domains of zircon in the CL images (Fig. 1) revealed clearly different isotopic features and trace element concentrations. The inherited cores contain higher U concentrations, to 799 ppm, compared to those of the stubby domains. U-Pb isotope data of the stubby domains are mostly concordant (Fig. 2) and yield apparent $^{206}Pb/^{238}U$ ages ranging from 554 to 494 Ma (weighted mean age 528 Ma). The inherited cores show large scattered isotopic ratios (Fig. 2), indicating that they have been affected by several Pb-loss events. If it is assumed that Pb loss from

[1]GSA Data Repository item 2003101, Table DR1, rare earth element contents of zircons, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA, editing@geosociety.org, or at www.geosociety.org/pubs/ft2003.htm.

TABLE 1. U-Th-Pb SHRIMP DATA OF ZIRCONS FROM THE Ti-CLINOHUMITE–BEARING GARNET PERIDOTITES

Sample	Domain	Content (ppm)			Th/U	$^{207}Pb^*/^{206}Pb^*$	$^{238}U/^{206}Pb^*$	Age (Ma)	
		U	Th	^{206}Pb				$^{206}Pb^*/^{238}U$	$^{207}Pb^*/^{206}Pb^*$
A41-01.01	stubby	184.1	21.6	14.367	0.120	0.0608 ± 0.0011	11.134 ± 0.017	554.4 ± 8.2	516.7 ± 79.2
A41-02.01	stubby	212.4	26.2	15.906	0.127	0.0613 ± 0.0014	11.573 ± 0.214	534.3 ± 9.5	611.1 ± 64.0
A41-13.01	stubby	194.8	23.0	14.223	0.121	0.0594 ± 0.0008	11.892 ± 0.235	520.5 ± 9.9	491.3 ± 53.0
A41-14.01	stubby	168.9	24.6	11.673	0.149	0.0573 ± 0.0011	12.546 ± 0.307	494.4 ± 11.7	445.5 ± 63.1
A41-24.01	inherited	799.2	654.7	62.237	0.840	0.0706 ± 0.0011	11.251 ± 0.155	548.9 ± 7.2	633.0 ± 71.2
A41-25.01	stubby	126.4	14.6	9.2164	0.119	0.0622 ± 0.0013	11.988 ± 0.429	516.5 ± 17.8	375.9 ± 105.3
A41-27.01	inherited	407.4	42.4	41.036	0.107	0.0841 ± 0.0008	8.602 ± 0.383	709.0 ± 29.9	1274.2 ± 21.8
A41-30.01	stubby	242.7	27.2	18.259	0.115	0.0593 ± 0.0008	11.512 ± 0.143	537.0 ± 6.4	564.8 ± 32.8
A47-15.01	stubby	208.0	24.3	15.663	0.120	0.0591 ± 0.0009	11.498 ± 0.222	537.6 ± 10.0	561.0 ± 40.5
A47-16.02	inherited	386.3	15.0	33.028	0.040	0.0629 ± 0.0006	10.124 ± 0.343	607.2 ± 19.6	701.7 ± 21.2
A47-17.01	stubby	318.0	43.5	22.545	0.140	0.0584 ± 0.0010	12.231 ± 0.201	506.6 ± 8.0	483.0 ± 50.0
A47-17.02	stubby	175.0	16.5	13.213	0.097	0.0608 ± 0.0010	11.477 ± 0.279	538.5 ± 12.5	598.1 ± 44.1
A47-25.01	inherited	519.1	7.1	38.373	0.014	0.0590 ± 0.0006	11.710 ± 0.316	528.3 ± 13.7	564.4 ± 24.5
A47-25.02	stubby	261.8	6.3	19.058	0.025	0.0586 ± 0.0011	11.921 ± 0.268	519.3 ± 11.2	475.6 ± 55.1
A47-26.01	inherited	427.0	5.5	29.236	0.013	0.0587 ± 0.0015	12.651 ± 0.288	490.4 ± 10.7	534.5 ± 57.8
A47-30.01	stubby	225.2	22.4	16.547	0.102	0.0580 ± 0.0010	11.799 ± 0.536	524.4 ± 24.0	477.7 ± 89.0
A47-31.01	stubby	188.9	17.2	14.123	0.093	0.0591 ± 0.0011	11.603 ± 0.284	532.9 ± 12.5	502.7 ± 62.4

Note: Pb* corrected for common Pb using ^{204}Pb. All errors are 1 sigma of standard deviation.

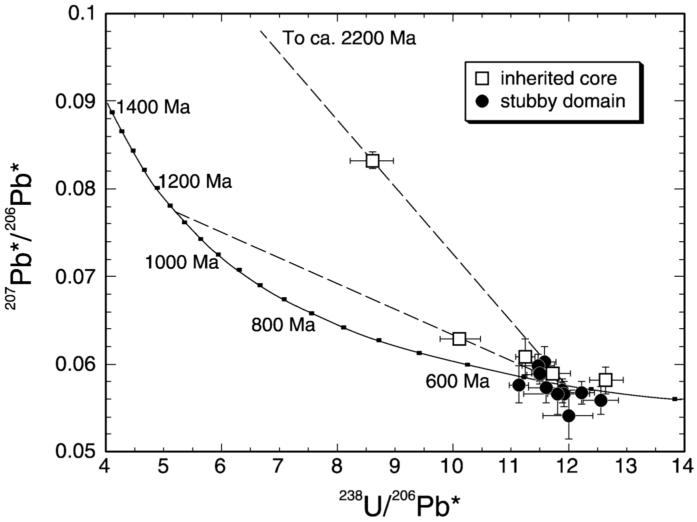

Figure 2. Tera-Wasserburg diagram of SHRIMP analyses of zircons from Ti-clinohumite garnet peridotite. Inherited cores show relatively scattered isotopic data compared to stubby domains. Asterisk indicates radiogenic isotope.

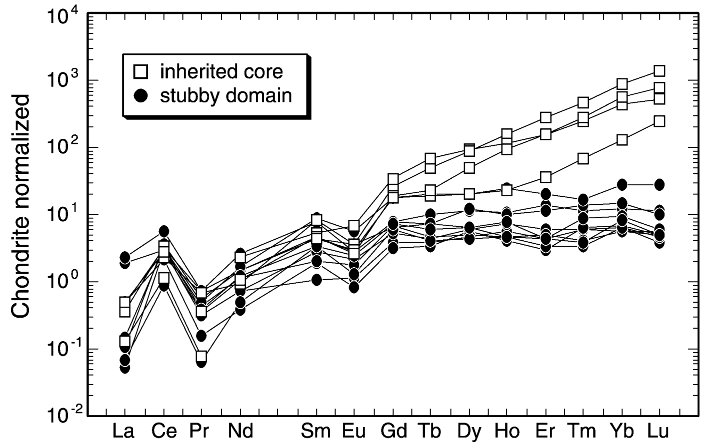

Figure 3. Rare earth element (REE) pattern of zircons normalized to chondrites through use of abundances given by Anders and Grevesse (1989). Inherited cores and stubby domains show clearly different REE patterns; inherited domains are characterized by higher heavy REE abundance compared to stubby domains.

the cores occurred at the time of the latest thermal event that affected the rocks (ca. 520 Ma), the upper intercepts of presumed mixing lines (discordias) indicate that the inherited cores may have grown in the Proterozoic (ca. 2200–1100 Ma). The country gneisses in this massif also contain several inherited zircons of Middle Proterozoic age (Claoue-Long et al., 1991; Katayama et al., 2001). The stubby zircon domains contain a very low concentration of heavy (H) REEs (Yb $<$ 6.7 ppm) and are characterized by an approximately flat REE pattern (Fig. 3 and Table DR1 [see footnote 1]). The REE characteristics of stubby zircon domains from the Ti-clinohumite garnet peridotites are similar to those reported in kimberlite (Heaman et al., 1990; Belousova et al., 2002). The inherited zircon cores have a different REE pattern, i.e., relatively steep with pronounced HREE enrichment (Yb/Gd $>$ 9.60 and Yb $>$ 64.0 ppm; Fig. 3). These patterns were interpreted to indicate that the inherited cores are similar to zircons grown at depths where plagioclase or spinel are stable, and the stubby rims were grown at greater depths where garnet is stable, and hence show a flat pattern. The Proterozoic zircon cores may represent a relict origin of emplacement and recrystallization of the peridotites at relatively shallow depths. However, the stubby zircon domains yielded ages for the UHP metamorphism similar to those obtained from the adjacent pelitic gneisses and eclogite, which yielded zircon SHRIMP dates of 537–530 Ma (Claoue-Long et al., 1991; Katayama et al., 2001). The peak UHP age in this region was initially reported by Claoue-Long et al. (1991) through average age distribution of analyzed zircons (530 $\pm$ 7 Ma), but subsequently determined precisely using CL pattern and microinclusion assemblages (537 $\pm$ 9 Ma; Katayama et al., 2001). The comparison of the radiogenic ages of the ultramafic rocks and country rocks is shown in Figure 4. The Sm-Nd mineral isochrons from the diamond-bearing rocks and associated rocks have also yielded similar peak UHP ages of 535–524 Ma (Shatsky et al., 1999). Garnet peridotites from the other UHP terranes, including the Alps and the Erzgebirge, yielded Sm-Nd ages similar to those of the country gneisses and eclogites (Becker, 1993; Schmadicke et al., 1995). However, a large age contrast between garnet peridotites and eclogites in the country rocks was reported in the Norwegian Caledonides (Brueckner et al., 1996) and the Sulu terrane (Yang and Jahn, 2000), and was interpreted as relict peridotites emplaced in crustal sequence before subduction.

Chemical features of the garnet peridotites, characterized by high H_2O and HFSE concentrations, require a metasomatic process in the subduction zone. Many lines of evidence indicate that microdiamonds from the Kumdy-Kol area were precipitated from supercritical fluid or melt during the UHP metamorphism (De Corte et al., 1998; Dobrzhinetskaya et al., 2001). Such fluid or melt may have migrated into the mantle rocks and contributed to the crystallization of zircon and Ti-clinohumite in the ultramafic layer at great depths. The stability of Ti-clinohumite has been experimentally investigated; it is considered to be stable at depths $>$150 km, depending on the coexisting phases present and its composition (Merrill et al., 1972; Engi and Lindsley, 1980; Weiss, 1997). The studied garnet peridotites formed at $>$35 kbar on the basis of (1) the coexistence of Ti-clinohumite with olivine and ilmenite and (2) the low F content of Ti-clinohumite. Iizuka and Nakamura (1995) performed sandwiched experiments of basaltic and peridotitic materials at high P-T conditions and succeeded in forming Ti-

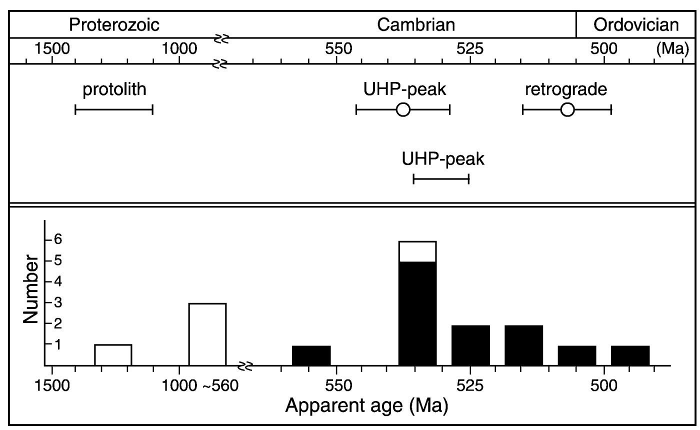

Figure 4. Comparison of radiogenic ages of Ti-clinohumite–bearing garnet peridotites and previous data from diamond-grade country rocks in Kokchetav massif. Zircon U-Pb dating of country rocks yielded different stages, originated from protolith (1400–1100 Ma), ultrahigh-pressure (UHP) peak (537 $\pm$ 9 Ma), and retrograde (507 $\pm$ 8 Ma), which was assisted with microinclusion assemblages in zircon (detail in Katayama et al., 2001). Sm-Nd age was derived from country gneisses and eclogites in same region, which yielded 535–524 Ma (Shatsky et al., 1999). In Ti-clinohumite–bearing garnet peridotites, apparent age is $^{206}Pb/^{238}U$ age for stubby domains (black bar; i.e., UHP peaks) and $^{207}Pb/^{206}Pb$ age for inherited cores (white bar; i.e., protolith). Top panel, top line—zircon U-Pb of diamond-bearing gneisses (Katayama et al., 2001); top panel, bottom line—Sm-Nd of mineral isochrons (Shatsky et al., 1999); bottom panel—zircon U-Pb of Ti-clinohumite–bearing garnet peridotites (this study).

clinohumite in the peridotite layer at 80 kbar (corresponding to 240 km depth).

In essence, garnet peridotites of possible Proterozoic age were metasomatized during the subduction of the Kokchetav supracrustal rocks to depths of >200 km. Some fragments of the metasomatized mantle rocks were trapped in the slab and exhumed together with diamond-grade UHP metamorphic rocks. However, most parts of the metasomatized peridotites probably have been transported to even greater depths by corner convection of the mantle wedge and have served as important fluid carriers to the mantle boundary layer. The deeply transported metasomatized rocks could contribute to sources of intraplate magmas such as kimberlites and alkali basalts, because these rocks have high volatile and HFSE concentrations similar to those of the Ti-clinohumite–bearing garnet peridotites.

ACKNOWLEDGMENTS

We thank Y. Ogasawara, K. Okamoto, and S. Omori for helpful discussion and K. Horie for support of sensitive high-resolution ion microprobe (SHRIMP) analyses. Constructive comments by N.V. Sobolev and an anonymous reviewer helped to improve this manuscript. Supported in part by a research fellowship of the Japan Society for the Promotion of Science (to Katayama) and in part by the Civilian Research Development Fund (RG1-2387-NO-02).

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Manuscript received 28 January 2003
Revised manuscript received 21 April 2003
Manuscript accepted 23 April 2003

Printed in USA

Geology

Dating of zircon from Ti-clinohumite–bearing garnet peridotite: Implication for timing of mantle metasomatism

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Geology 2003;31;713-716
doi: 10.1130/G19525.1

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