Role of partial melting in the evolution of the Sulu (eastern China) ultrahigh-pressure terrane

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Abstract

Strongly deformed potassium feldspar-rich dikes are widely distributed in the northern part of the Sulu ultrahigh-pressure (UHP) metamorphic terrane, eastern China. The fact that the crystallization ages of these dikes overlap with the age of peak UHP metamorphic conditions implies the presence of melt during metamorphism. Sr isotopic ratios of the dikes are compatible with their origin as partial melts of the dominant felsic Sulu gneiss. Partial melting may be the key to solving several unusual features of the Sulu and other UHP terranes, such as the almost complete lack of mineralogical evidence for UHP conditions and the limited growth of zircon during UHP conditions in the dominant felsic gneiss. In addition, because partial melting will cause a drastic reduction in the strength of the UHP gneisses, the most likely exhumation mechanism is diapirc rise of a low-viscosity, partially molten mass containing entrained blocks of eclogite, and not a thin sheet as usually proposed.

Keywords: Sulu terrane, melting, ultrahigh-pressure metamorphism, radiometric age, exhumation tectonics.

MELTING OF ULTRAHIGH-PRESSURE TERRANES

Ultrahigh-pressure (UHP) metamorphic terranes form at depths in excess of 90 km, and studies of these regions are one of the few ways to obtain information on processes occurring in the root zones of major collisional belts. Typically UHP terranes consist almost entirely of felsic gneiss, and the properties of this rock type will determine the large-scale behavior of the terrane. However, because the felsic gneiss only very rarely preserves evidence for UHP conditions (e.g., Ye et al., 2000) most studies have focused on the mafic eclogite units that occur as scattered blocks or lenses within the gneiss. UHP metamorphism commonly reaches temperatures in excess of 800 °C at pressures of 3 GPa or more (e.g., Ernst and Liou, 1999). Under these conditions, partial melting of the felsic gneisses is a likely process, and will occur in the presence of free water (e.g., Huang and Wyllie, 1981). Melting could also take place by breakdown of hydrous minerals such as phengite. In some UHP terranes such as the Sulu belt of eastern China, the likelihood of melting is also suggested by the development of roughly isothermal decompression paths through much of the exhumation history (Banno et al., 2000; Nakamura and Hirajima, 2000), which would favor decompression melting. If melting took place it would have a major effect on the physical and chemical properties of the UHP terrane, and the possible importance of this process was emphasized by Wallis et al. (1999) and Hermann et al. (2001). However, direct evidence for partial melting related to UHP metamorphism has only been reported on a very small scale (Philippot, 1993; Ye et al., 2001). In general, the anhydrous nature of UHP belts is emphasized (Rumble, 1998), and the role of partial melting is thought to have been insignificant (e.g., Liou et al., 1995).

Here we present new evidence that suggests that the Sulu UHP terrane has undergone syn-metamorphic partial melting and that the melting products are locally preserved. We suggest that only by considering this process can the history of the belt be properly understood, including explanation of preservation of UHP minerals, interpretation of zircon U-Pb ages, and elucidation of appropriate exhumation processes.

AGE DISTRIBUTIONS IN THE SULU BELT

The Sulu terrane is contemporaneous with the Dabie terrane to the west (Ames et al., 1993) (Fig. 1), and together they constitute the largest domain of UHP metamorphism in the world. We refer to the dominant felsic gneiss as the Sulu gneiss. Scattered within the Sulu gneiss are a large number of blocks or lenses of eclogite, peridotite, and marble (e.g., Wallis et al., 1999; Wang et al., 1995). The Sulu terrane is thought to have originated as the northern fringes of the Southern China (or Yangtze) block and to have undergone UHP metamorphism when it was subducted below the Northern China (or Sino-Korean) block during the Triassic (e.g., Ames et al., 1996; Ernst and Liou, 1995). Geochronological studies show there were three main stages in the evolution of the Sulu belt: (1) protolith formation at 800–700 Ma (Ames et al., 1996), (2) UHP metamorphism that peaked ca. 230 Ma (Li et al., 1999), and (3) Cretaceous, largely posttectonic, granitic plutonism (Liou et al., 1999). To confirm the published protolith age and to investigate the effects of the UHP metamorphism on zircons of the granitic Sulu gneiss, we used the high-spatial-resolution chemical thorium–uranium–total lead isochron method (CHIME) that has an analytical spot size of ~5 μm. The cores of the zircon grains indicate a formation age of 709 ± 39 Ma (Figs. 2A, 2D), in agreement with the published protolith ages for the Sulu region. The rims show a scatter of ages, including some localized spots suggesting ages of ca. 240 Ma (Fig. 2D). The location of the spots having young ages shows no clear association with the growth zoning observed in backscattered-electron images. We therefore interpret the age distribution as representing incomplete isotopic reequilibration in the rims during UHP metamorphism with little or no evidence for contemporaneous growth of zircon.

FIELD EVIDENCE FOR MELTING

In the northern Sulu terrane, two field observations suggest the possibility of partial melting: (1) the presence of gneiss displaying localized patches with an igneous texture (see Fig. 5C in Wallis et al., 1999) and (2) the widespread presence of centimeter–to 10-m-scale granitic dikes, some of which are strongly deformed and clearly involved in the main phase of orogenesis (Figs. 1 and 2C). These observations suggest that the possibility of partial melting associated with the Triassic UHP event should be investigated. However, these features could also be related to Cretaceous igneous activity, and such young re...
Yangtze craton
Triassic Sulu gneiss with coesite eclogite
Sino-Korean craton
Archean gneiss
Lower Paleozoic metasediments
Postorogenic units
Cenozoic sediments
Mesozoic sediments
Mesozoic granite
WR Rb-Sr v Ksp-rich dikes
SHRIMP age CHIME age

Figure 1. Simplified geologic map of northern Sulu terrane showing location of samples used for dating in this study and regions where strongly deformed potassium feldspar-rich dikes were observed. WR—whole rock; SHRIMP—sensitive high-resolution ion microprobe; CHIME—chemical Th-U total Pb method.

AGE OF DIKES
U-Pb Dating
Two distinct types of dikes can be distinguished: a peraluminous type rich in potassium feldspar, poor in mica, and strongly deformed (Fig. 2C), and a second type richer in mica, poorer in potassium feldspar, and weakly deformed to nondeformed (Fig. 2B).

The mica-poor dikes are leucogranitic (FeO + MgO + TiO₂ < 2 wt%) and have high total alkali contents of 8.9–10.7 wt%, compatible with the compositions predicted by experimental data for partial melting of felsic rocks at high pressures (Table DR1; Patiño Douce and McCarthy, 1998; Hermann and Green, 2001). To determine the relationship between the formation of the potassium feldspar-rich dikes and the UHP metamorphism, we used U-Pb dating of zircons separated from samples of the dikes to determine the crystallization age. It is important to look for possible distinct stages in growth of zircon and to distinguish between rims and cores of the zircons; therefore, we used sensitive high-resolution ion-microprobe (SHRIMP) spot analyses. The zircon grains are typically ~200 μm long, and cathodoluminescence images show oscillatory zonation locally with a well-defined rounded core. Analyses of rims plot within error on concordia and show that the main phase of zircon growth was Triassic: ages range from 230 to 200 Ma (Fig. 2F; Table DR2 [see footnote 1]). The ages are identical within individual dikes, suggesting that the age range represents a period during which melt was forming and crystallizing. This period coincides with the age of the UHP metamorphism and is clearly distinct from the Cretaceous igneous activity. The cores of zircon grains from the dikes give mainly discordant results; a few concordant ages of 750–700 Ma are consistent with the estimates of the protolith age of the Sulu gneiss.

The micaceous dikes did not produce enough zircon suitable for analyses, but a biotite-potassium feldspar–whole rock–plagioclase Rb-Sr isochron gives an age of ca. 100 Ma (Fig. 2E; Table DR3 [see footnote 1]) and implies that these dikes formed in association with the widespread Cretaceous igneous event.

Sm-Nd Dating
Sm-Nd mineral isochron dating of eclogite in the Sulu terrane gives ages between 234 and 214 Ma (Li et al., 1999). This range is generally taken to represent the age of eclogite formation and, therefore, the peak of metamorphism. The age range of the rims of zircon determined from the SHRIMP analyses, therefore, coincides with the age of UHP metamorphism (Fig. 2F). This result implies that growth of the zircon began around the time of peak of UHP metamorphism. A significant amount of the zircon growth also took place after the peak of metamorphism.

Sr ISOPTERE RATIOS
The geochronological studies show there was magma present in the Sulu gneiss at the time of UHP metamorphism. We can test the hypothesis that this magma originated as a partial melt of the Sulu gneiss by using Rb-Sr isotope analyses. With the exception of one outlying datum, a plot of whole-rock ⁸⁷Sr/⁸⁶Sr ratios vs. ⁸⁷Rb/⁸⁶Sr ratios for samples from the northern Sulu belt shows a clear linear distribution implying formation of these samples with very similar initial Sr ratios ca. 720 Ma (Fig. 3; Table DR3 [see footnote 1]). This age is in agreement with other estimates of the protolith age. The implied initial ⁸⁷Sr/⁸⁶Sr ratio (Sr₀) is constrained to be <0.7070. Subsequent partial melting should produce melts with a greater Sr₀. To estimate the Sr₀ of the dikes, we used the crystallization ages and the bulk ⁸⁷Sr/⁸⁶Sr ratios (Fig. 3). The results show high Sr₀ values—all above 0.7088 and up to 0.7139—compatible with an origin as partial melt of the Sulu gneiss.

The total amount of melt is difficult to estimate, but the proportion of potassium feldspar–rich dikes observed in field studies of the northern Sulu belt suggests that 5%–10% of melt is a reasonable estimate. Similar dikes are very rare in the Sulu terrane to the south of Qingdao, implying either that there was less melt or that it has migrated away from this region.

In summary, the overlap of crystallization ages of dikes with the age of UHP metamorphism shows that there was melt present in Sulu gneiss during the peak and immediate postpeak history of UHP metamorphism. In addition, the field observations and Sr isotope data are strong circumstantial evidence pointing toward partial melting of the Sulu gneiss. We do not claim to have proved conclusively

¹GSA Data Repository item 2005015, Table 1, whole-rock chemical analyses, Table 2, SHRIMP U-Pb zircon results, and Table 3, Rb-Sr isotopic data, is available online at www.geosociety.org/pubs/ft2005.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, PO. Box 9140, Boulder, CO 80301-9140, USA.
Figure 2. A: Backscattered-electron image of zircon grain showing rim and core (separated by white dashed line) defined in this study through ages of analyzed spots (open circles). B: Weakly deformed two-mica granitic dike. Lid of clinometer is ~7 cm wide. C: Strongly deformed potassium feldspar–rich dike. Person for scale. D: Chemical U-Th-Pb method (CHIME) age of zircon shown in A. Results give age of ca. 710 Ma for core and suggest that rim underwent partial reequilibration ca. 240 Ma. Number of data points (core) 546, mean square of weighted deviates (MSWD) 5.06, intercept 0.000 ± 0.001. UO₂* represents UO₂ and additional amount equivalent to ThO₂ content. E: Rb-Sr mineral age of micaeous granitic dike (Fig. 2B). Results give Cretaceous age. F: SHRIMP ages for zircons separated from potassium feldspar–rich dikes (Fig. 2C), showing clear overlap with Sm-Nd mineral isochron ages from eclogite (Li et al., 1999). Lengths of bars represent 2σ errors.

that the Sulu gneiss underwent large-scale partial melting; however, we think our data make it very likely. We now examine some of the consequences of such a process.

IMPLICATIONS OF PARTIAL MELTING OF THE SULU GNEISS
Preservation of UHP Minerals
Partial melt forms along grain boundaries. The presence of even small amounts of such melt will greatly increase the rate of mineral reactions in the rock and can help explain why coesite and other minerals characteristic of UHP conditions are so rare in the acidic Sulu gneiss, which has a relatively low solidus temperature, but relatively common in mafic lithologies.

Growth of Zircon
Zirconium is an incompatible element and during partial melting will preferentially be incorporated in melt. This geochemical behavior can explain the very limited amount of zircon growth in the Sulu gneiss compared to the well-developed Triassic zircons in the potassium feldspar–rich dikes: most of the zirconium was concentrated in the melt rather than being available for new growth in the gneiss. The reported isothermal decompression paths imply that the proportion of melting will increase during exhumation; therefore, the main stage of melt formation and associated zircon crystallization are expected to be after the peak of metamorphism. This can explain why zircon U-Pb ages on average tend to be younger than eclogite Sm-Nd ages in this region.

Exhumation Tectonics
Most explanations for the exhumation of the Sulu-Dabie UHP terrane invoke the expulsion of a relatively thin sheet upward along the subduction zone that it first descended (e.g., Faure et al., 1999; Maruyama et al., 1994). To maintain a long aspect ratio requires a strong rigid sheet (StoÈckhert et al., 1997) and/or rigid bounding walls. However, Wallis et al. (1999) pointed out that there is evidence for high-strain ductile deformation throughout the Sulu terrane, suggesting that these UHP rocks behaved in a highly ductile fashion during metamorphism. Wallis et al. (1999) also presented structural data suggesting that the full thickness of the UHP units in the northern Sulu terrane is at least 40 km. This value is much greater than the thickness of continental crust that can reasonably be expected to subduct (e.g., Molnar and Gray, 1979), implying that there has been considerable postsubduction thickening. We propose that these features are best explained in a model in which partial melting of the Sulu gneiss took place at depth. There is an exponential decrease in the strength of rocks with increasing proportion of melt (Rutter and Neumann, 1995). The reduction in strength associated with partial melting of the Sulu gneiss is likely to have allowed the buoyant subducted rocks to rise back toward the surface as a mobile partially molten low-viscosity diapir. In contrast to the felsic

Figure 3. Whole-rock Sr isotope data for northern Sulu terrane, suggesting that most rocks of this region were formed with similar initial 87Sr/86Sr ratio (Sr₀) ca. 720 Ma. Potassium feldspar–rich dikes all show significantly higher Sr₀ values compatible with origin as partial melts. Data include results from Ishizaka et al. (1994) and Ames et al. (1996). Upper limit of 0.7070 for Sr₀ of Sulu gneiss is given by 700 Ma isochron.
gness, the more refractory eclogite and other blocks are less completely reequilibrated and commonly preserve UHP mineral assemblages. The rise of this diapir body would result in strong vertical shortening and lateral spreading of the UHP acidic gneiss domain (Fig. 4); this scenario is in stark contrast to the commonly invoked thin rigid sheet type of exhumation model (Fig. 4). The planned continental deep drilling in the Sulu terrane is well suited to resolving these two views: earlier suggestions involved UHP rocks underlain by a low-pressure unit at a depth of a few kilometers, whereas we suggest that the UHP rocks should be underlain by more UHP rocks.

CONCLUSIONS

The presence of strongly deformed dikes with crystallization ages that overlap with the peak age of UHP metamorphism in combination with field studies and Sr isotope ratios of the dikes compared to those of the Sulu gneiss suggests that partial melting of the Sulu gneiss took place in association with the UHP metamorphism. Partial melting may be the key to solving several unusual features of the Sulu and other UHP terranes, such as the almost complete lack of mineralogical evidence for UHP conditions in the felsic gneiss and the limited growth of zircon in the gneiss during UHP conditions. Partial melting will cause a drastic reduction in the strength of the UHP gneisses, implying that the most likely exhumation mechanism is diapiric rise of a mobile, partially molten mass with entrained blocks of eclogite.

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