Linking granulites, silicic magmatism, and crustal growth in arcs: Ion microprobe (zircon) U-Pb ages from the Hidaka metamorphic belt, Japan

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ABSTRACT

There is no consensus as to how the extreme metamorphic conditions required to form granulites are attained, or how these rocks relate to crustal growth and differentiation processes. Studying young granulites offers two advantages: the tectonic setting is likely to be well constrained, and the ambiguities that result from overprinting by younger metamorphic events are potentially avoided. We report the first ion microprobe U-Pb (zircon) ages for orthopyroxene-bearing granulites, tonalites, and gabbros of the Cenozoic Hidaka metamorphic belt (Hokkaido, Japan) to clarify the magmatic-metamorphic connection in this area. The data support a two-stage evolution for this terrane, which is attributed to episodes of supra-subduction zone magmatism (late Eocene) and back-arc extension (early Miocene). We relate granulite facies metamorphism and garnet-orthopyroxene tonalite generation to mafic magma under-accretion and lithosphere thinning due to the opening of the Japan Sea at 19 Ma. The Hidaka granulites are thus among the youngest exposed granulites on Earth, and manifest the thermal response to continental growth.

Keywords: Granulite, zircon, U-Pb dating, Hidaka metamorphic belt.

INTRODUCTION

The formation of granulites continues to attract controversy. The nature of the heat source and the tectonic controls responsible for high to ultra-high temperatures (750 °C to >1000 °C) at moderate pressures are particularly contentious. What are the relative roles of extension and mafic magma underplating in accretionary arc-backarc systems, as opposed to crustal thickening during collisional orogenesis in the formation of these rocks (Sandiford and Powell, 1986; Ellis, 1987; Harley, 1989; Collins, 2002; Brown, 2003, 2007)? This bears on the fundamental question of whether granulites are intimately linked to the generation of new crust, implicit within an arc-backarc origin, or whether they simply manifest intra-crustal reworking during continental assembly. The answers lie with the study of young granulites, which are less likely to have experienced structural/metamorphic overprints, and whose tectonic context is easier to establish.

The Hidaka metamorphic belt (Hokkaido, Japan) provides a rare occurrence of Cenozoic granulites at Earth's surface, and is a key area in the quest for a better understanding of granulite formation. Uplifted by a Miocene collision between the Japan and Kuril arcs (Kimura, 1986), this terrane comprises a remarkably complete arc sequence that encompasses upper mantle to shallow crustal depths (Komatsu et al., 1989; Osanai et al., 1991). Migmatitic metasedimentary and metabasic granulites are widespread in the lower part of the sequence, juxtaposed with voluminous tonalitic to gabbroic intrusives. There are two conflicting tectonic scenarios for granulite formation and magmatism in this area. Maeda and Kagami (1996) proposed that the granulites formed from accretionary wedge materials in a forearc setting in response to a thermal pulse triggered by subduction of the Kula-Pacific ridge in the late Paleocene (ca. 55 Ma). Tholeiitic gabbros that are chemically akin to mid-oceanic ridge basalts (MORB), which locally comprise 30% of the section, are the supposed magmatic manifestation of this collision. In contrast, Kimura (1996), reiterated by Usuki et al. (2006), attributed granulite generation and plutonism to incipient rifting of the Hidaka crust during opening of the Japan and Kuril basins at 25–17 Ma. This idea receives support from ion microprobe ages of 24–17 Ma for zircons of metasedimentary (but orthopyroxene-free) gneisses from the central Hidaka belt (Usuki et al., 2006). The resolution of these models hinges upon the critical timing relationships between granulite facies metamorphism, mafic-silicic magmatism, and the inferred ridge subduction and rifting events, which remain poorly constrained.

To address these issues, and to clarify the interplay between granulite genesis and crustal growth, we report new ion microprobe U-Pb data from zircons of metasedimentary granulites and key igneous samples from the Hidaka metamorphic belt. The data reveal that the Hidaka sequence was constructed in two thermal pulses in the Eocene (37 Ma) and early Miocene (19 Ma). We correlate these with episodes of continental arc magmatism and backarc spreading, respectively (the latter involving basaltic input and granulite facies metamorphism), and we discuss the significance of granulites for continental crustal evolution.

GEOLOGICAL SETTING

The Hidaka metamorphic belt constitutes an arcuate 10–20-km-wide, 140-km-long strip of ultramafic, plutonic, and metamorphic rocks that occupy the southeastern part of Hokkaido (Fig. 1). The belt occurs inboard of the present-day junction between the Japan and Kuril trenches and continues northwest beneath Quaternary volcanic deposits to Sikhote-Alin and Sakhalin, where time-equivalent plutonic and volcanic rocks outcrop (Okamura et al., 1998, 2006). Metamorphic grade, and inferred crustal depth, in the Hidaka sequence decreases from granulite facies in the west to zeolite facies in the east under a high geothermal field gradient of 40 °C/km (Komatsu et al., 1989). Metamorphic rocks define a clockwise pressure-temperature-time path (Osanai et al., 1991, 1992), as commonly inferred for granulites (e.g., Harley, 1989), with estimated peak metamorphic grades (~870 °C, 730 MPa) approaching ultra-high temperature conditions (Harley, 1989). The metasedimentary protoliths are correlated with the Nakanogawa Group, which was deposited in a near-trench environment near the Eurasian continental margin from the Cretaceous to Eocene (Kimura, 1994). At the deepest levels, the Hidaka metamorphic sequence is dominated by metabasic granulites and amphibolites derived from basaltic precursors, intercalated with metapelitic granulite horizons. Sheets of orthopyroxene tonalite containing peraluminous (garnet ± cordierite) or metaluminous (hornblende) minerals are abundantly distributed throughout these units, and crystallized under granulite facies conditions at initial temperatures exceeding 900 °C (Shimura et al., 1992, 2004). Felsic igneous rocks emplaced at higher crustal levels are increasingly differentiated and form homogeneous granite plutons at shallow depth. K-Ar and Rb-Sr mineral ages for the Hidaka intrusives cluster between 40 and 28 Ma and 20–15 Ma (Arita et al., 1993; Saheki et al., 1995). However, the accepted timing of peak metamorphism and plutonism in this area is ca. 55 Ma, based on apparent whole-rock Rb-Sr isochrons defined by granulite-garnet tonalite samples (Owada et al., 1991) and a hornblende tonalite (Owada et al., 1997).

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SAMPLE DETAILS

Zircon U-Pb isotope data were acquired for nine samples: a pyroxene gabbro, three metasedimentary granulites, one amphibolite, three orthopyroxene tonalites, and a high-level granite (Fig. 1). The gabbro (P2) was sampled from the upper part of the Pankenushi layered gabbro complex in the northern part of the metamorphic belt, overlying a 5-km-thick cumulate olivine gabbro-troctolite-anorthosite succession. These gabbros are MORB-like, and crystallized from dry parental magmas in the deep crust (Maeda and Kagami, 1996). The metamorphic rocks were obtained from two different localities in the lowermost part of the sequence. These include a garnet-orthopyroxene-cordierite gneiss (4HB29), orthopyroxene-cordierite-gedrite gneiss (HB1) and brown hornblende amphibolite (HB2) from the Horobetsu River, and a garnet-orthopyroxene gneiss enclave (HD19e) from the Pankenushi River 50 km further north. The Horobetsu granulites host thin layer-parallel and thicker discordant leucosomes that contain coarse orthopyroxene lozenges and either garnet (4HB29) or cordierite prisms (HB1), the latter enclosing acicular zircons. These and other granulite outcrops in the Hidaka Belt show abundant evidence for melt segregation and accumulation in interboudin partitions and dilatent shear zones. The garnet-orthopyroxene tonalite samples derive from intrusives in the Pankenushi River (HD19) and Niikappu River areas (HD23). Garnet-aluminous orthopyroxene pairs of sample HD19 preserve equilibria established at 650 MPa and 890 °C (Shimura et al., 2004), the highest grade conditions reported for the Hidaka tonalites. An orthopyroxene-hornblende tonalite was also collected from the Niikappu River, occurring as a sheet enclosed within peraluminous tonalite. Lastly, a hornblende granite sample was obtained from the Nupinai pluton, which intrudes biotite-grade metagreywackes.

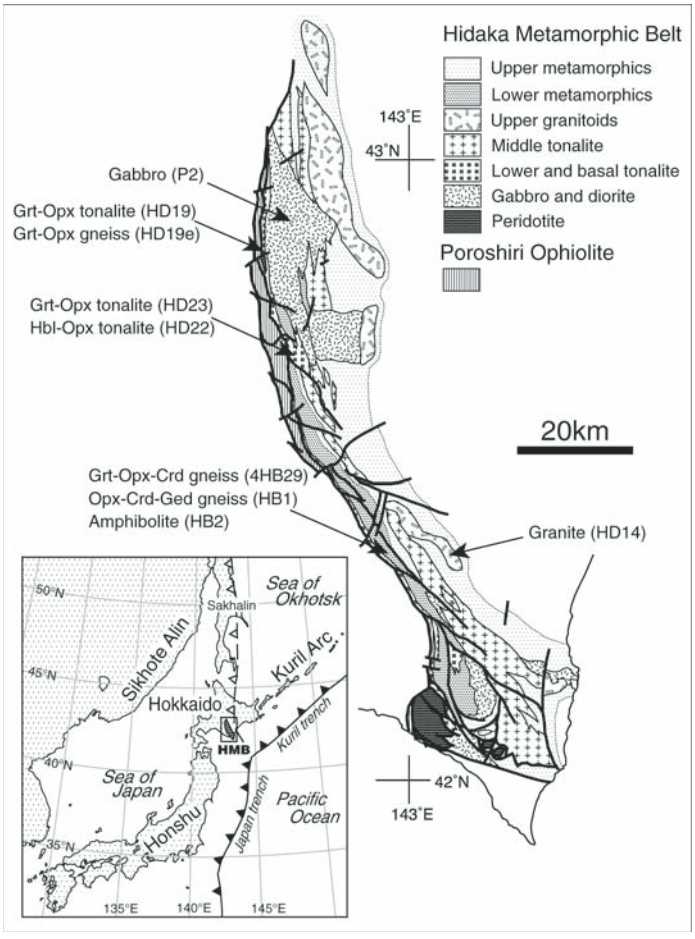


Figure 1. Geologic map of the Hidaka metamorphic belt (HMB) showing sample localities (mineral symbols after Kretz, 1983). The Hidaka Main Thrust (HMT) delineates the base of the sequence. Inset depicts the outcrop area of HMB in relation to extant arc-trench systems and the inferred northern extension of the Japan trench in the Paleogene (dashed line; from Kimura, 1994).

RESULTS

Zircons from each rock were mounted in epoxy, polished, and imaged by cathodoluminescence (CL) at Niigata University. Most zircons from the granulites and garnet tonalites show pronounced core-rim structures, such that oscillatory or sector-zoned cores are mantled by CL-bright euhedral overgrowths that may have fine oscillatory zoning or may be almost featureless (Figs. 2A–2C, 2E). The cores are commonly embayed and partially resorbed (Fig. 2B). Elongate sector-zoned grains without discernible cores represent a minor population (Fig. 2D) that in the granulites are CL-dark and U-rich. The zoning characteristics of zircons from the other rocks accord with single-stage growth. Broad oscillatory and sector zoning occurs in zircons from the gabbro and hornblende tonalite, whereas the granite-hosted zircons exhibit the intricate oscillatory zoning typical of zircons precipitated from differentiated magmas (Fig. 2F). The gabbro zircons are anhedral, presumably reflecting crystallization in interstitial melt pockets, whereas short prismatic crystal forms predominate in the hornblende tonalite and granite. The amphibolite zircons are equant and multifaceted, with irregular sector and fir-tree zoning and diffuse banding, as characteristic of zircon growth during high-grade metamorphism (Corfu et al., 2003).

The U-Pb isotope data (Table DR1 in the GSA Data Repository[1]) were acquired with a Cameca 1270 ion microprobe at the University of Edinburgh. The granulite zircon cores have a spectrum of apparent ages, with a dominant peak at 50–60 Ma (Fig. 3A). However, the pooled rim analyses, and analyses of acicular zircons, define a precise age group at 19.3 ± 0.3 Ma (Fig. 3B). These zircon rims extend to very low Th/U ratios (0.3 to <0.01). The amphibolite zircons also have moderately low Th/U ratios (0.23–0.13) and are indistinguishable in age from the granulite zircon rims (18.7 ± 0.5 Ma; Fig. 3B), but lack evidence for older cores. We interpret these data to reflect zircon growth during granulite facies metamorphism

[1]GSA Data Repository item 2007198, ion microprobe U-Pb (zircon) isotope data for rocks of the Hidaka metamorphic belt, Japan, is available online at www.geosociety.org/pubs/ft2007.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

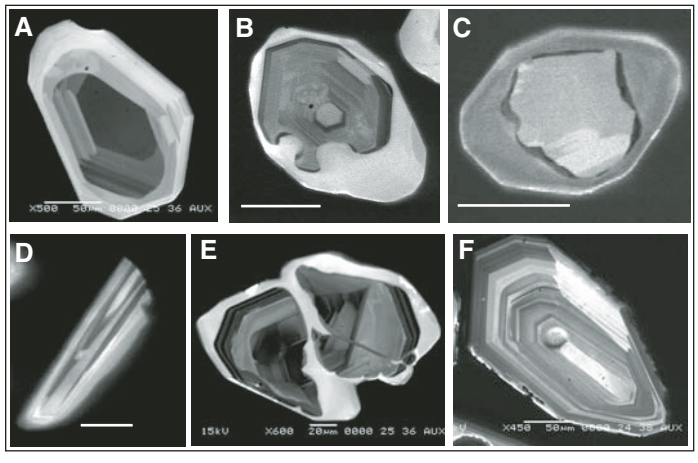


Figure 2. Cathodoluminescence images of zircons from the Hidaka samples. A and B: Grt-Opx tonalite HD19. C: Grt-Opx-Crd granulite 4HB29. D: Grt-Opx tonalite HD23. E: Grt-Opx granulite HD19e. F: Hbl granite HD14, with an ion microprobe pit visible in the center. Scale bars are 50 μm, except in E (20 μm).

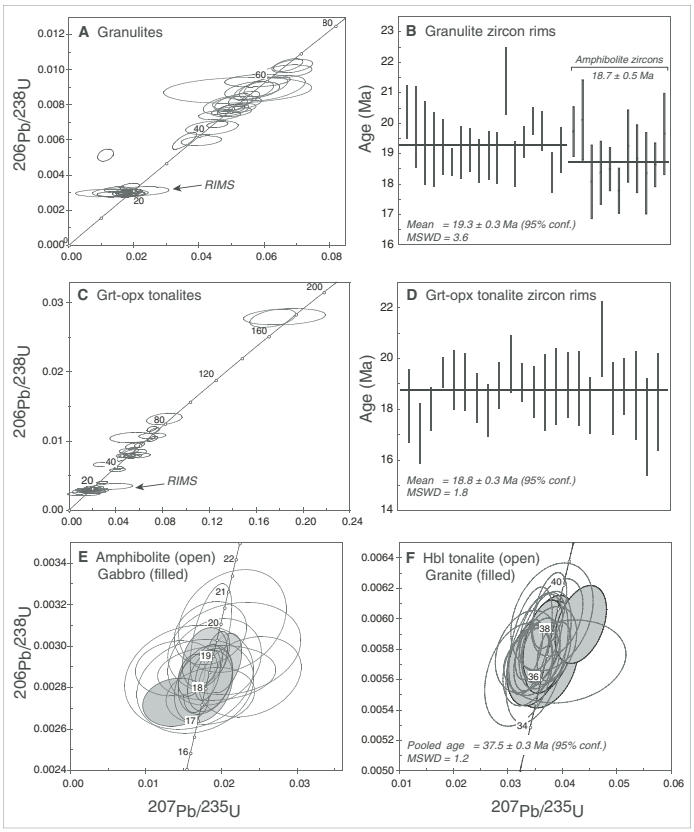


Figure 3. Concordia diagrams and weighted average $^{206}Pb/^{238}U$ ages for zircons of the Hidaka belt samples (error ellipses and error bars are 2σ). All data are corrected for common lead. Nine analyses with ages between 205 Ma and 2740 Ma are not shown in A.

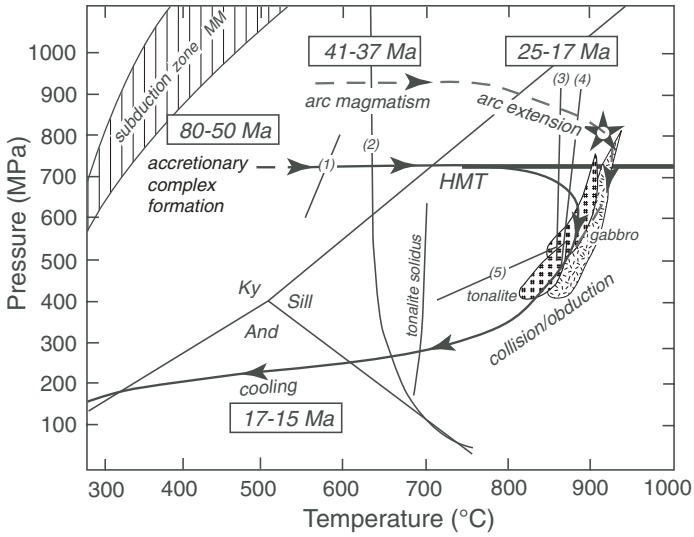


Figure 4. Re-interpretation of the tectono-metamorphic evolution of the Hidaka belt, showing a generalized *P-T*-time trajectory that links the new geochronological data to inferred tectonic setting. Vertical striped field, defined by blueschist belts (Ernst, 1988), shows the possible early *P-T* path of the accretionary prism precursors to the Hidaka granulites (e.g., as inferred by Osanai et al., 1992; the forearc accretion age is from Kimura, 1994) prior to magmatic heating at ca. 37 Ma and extension at 25–19 Ma (dashed arrowed path), leading to peak crustal anatexis and granite generation (star symbol). The solid *P-T* loop is deduced for the exposed granulites (Osanai et al., 1992). Cooling ages reflect the K-Ar closure temperature in micas. Metamorphic reactions are (1) Ms+Chl = St+Bt+Qtz+H_2O; (2) Ms+Qtz+H_2O = Als+Kfs+L; (3) Bt+Sill+Qtz = Grt+Kfs+L; (4) Bt+Plag+Qtz = Grt+Opx+Kfs+L; (5) Bt+Sill+Qtz = Crd+Kfs+L (Osanai et al.; 1992; Shimura et al.; 2004).

and incipient anatexis near 19 Ma, with the cores of the granulite zircons being relict protolith (detrital) grains. Formation of the 19 Ma zircon in part reflects melt crystallization, so this age might slightly post date the thermal peak. Nevertheless, the inferred Miocene metamorphic age overlaps that quoted by Usuki et al. (2006) (20.6 ± 1.0 Ma) and confirms that the Hidaka granulites are among the youngest exposed on Earth. Zircons in the garnet tonalites show similar age patterns to the granulite-hosted zircons (Figs. 3C, 3D). In this case, we consider the rim ages to denote tonalite magma crystallization at 18.8 ± 0.3 Ma, and attribute the older cores to inherited relics from a metasedimentary protolith. A single zircon age population at 18.5 ± 0.3 Ma (Fig. 3E) suggests that consolidation of the gabbro coincided with granulite and garnet tonalite generation.

In contrast, zircons in the hornblende tonalite and granite are significantly older (Fig. 3F), yielding tightly clustered $^{206}Pb/^{238}U$ ages near 37 Ma. There is no evidence for inheritance or younger rims. These data are the first compelling indication of widespread late Eocene plutonism in the Hidaka belt.

TECTONIC CONTROLS ON GRANULITE FORMATION

Previous tectonic models for the Hidaka metamorphic belt (e.g., Maeda and Kagami, 1996) have been hampered by the concept of magmatism and peak metamorphism at 55 Ma, even though bimodality has long been implied by the K-Ar ages. In pinpointing dual thermal pulses in the Hidaka belt at 37 Ma and 19 Ma, our results demand a re-appraisal of the tectonic and metamorphic evolution of this terrane (Fig. 4).

The key to understanding these events lies with the geochemistry of contemporaneous igneous rocks, especially those of Sakhalin–Sikhote Alin. Eocene volcanic activity on Sakhalin involved the eruption of arc basalts above a west-dipping subduction zone that represents the northern extension of the modern Japan arc (Okamura et al., 2006). We infer an analogous continental arc setting for the Hidaka belt in the late Eocene (see Kimura, 1994). In addition to the hornblende tonalite and granite dated herein, a gabbroic complex in the southern Hidaka has also been dated at 35 Ma (K-Ar; Ishihara and Terashima, 1985). The gabbros are distinctive in being calc-alkaline, having primary hydrous phases, and being associated with Cu-Ni sulphide deposits (Takahashi, 1983), all of which suggest an arc-related genesis. Intrusion of felsic and mafic plutons into forearc and trench-fill metasedimentary units might reflect prior thickening and underthrusting of the accretionary prism due to high sediment supply (Kimura, 1994), or be due to arc retreat (e.g., Collins, 2002).

Tholeiitic and MORB-like olivine gabbros represent the major phase of mafic magmatism in the Hidaka belt and are voluminously expressed in the Pankenushi gabbro complex. Our results demonstrate that the emplacement of these rocks coincided with initial backarc spreading in the nascent Japan Sea and Kuril basin in the early Miocene (25–17 Ma), as the Hidaka belt evolved from a continental arc to an oceanic backarc realm. The Pankenushi gabbros thus formed in response to the upwelling of MORB-source mantle during regional extension induced by rollback of the Japan and Kuril arc systems, rather than by ridge-trench interaction. Synchronous zircon crystallization in these gabbros and the granulites is the best evidence yet linking granulite facies metamorphism in the Hidaka belt to basaltic input coupled with lithospheric thinning during backarc extension at ca. 19 Ma (Kimura, 1996; Usuki et al., 2006), manifest by the thermal peak along the decompression segment of the *P-T* path (Fig. 4). Decompression, in tandem with mafic magma under-accretion, facilitated biotite dehydration melting in the metapelites, as consistent with the outcrop evidence for widespread syn-anatectic extension. This process conceivably generated the

19 Ma garnet-orthopyroxene tonalites (Osanai et al., 1992; Shimura et al., 2004). Mantle-derived heat sources are commonly invoked to explain high-temperature metamorphism (e.g., Bohlen and Mezger, 1989), but only rarely (e.g., Yoshino and Okudaira, 2004) can a direct field and chronological connection be made. Granulites formed in this way may have isobaric cooling paths and remain at depth (Sandiford and Powell, 1986), but the Hidaka granulites were obducted shortly after formation by collision between the Japan arc and the Kuril forearc, as the latter rotated and migrated southwestward during oblique subduction and Kuril basin opening (Kimura, 1986). Rapid uplift and cooling explains the overlap between the zircon U-Pb ages for the granulites and the K-Ar ages.

Granulite generation in the Hidaka metamorphic belt involved the reworking of older protoliths, but was due to the enhanced heat flux attending subduction zone retreat and the addition of juvenile crust. There is increasing recognition of the potential for granulite genesis in backarcs, and of the role of backarc environments in crust formation (Collins, 2002; Brown, 2007). We note that in the ancient rock record, the ages of granulite terranes cluster in narrow time windows near 2.7, 1.9, and 1.1 Ga (Harley, 1989; Brown, 2006) that correspond with peaks of accelerated crustal growth (Condie, 1998). Far from being a petrological anomaly, granulite-facies metamorphism may be a hallmark of tectonically driven mantle differentiation processes and continental growth on Earth.

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