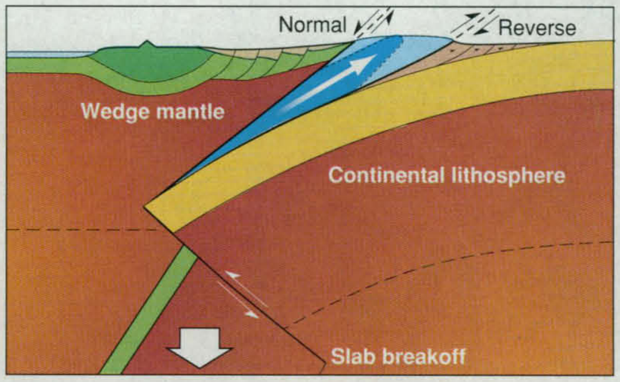
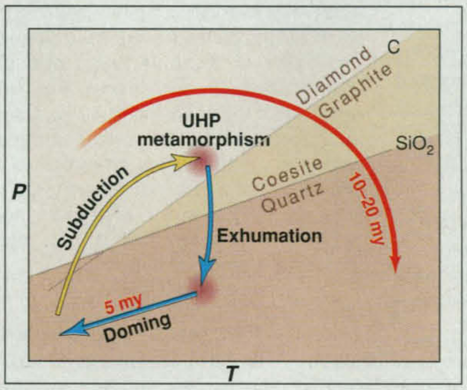
TECTONICS

Seeing a Mountain in a Grain of Garnet

J. G. Liou, S. Maruyama, W. G. Ernst





A tectonic model (top) of subduction and exhumation of crustal materials from the continental lithosphere. The UHP (blue) and high-pressure (green) slabs returned to shallow depths after recrystallization within the coesite or diamond stability field [see figure (right)] at depths of over 100 km, due to slab breakoff and buoyancy of a low-density continental sheet. Pressure-temperature diagram (right) showing stability regions of carbon and silica. Arrows show the time cycle for subduction shown in figure (top). Subduction and exhumation each require about 10 million years (my).

When continents collide, mountains are formed; the Himalayas, for instance, are evolving even now as India collides with Asia and is driven deep into the Earth by subduction. Past collision belts such as the Alps, the Urals, and the Appalachians are more deeply eroded than the younger Himalayas, and thus expose rock that was formed at higher pressure. Study of these rocks has provided new understanding of this collision and subduction process. In particular, over the past several years, high-pressure minerals such as diamond and coesite have been discovered in these mountain roots, implying that rocks had been subducted to a depth of 100 km (equivalent to a pressure of 3.0 GPa), and then returned to the surface. Now, on page 91 of this issue, Darling *et al.* report finding inclusions of the low-pressure mineral cristobalite in garnets from the Appalachians (*1*). The presence of these inclusions creates a riddle: How did a low-pressure phase form and stay preserved in a high-pressure rock? The answer may help uncover some of the mystery of the continental collisional belts.

Geologists have recently discovered tiny inclusions of diamond and the high-pressure SiO_2 polymorph coesite in strong, chemically resistant container grains of garnet, clinopyroxene, and zircon from ultrahigh-pressure (UHP) metamorphic rocks in nearly a dozen collision belts within Eurasia and Africa (*2*). In northern Kazakhstan, microdiamond inclusions in metasedimentary rocks possess markedly low $^{13}C/^{12}C$ ratios, indicating that the diamond had a biogenic precursor (*3*); this conclusion is supported by the assemblage of UHP metamorphosed near-surface continental-crust lithologies. The occurrence of diamond means that portions of this UHP crustal terrane were exhumed from depths exceeding 120 km, as such depths are necessary for the formation of diamond rather than graphite. The realization that some segments of continental and oceanic crust have been subducted to such depths and subsequently returned to the surface challenges the conventional understanding of tectonic processes and raises important questions. Among them are the problem of how low-density continental crust is subducted, the genesis of magmatic arcs, the causes of intermediate-depth earthquakes, the scale of geochemical recycling of elements from the top of the crust to deep within the mantle, and the tectonics responsible for the formation and growth versus rifting and destruction of the continents.

Geologists are particularly interested in the answers to questions such as (i) How do we recognize and distinguish UHP metamorphosed crust from that subjected to shallower burial and recrystallization? (ii) What kinds of crust-mantle interactions take place during subduction, and how do such processes affect global geochemical recycling? (iii) Are coesite- and diamond-bearing rocks in situ with respect to the enclosing rocks or are they foreign blocks within a low-pressure matrix? (iv) How deeply can slices of continental crust be subducted en masse? (v) What are the structural relationships of UHP units with adjacent lower pressure units? (vi) What other mineralogical and geochemical evidence points to UHP metamorphism at mantle depth? (vii) Does the devolatilization of UHP crustal sections at depth play a role in the production of magmas during collision? And (viii), what exhumation mechanisms and rates of ascent prevent UHP mineral assemblages from being completely transformed into low-pressure polymorphs?

In contrast to the metastable preservation of high-pressure minerals, the report by Darling *et al.* provides direct evidence of the metastable persistence of a low-pressure, high-temperature SiO_2 polymorph, cristobalite, as inclusions in high-pressure granulite garnet from Gore Mountain, New York. Cooling of the parental rocks from temperatures in excess of 600°C took more than 100 million years (*1*). Preservation of this low-pressure polymorph may have important implications for understanding uplift and exposure of high-pressure rocks and persistence of other metastable phases. Lack of fluid appears to have been responsible for such preservation. A similar interpretation was offered to explain the preservation of coesite inclusions in UHP host minerals.

A scenario depicting the UHP metamorphism and exhumation of a crustal slice within a continental collision belt is presented in the figure. We postulate that a continental slab is subducted to mantle depths where it undergoes deformation and recrystallization. Slab breakoff and the resultant buoyancy of a low-density continental sheet are responsible for the return of UHP rocks toward the surface (*5*, *6*). The exhumation and preservation of minerals such as coesite and microdiamond depend on the rate and path of return flow, the availability of fluid and its infiltration, and the intensity of subsequent deforma-

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tion and recrystallization. Many inclusions of coesite and diamond that are shielded in a strong mineral host have recently been reported.

Intergranular coesite crystals sited along grain boundaries are much rarer but have been found in the Sulu UHP eclogites of east-central China (*7*). These coesite grains exhibit variable degrees of conversion to quartz aggregates. Metagabbro and metagranitic rocks with preserved relict igneous minerals and textures occur in the same Sulu locality; they represent early stages in the progressive conversion of metagabbro to coesite-bearing eclogite. These features suggest that reaction rates are slow; in experiments, the presence of only ~450 ppm of intergranular fluid is sufficient to transform coesite completely to quartz during exhumation at temperatures greater than 300°C (*8*). The total absence of fluids during subduction to mantle depths (~10 million years) and exhumation to crustal levels (~10 million years) may be the key for such sluggish prograde and retrograde reactions (*6*). This suggestion is consistent with the occurrence of similar intergranular coesite grains from a mantle-derived eclogitic xenolith in a South African kimberlite pipe (*9*). It is also compatible with inferences drawn from Sulu UHP rocks regarding the lack of fluid attending recrystallization, as reflected by the lowest $^{18}O/^{16}O$ ratios ever recorded for silicates (*10*); isotopic equilibrium between minerals and host rocks suggests that these units acquired compositions with low oxygen isotope ratios during meteoric water-rock interactions before UHP metamorphism, then were isolated from fluid interaction during their descent to and return from mantle depths.

Recent research on regional metamorphic rocks containing coesite and diamond has produced a dramatic restructuring of our understanding of continental collision processes. The extremely rare occurrence of intragranular coesite suggests that the lack of fluid during rapid exhumation of UHP rocks may have played a more important role than the fact that the inclusion was contained in a small "pressure vessel." Geologists need to intensify their search for such tiny inclusions in order to uncover more completely the extent and magnitude of profound subduction and exhumation of segments of the continental crust.

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BIOCHEMISTRY

The Cis-Trans Paradox of Integrase

Makkuni Jayaram

Successful in vitro analyses marked the beginning of the end of recombination as a geneticist's playground. I can already hear the biochemists circling in the night.

—F. STAHL (*1*, p. 1356)

I smiled because I am a biochemist. Now I see crystallographers and other physical chemists stacking up in the sky.

—N. COZZARELLI (*2*, p. 13)

Recombination is the ubiquitous process whereby organisms reshuffle their genetic information. This genetic exchange occurs between DNA molecules from the two parents or between two DNA segments within the same molecule. Such recombination may be general, occurring between two DNA substrates with extensive homology, or site-specific, occurring between two specific, relatively short DNA targets. The "conservative" site-specific recombinases of the integrase (Int) family (from phage λ) execute recombination with a remarkable degree of mechanistic parsimony (*3*). They break the DNA chains at two specific positions in each recombination partner and rejoin the breaks across partners by using chemical steps that do not require phosphodiester hydrolysis or the degradation or synthesis of DNA. Rather, the DNA exchange is a two-step process involving pairwise single-strand breakage and joining. The chemistry of the reaction is discharged by one or two recombinase enzymes with architectural help, in certain instances, from accessory protein factors. Recent findings that members of the Int family may follow disparate paths to arrive at a common recombination chemistry have been disconcerting. Now in this issue on page 126, Kwon *et al.* (*4*) present the structure of the λ Int catalytic domain, which promises reasonable solutions to some of the mechanistic concerns.

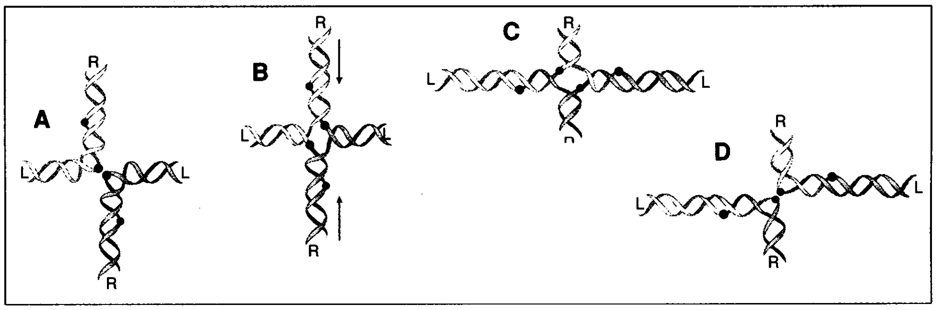

Fig. 1. "A reversible coalescence of two circles..." (*5*, p. 136). One pair of strands exchanges to form a Holliday junction (A→B); this intermediate isomerizes (B→C), and the reciprocal recombinants form (C→D). Green, the two scissile phosphodiesters that participate in strand exchange; red, the inactive phosphodiesters. The scheme is an elaboration of the original proposal by Campbell (*5*). L and R refer to left and right arms flanking the strand-exchange region.

The elegant simplicity of the Campbell model for λ integrative recombination (*5*) (see Fig. 1), which unites two DNA circles into one, inspired the design of genetic and biochemical strategies to grapple with the mechanistic problems of the reaction. At least four of the Int family recombinases (λ Int, *Escherichia coli* XerC/XerD, Cre from phage P1, and Flp from the 2-μm yeast plasmid) use fundamentally the same mecha-

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