PERSPECTIVES: GEOPHYSICS

Into the Forbidden Zone

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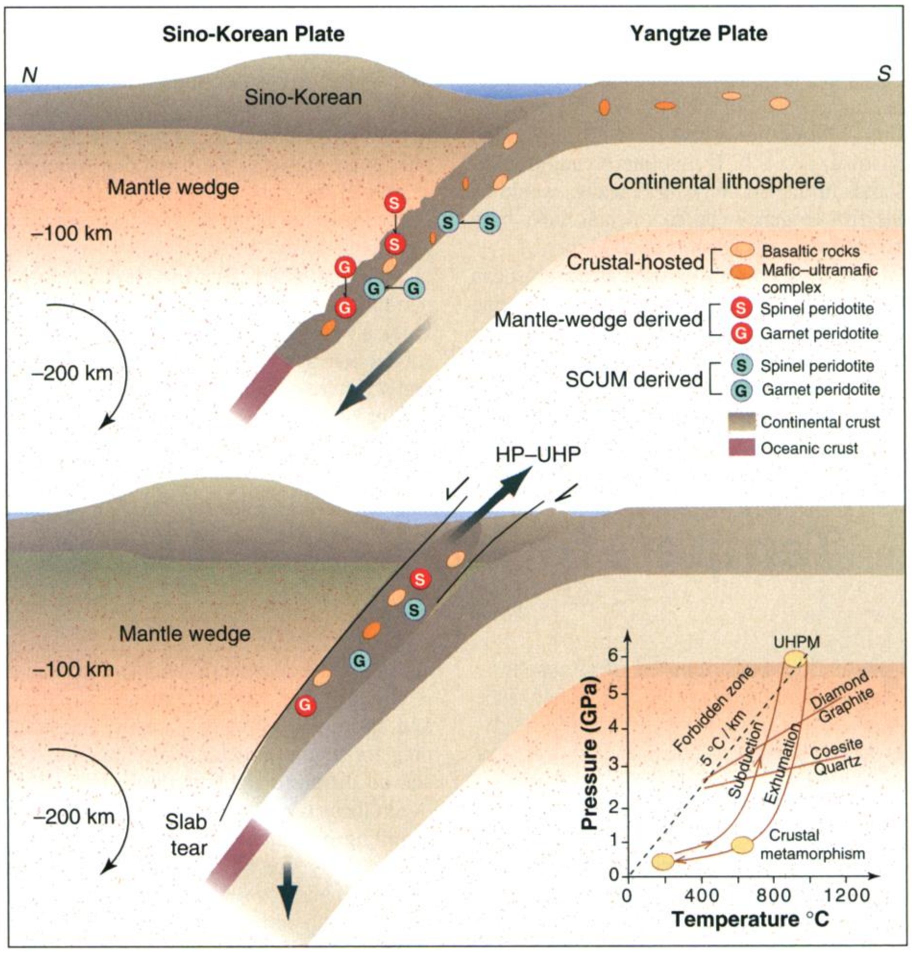
It is an accepted tenet of geology that very low temperatures at high pressures constitute a "forbidden zone" never realized in Earth (*1*): All rocks from deep within Earth appear to have experienced temperatures corresponding to a temperature increase by 5° to 10°C/km from Earth's surface (*2*), and pressure-temperature conditions of 800°C/6 GPa, or 600°C/4 GPa, were long believed never to be realized. Recent research on ultrahigh-pressure (UHP) terranes casts doubt on this paradigm, however, with major implications for understanding plate tectonics.

UHP terranes, with areas of up to 20,000 km^2, mostly consist of crustal rocks. Inclusions of high-pressure mineralsæcoesite and/or diamondæindicate that these rocks have experienced pressures of more than 3 GPa during aborted subduction to depths as great as 135 km (see the inset in the figure). A small portion of the terranes is made up of garnet peridotites, ultramafic rocks that range from crustal intrusions subducted along with the rest of the continental crust, to slivers of underlying mantle faulted into the subducted crust, to dense blocks of overlying mantle that sank into the subducted crust (*3*). Two exciting findings have come from recent studies of such UHP garnet peridotites. Bodies in the Western Gneiss Region of Norway and Alpe Arami of the western Alps were shown to be derived from depths between 185 and 250 km, and garnet peridotites of the Sulu-Dabie terrane of east central China may have recrystallized in the forbidden zone at these depths.

Evidence of the unusually deep origin of some UHP garnet peridotites comes from submillimeter-scale minerals included within larger grains. Garnets in peridotites from the Western Gneiss Region contain pyroxene needles, indicating that exsolution (unmixing) has occurred after initial formation of a supersilicic garnet at depths >185 km (*4–6*). Similarly, the Alpe Arami garnet peridotite of northern Italy contains exsolution lamellae of clinoenstatite within diopside, with crystallographic evidence implying initial formation at depths >250 km (*7*). Unusual $FeTiO_3$ rods observed in olivine from this same rock (*8*) have also been found in Chinese UHP peridotites (*9*), implying that rocks of such deep derivation may be widespread. These peridotites originate in the mantle, and their mineralogical characteristics imply that they have experienced recrystallization at high temperatures (>1000°C); in some cases, their recrystallization ages are considerably older than their host country rocks (*10*, *11*). The most plausible explanation for how these deep, mantle-borne garnet peridotites arrived at Earth's surface is that they were transported upward by asthenospheric upwelling to depths of about 135 km, tectonically inserted into subducted continental crust, and then exhumed.

Other evidence of UHP metamorphism of garnet peridotites comes from unusual matrix minerals and from the composition of the garnet and other minerals in the rocks, which allow conclusions to be drawn regarding the processing conditions they must have experienced. Among all reported Eurasian garnet peridotites, pressure/temperature (*P*/*T*) ratios (*12*, *13*) are highest for those in the Sulu-Dabie UHP terrane of east-central China, indicating processing conditions of 750° to 950°C and 4.0 to 6.7 GPa. Some of these *P-T* conditions lie within the forbidden zone (*13–16*). The very high pressures are confirmed by the presence of other high-pressure minerals (*15*, *17*) and by the occurrence of diamond in nearby garnet peridotite and eclogite (*18*) and of hydroxyl-rich topaz (which requires



Cold subduction reaches ultrahigh pressures. Interpretive model for the dual origins of Dabie-Sulu peridotites in the collision zone between the Sino-Korean and Yangtze plates of east-central China [modified after (*26*)]. In the top panel, mafic-ultramafic materials and continental rocks of the Yangtze Plate, together with fragments of spinel and garnet peridotites from the mantle wedge above and subducted continental upper mantle (SCUM) below, are subducted to depths greater than 100 km, where these rocks are subjected to UHP metamorhpism. In the bottom panel, the peridotites are shown being carried upward within a detached sliver of the continental margin while subduction continues at deeper levels. **(Inset)** Pressure-temperature diagram showing the subduction/exhumation *P-T* path of some Dabie-Sulu garnet peridotites. These rocks have experienced UHP metamorphism (UHPM) at mantle depths in the *P-T* regions considered to be the forbidden zone.

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low temperatures) in adjacent kyanite quartzite (*17*).

Some of the forbidden zone garnet peridotites in the Dabie-Sulu UHP terrane may have been placed in the crust before subduction and subjected to in situ UHP metamorphism together with the subducted slab. In particular, the Bixiling and Maowu mafic-ultramafic complexes of the Dabie Mountains in central China are interpreted as layered crustal intrusions (*13*, *16*, *19*). The reasons are as follows. The primary modal layering observed in the Bixiling rocks can be attributed to fractional crystallization of basaltic magma at crustal depths. Similarly, Maowu contains layers likely derived from plagioclase (a mineral stable only in crustal rocks) and high-temperature–low-pressure inclusions in garnets that require a crustal metamorphic event before subduction. Furthermore, both have UHP metamorphic ages of ~220 million years, younger than their crystallization ages of <300 million years for Bixiling and 450 million years for Maowu. Finally, there is evidence that both have experienced crustal contamination, as indicated by high $^{87}Sr/^{86}Sr$ ratios (Maowu) and low $\delta^{18}O$ (Bixiling and Maowu) (*20–22*). If this interpretation withstands further scrutiny, these bodies would be the first evidence that continental rocks have been subducted to depths of 200 km.

The most obvious location where crust can be subducted to 200-km depth without being heated beyond 900°C is a cold, steady-state subduction zone where old lithosphere is rapidly subducted, such as beneath northeast Japan, where the 130-million-year-old Pacific Plate is foundering at 90 mm/year (*23*). As pointed out by Peacock (*24*), UHP rocks (even the aforementioned bodies from the forbidden zone) are actually hotter than the coldest conditions calculated for mature, cold subduction zones. Most UHP localities do not appear to be associated with a coeval volcanoplutonic arc, however, suggesting that they do not form in long-lived subduction zones. Crustal rocks in an incipient subduction zone that has not reached a thermal steady state (see the figure), may reach a temperature of 900°C at 200-km depth are carried to 200-km depth if subduction is rapid enough that advection dominates conduction. For example, if subduction to 200-km depth takes ~5 million years, rocks in the middle crust of the subducted slab will undergo little heating, as the characteristic diffusion distance for this time scale is 10 to 15 km.

The discovery of these ultramafic denizens of the forbidden zone confirms the cold subduction-zone models of Peacock and Wang (*23*). These cold subduction zones are clearly the sites of major recycling of H_2O into the mantle, because high-pressure experiments on mafic-ultramafic compositions (*25*) reveal that numerous important hydrous phases are stable in the forbidden zone. Research in the past 10 years on UHP rocks containing coesite and diamond has produced a dramatic restructuring of our understanding of plate tectonics. The discovery of garnet peridotites from the forbidden zone now provides a revolutionary new window into the subduction of continental margins, the thermal structure of subduction zones, and the recycling of volatiles into the mantle.

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PERSPECTIVES: CLIMATE CHANGE

Temperatures High and Low

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Satellite measurements of atmospheric temperatures have been available since 1979 through retrievals from Microwave Sounding Units (MSUs). These measurements show virtually no warming trend in the lower troposphere, the layer from about 1 to 5 km above Earth's surface. In contrast, measurements taken in situ at Earth's surface indicate a globally averaged warming of between 0.3° and 0.4°C over the same period. Papers in this issue by Santer *et al.* (*1*, p. 1227) and Gaffen *et al.* (*2*, p. 1242) use a combination of observations and model simulations to throw further light on these trends and bring a partial reconciliation.

Understanding the difference between surface and tropospheric temperature trends is crucial for modeling climate, explaining and attributing climatic changes, and planning for future climate monitoring. The observed differential temperature trends between these layers may result from biases or sampling inadequacies in the observations, fluctuations caused by short-term events such as El Niño or volcanic eruptions, and/or longer term natural or human-induced changes. The vertical structure of the observed trends may differ from that predicted by models because of observational biases, spatial and temporal sampling uncertainties, and shortcomings in the models or in the human and natural forcings (such as greenhouse gas emissions and volcanic eruptions) provided to them. These possibilities were recently examined by an expert panel for the U.S.'s National Research Council (NRC) (*3*).

Santer *et al.* (*1*) use surface and MSU data to argue that a small but not negligible part of the observed differential temperature trend has arisen from incomplete surface temperature sampling. This finding lends support to the NRC panel's recommendation (*3*) that a worldwide temperature monitoring system must be implemented that ensures the continuity and quality control of critically important data sets. Santer *et al.* also use coupled atmosphere-ocean model simulations to explore the impacts of stratospheric ozone depletion and of the 1991 eruption of Mount Pinatubo. They conclude that, together, these forcings may explain a further third of the discrepancy between the observed differential trends and those predicted by models forced with changes in greenhouse gases, direct and indirect sulfate forcing, and tropospheric ozone. In the models investigated by Santer *et al.*, unforced natural climate variability cannot explain the observed lapse rate changes. Santer *et al.* recommend additional simulations that take account of the uncertainties in the forcings and allow full assessment of the space-time patterns of the mod-

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