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High-pressure and ultrahigh-pressure metamorphic belts—Subduction, recrystallization, exhumation, and significance for ophiolite study

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ABSTRACT

Alpine-type **orogenic belts are produced by short-lived subduction of an ocean basin and the underflow of continental crust, resulting in suturing. Old, relatively competent sialic basement and superjacent units characterize these complexes; ophiolites, chiefly enriched mid-ocean ridge basalt and suprasubduction-zone complexes are common in some belts, but are rare in others. Metamorphism of deeply subducted (60–140 km) parts of the orogen ranges from high pressure to ultrahigh pressure , and is not paired. Coeval calcalkaline arc rocks are uncommon. In contrast, paired** ***Pacific-type*** **orogenic belts develop within and landward from long-lived subduction zones. They consist of an outboard trench + accretionary prism deposited on oceanic crust, and an inboard volcanic-plutonic continental margin or island arc. The trench assemblage consists of graywacke + shaley mélanges, minor but widespread deep-water cherts and/or carbonates, and ubiquitous disaggregated ophiolites, especially normal mid-ocean basalt and ocean island basalt varieties, all recrystallized under high-pressure conditions at depths of 15–70 km. A massive, coeval calcalkaline arc dominates the subparallel terrane landward from the trench, and high temperatures characterize the associated metamorphism. In both high-pressure–ultrahigh-pressure Alpine and high-pressure Pacific-type metamorphic terranes, outboard thrust faults chiefly dip landward beneath the stable, nonsubducted plate, and fold vergence is seaward, reflecting similar convergent plate-tectonic settings; inboard, antithetic thrusting characterizes some contractional realms. High pressures and low temperatures in these belts attest to dynamic subduction-zone conditions. Because of their structural integrity, some Alpine-type microcontinents, island arcs, or continental promontories are carried down as much as 140 km, well into the brittle-ductile transition region, before decoupling from the sinking mantle lithosphere. In sharp contrast, incompetent Pacific-type graywacke + shale terranes generally separate from descending oceanic lithosphere at much shallower depths.**

The ascent of packets of subducted material as thin aspect-ratio sheets 1–5 km thick, combined with normal faulting above and subduction-zone thrusting below, promotes conduction cooling and partial preservation of decompressing high-pressure and ultrahigh-pressure metamorphic complexes. Worldwide, subduction-zone terranes consist of dominantly of small masses of high-density mafic blueschist-eclogite and/or anhydrous peridotitic lenses surrounded by voluminous, low-density quartzofeldspathic ± serpentinitic material, hence the bulk terrane density is less than that of unaltered, dynamically displaced mantle; exhumation to mid-crustal levels is largely buoyancy driven. Partial preservation of high-pressure–ultrahigh-pressure relict phases reflects rapid ascent combined with mineralogic armoring and a general lack of catalytic aqueous fluid. Exposure of rising high-pressure and ultrahigh pressure metamorphic belts

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is a consequence of erosional decapitation and gravitational collapse of the subduction complex. Many exhumed high-pressure–ultrahigh-pressure sheets are of relatively small volume, and for these, only modest amounts of sedimentary debris are provided to successor basins.

Keywords: subduction zone metamorphism, high pressure, ultrahigh pressure, continental collision, Circumpacific subduction.

CONTRASTS BETWEEN ALPINE- AND PACIFIC-TYPE SUBDUCTION ZONES

Historical Development

With development of plate-tectonic theory in the 1960s, Earth scientists realized that submarine trenches mark zones of convergence, commonly between nonsubducted continental lithosphere and a descending oceanic plate (Isacks et al., 1968). That process has been called Circumpacific or *Pacific-type* subduction (type B subduction of Bally, 1981). Intracontinental, *Alpine type* orogenic belts (Bally's type A subduction) were also recognized as ocean-margin suture zones (Dewey and Bird, 1970; Moores, 1970; Molnar and Tapponier, 1975). Amalgamation of continental, microcontinental, and/or island-arc crustal entities occurs in response to the underflow of oceanic lithosphere initially separating sialic crust-capped portions of plates. But, as emphasized by many workers (Fitch, 1972; Irwin, 1972; Coney et al., 1980; Jones, 1983; Howell, ed., 1985), pure convergence is possible only at specific sites along curvilinear consumptive plate boundaries, reflecting the spherical nature of the globe-encircling plates; many terrane amalgams are sutured by oblique convergence and/or nearly pure strike-slip motion.

Intact and tectonically disaggregated tracts of oceanic crust and mantle underpinnings characterize oceanic (principally normal mid-ocean ridge basalt [N-MORB] and ocean island basalt [OIB]) and island arc/continental margin (chiefly enriched mid-ocean ridge basalt [E-MORB] and island arc tholeiite [IAT]) environments. The open ocean varieties found in Pacific-type accretionary complexes have been subducted and are intensely metamorphosed, whereas some suprasubduction-zone (SSZ) arc ophiolites are only feebly recrystallized.

Pacific-Type Plate Junctions

Pacific-type convergent boundaries evolve where vast tracts of oceanic lithosphere are consumed without the introduction of significant amounts of continental crust into the subduction zone, as is characteristic of the post-Paleozoic history of the eastern and western Circumpacific. This plate-tectonic situation gives rise to an outboard ophiolite-bearing, but largely metasedimentary, accretionary trench complex, a medial, longitudinal forearc basin, and an inboard, coeval calcalkaline volcanic-plutonic arc. The relatively narrow trench section consists of a low-temperature, low-heat-flow belt in which folds verge oceanward and outboard thrust faults roughly parallel the subduction zone, whereas the broad magmatic arc on the stable, nonsubducted plate is characterized by open folding and a high-temperature, high-thermal-flux regime (Miyashiro, 1961, 1967; Ernst et al., 1970; Dickinson, 1972). The former is deposited exclusively on oceanic crust (e.g., Franciscan, Aleutian, and Chile-Peru trench systems); the latter is constructed on pre-existing basement of the continental margin or island arc ± older oceanic crust (e.g., Sierran, Indonesian, and Andean arcs).

Alpine-Type Plate Junctions

Alpine-type convergent boundaries form where subduction of an ocean plate results in the transport, arrival at a trench, and underflow of a continent, microcontinent, or island arc, generally beneath sialic crust surmounting a stable hanging-wall plate (the mantle wedge). The leading edge or salient of the sialic terrane may descend to considerable depths, conducted down by the surrounding, oceanic lithosphere, because the overall density of the plate exceeds that of the underlying asthenosphere. Accompanying subduction, the aggregate continental thickness is increased by underplating, crustal contraction, and amalgamation. Sutures are characterized by major collisional mountain belts, allochthonous thrust sheets dipping under the nonsubducted plate, and a distinct paucity of calcalkaline igneous activity. Typical examples include the Urals, Alps, and Himalayas (Hamilton, 1970; Dal Piaz et al., 1972; Molnar et al., 1987; Burchfiel et al., 1989). Of course, it is possible for continental lithosphere to descend beneath young, hot—thus less dense—oceanic lithosphere (e.g., Oman and Sulawesi; Searle et al., 2001), but such configurations are less common because most oceanic plates are negatively buoyant relative to adjacent continental plates.

Intermediate-Type Plate Junctions

Plate-tectonic regimes transitional between these orogenic end-member types are well represented by the modern Indonesian archipelago (Hamilton, 1979; Maruyama et al., 1996). This complex suture zone is the product of Pacific + Australian lithospheric underflow beneath the Eurasian + Philippine Sea plates, and by initial stages of subduction/suturing of the Australian continental crust. The junction between the Arabian Peninsula and Iran represents another intermediate example (Boudier et al., 1985, 1988; Chemenda et al., 1996; Gnos et al., 1997; Miller et al., 1998).

Physical Models of Subduction

The thermal evolution of convergent plate junctions has been studied by many workers, chiefly employing numerical simulations (Shreve and Cloos, 1986; Cloos and Shreve, 1988a, 1988b; Beaumont et al., 1996, 1999; Stüwe and Barr, 1998), but also including experimental studies (Tapponnier et al., 1982; Chemenda et al., 1995, 1996). Thermotectonic architectures are a function of many input parameters, some only poorly constrained. Among them are the physical states of the converging lithospheric plates (temperatures, spatial configurations, viscosities, densities), rates of convergence, states and amount of sedimentary loading, extent of frictional dissipation, degree of hydration, fluid expulsion and flow (channeled or pervasive), advective heat transport, kinetics of subsolidus reactions and of partial melting, and extents of coeval tectonic and surficial erosion. In spite of uncertainties, widely recognized principles have emerged from such studies.

The computed thermal structures of convergent plate regimes have been investigated extensively (e.g., Oxburgh and Turcott, 1971: Anderson et al., 1978; Thompson and Ridley, 1987; van den Beukel and Wortel, 1988; Peacock, 1990, 1992). A reasonable model of the thermal regime, presented by Turcotte and Oxburgh (1972), is shown in Figure 1. Rocks are poor thermal conductors, so a descending lithospheric slab remains cool at all upper mantle depths relative to its surroundings, whereas the landward volcanic-plutonic arc occupies a broad thermal high in the nonsubducted mantle wedge + overlying crust. Thermal models such as that illustrated in Figure 1 account for paired Circumpacific outboard high-pressure (HP) blueschist-eclogite, and inboard high-temperature (HT) andalusite-sillimanite metamorphic belts. Geologic relationships and mineral parageneses for such terranes were first emphasized by Miyashiro (1961, 1967) prior to the advent of plate-tectonic theory; his classic synthesis of the contrasting paired metamorphic belts of Japan is presented as Figure 2. As now recognized for the Japanese island arc and its Pacific-type paired metamorphic belts, the times of accretion of clastic sedimentary debris + off-scraped, far-traveled, pre-existing crustal fragments decrease monotonically seaward (Banno and Sakai, 1989; Nishimura, 1998).

Scale-model experiments and numerical simulations of subduction-zone environments describe various mass-transport scenarios, depending on different values of the physical parameters employed. During underflow, return of subducted lithotectonic packets from great depths to mid-crustal levels also is a sensitive function of the physical characteristics of the rock units involved. For Circumpacific and Alpine accretionary wedges and contractional (collisional) mountain belts, both calculations and laboratory experiments realistically simulate the observed accumulation and suturing of the accreted sialic crust. Hacker et al. (2003a) have combined the computed thermal structures and observed metamorphic phase-equilibrium assemblages with measured geophysical properties of the oceanic crust and underlying mantle to provide quantitative models for lithospheric slabs subducting to depths of ~200 km.

Calcalkaline Arcs and Volcanic-Plutonic Belts

Landward calcalkaline arcs characterize the post-Paleozoic Circumpacific realm, attesting to the consumption of thousands

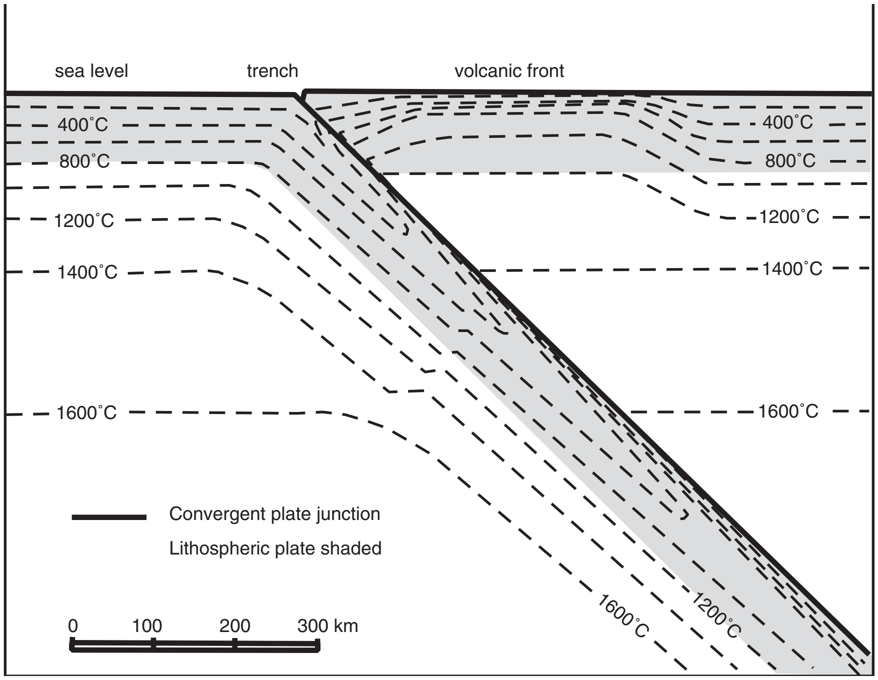


Figure 1. Computed thermal structure of a convergent lithospheric plate junction, after Turcott and Oxburgh (1972). Frictional dissipation along the inclined Benioff-Wadati shear zone has been assumed, accounting for the thermal bulge in the nonsubducted plate. Advective heat transfer by rising calcalkaline magmas has not been included, but also would contribute to the measured high heat flow of volcanic-plutonic arcs. Downward deflection of isotherms in the subducted slab is reflected in the low heat flow observed in the vicinity of oceanic trenches.

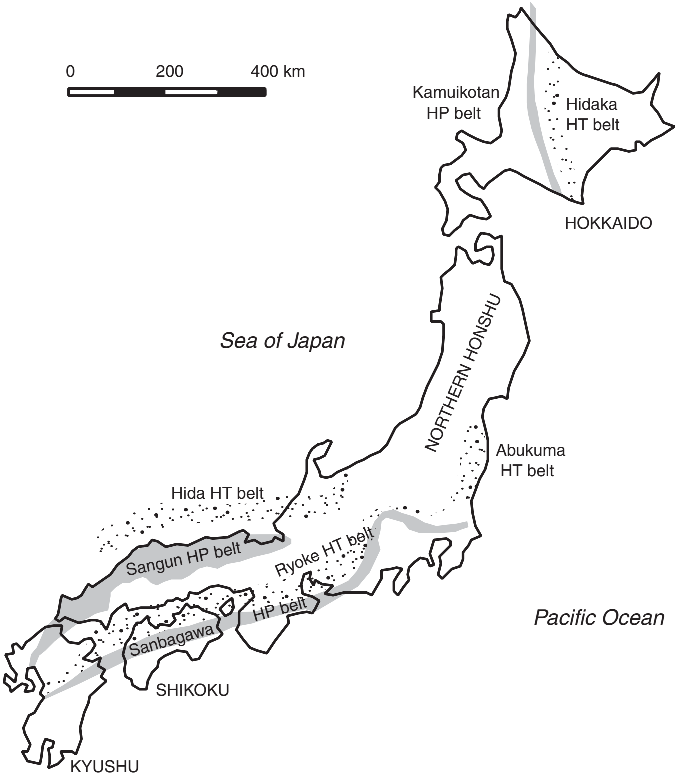


Figure 2. Compilation of the paired metamorphic belts of Japan, from Miyashiro (1961, 1967). Narrow, seaward ophiolitic HP metamorphic terranes are juxtaposed against broad, landward calcalkaline arcs and associated HT metamorphic belts.

of kms of oceanic lithosphere. Bulk-rock isotopic signatures show that, although partially melted quartzofeldspathic + pelitic crust yields peraluminous, S-type granite and contributes to mature island-arc and continental-margin magmas (Castro et al., eds., 1999), the calcalkaline suite contains an important contribution from the mantle wedge and/or subducted, eclogitized oceanic crust (DePaolo, 1981; Hawkesworth et al., 1993; Clift et al., 2001). These chemically intermediate volcanic and plutonic rocks represent new additions to the continental crust; other rock types represent mainly reworked material. Seaward, deposits of first-cycle, volcaniclastic sediments derived from the arc form fringing accretionary aprons (Dickinson, 1971, 1972, 1976); these detrital sediments may overwhelm the forearc basin, spilling over into the trench and onto the approaching oceanic plate. Igneous rocks in the outboard, Pacific-type subduction complex + accretionary wedge are exclusively tectonized ophiolites and other portions of the oceanic lithosphere (Coleman, 1977).

Granitoids and related volcanic rocks are rare in Alpine-type complexes. Unlike Circumpacific convergent margins, plutons are not set back on the stable, nonsubducted plate; instead, small peraluminous bodies locally invade the root zone of the imbricate nappe edifice. Variable amounts of ophiolitic rocks occur in some compressional orogens, but tectonic fragments of oceanic lithosphere are conspicuously missing from many contractional mountain belts, (e.g., Liou et al., 1996). The rarity of the ophiolite suite and calcalkaline arc rocks in some Alpine-type complexes reflects the underflow of only small ocean basins. Most ophiolites are tectonically emplaced along convergent margins, so where limited lithospheric underflow takes place, fewer asperities (Cloos, 1993) are sampled; for this reason, oceanic material is uncommon in a some Alpine-type orogenic belts (for instance: the Qinling-Dabie-Sulu belt, east-central China; the Pan African terrane; the Western Gneiss Region, SW Norway; the Eastern Alps). Large tracts of oceanic lithosphere must be returned to the deep upper mantle in order to generate the voluminous intermediate magmas and massive calcalkaline arc in the crust above a well-developed subjacent plumbing system (Ernst, 1971, 1999)

Metamorphic Belts

Coeval, paired metamorphic belts characterize Pacific-type subduction zones. Two examples are presented in Figure 3, illustrating the blueschist-eclogite HP terrane. The outboard subduction complex consists of units recrystallized at low temperatures and high pressures. Reflecting its dynamic plate-tectonic setting within the subduction channel (directly below the hanging-wall lithosphere, which acts as a stress guide), oceanward vergence of folds is ubiquitous; shearing and foliation + lineation are typical, with recovered depths of metamorphism ranging up to 15–70 km (Bailey et al., 1964; Ernst, 1971; Aoya, 2001). Landward, calcalkaline granitoids are emplaced into a consanguineous volcanic cover series and underlying, pre-existing basement. Both volcanic and basement rocks exhibit widespread recrystallization at high temperatures and low pressures. Metamorphic parageneses reflect the advective transport of heat introduced by rising magmas, and consist of a series of superimposed regional contact aureoles surrounding individual plutons (Barton et al., 1988). Hornfels and open, cylindrical folding typify such mid- and upper-crustal metamorphic terranes (Ernst, 1992).

Alpine subduction complexes contain abundant, pre-existing continental massifs, as well as penetratively deformed, superjacent autochthonous and allochthonous entities. Metamorphic belts of the Alpine type are not paired (Frey et al., 1974). High-pressure subsolidus recrystallization is the rule, with parageneses comparable to those of Circumpacific subduction complexes. A generalized map of the Alps is illustrated in Figure 4. Some contractional orogens include tectonic slices that retain scattered mineralogic relics including coesite and microdiamond—commonly as inclusions in tough, unreactive container phases such as zircon and garnet. These rare inclusions attest to ultrahigh pressures (UHP) and somewhat higher temperatures, but prograde geothermal gradients are similar to those that characterize Pacific-type subduction complexes

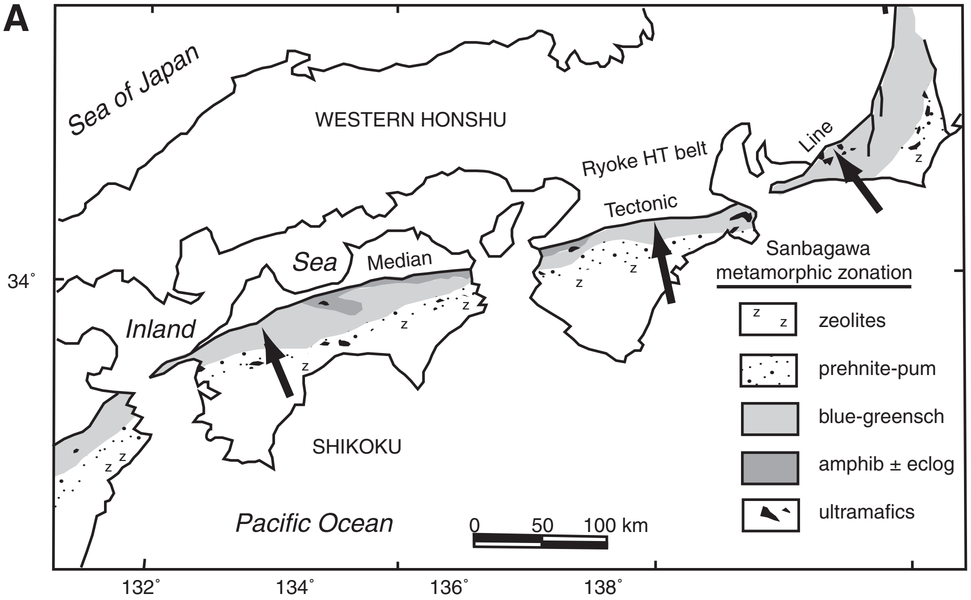
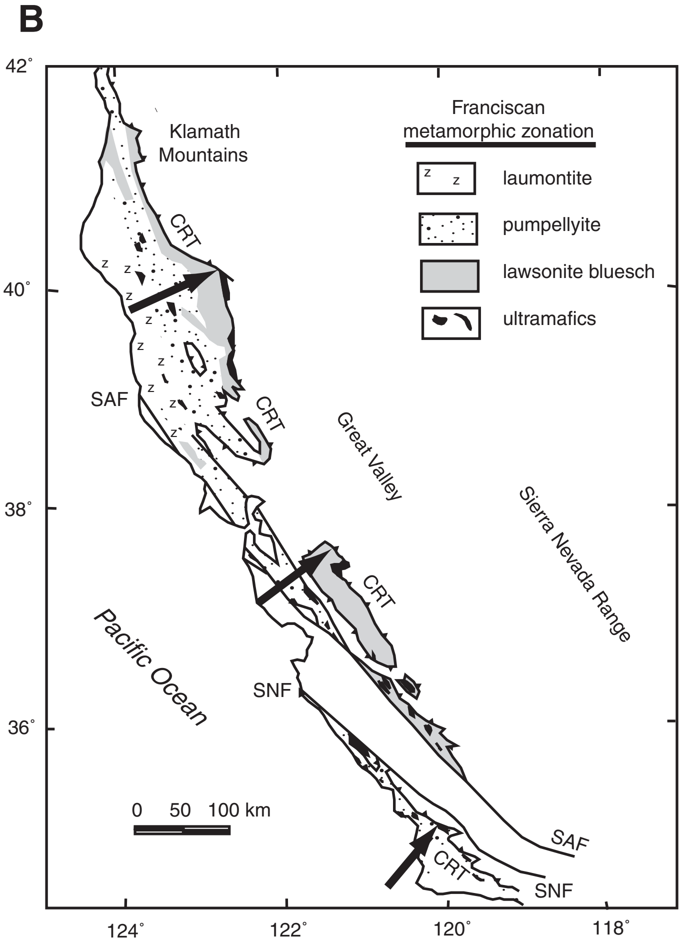


Figure 3. Generalized regional settings of Pacific-type HP metamorphic belts, showing directions of increasing subduction depths, now recovered, and prograde blueschist-eclogite metamorphism (arrows). A: Sanbagawa belt of SW Japan, after Hashimoto et al. (1970). B: Franciscan complex of western California, after Bailey et al. (1970). Abbreviations: CRT—Coast Range thrust; SAF—San Andreas fault; SNF—Sur-Nacimiento fault; amphi—amphibolite; eclog—eclogite; greensch—green schist; pum—pumpellyite.



(Chopin, 1984; Smith, 1984; Sobolev and Shatsky, 1990; Coleman and Wang, 1995). Pressure-temperature conditions reflect situations where an old segment of continental crust—annealed and, thus, well bonded to the oceanic lithosphere—enters the subduction zone and descends to depths of 60–140 km before decoupling from the downgoing plate. For such terranes, HP-UHP recrystallization results. HP, HT, and UHP metamorphic conditions are compared in Figure 5.

Summary of Subduction-Zone Metamorphic Features

Circumpacific convergence zones are characterized by widespread blueschist-eclogite belts, tectonic mélanges, and abundant dismembered ophiolite complexes, reflecting the underflow of thousands of kms of ocean lithosphere. Zones of continental underflow, on the other hand, tend to involve the consumption of relatively small intervening ocean basins, and the descent of sialic crust prior to amalgamation. Table 1 lists the contrasting lithologic natures of Alpine- and Pacific-type subduction-zone assemblages. Metamorphic prograde and retrograde pressure-temperature paths followed by such terranes during subduction and later exhumation are topologically similar, but some intracratonic contractional complexes retain relics of ultrahigh-pressure metamorphism (P_{max} = 2.5–4.0 GPa), whereas recovered outboard Circumpacific orogens typically consist of only high-pressure belts (P_{max} = 0.6–1.8 GPa). Both types are extensively retrogressed, but because HP belts tend to have formed at shallower depths during subduction, their exhumation commonly involves less complete back reaction due to low-temperature, more sluggish transformations compared with high-temperature back reaction rates overprinting UHP complexes.

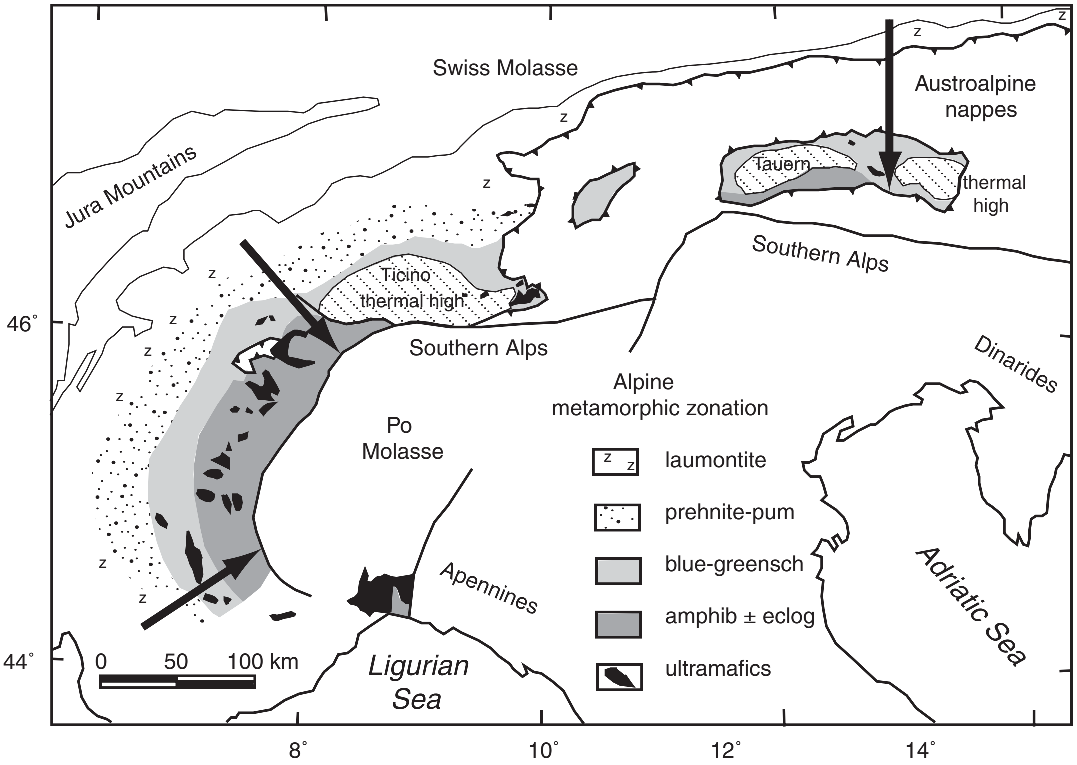


Figure 4. Generalized regional setting of the Alps, after Ernst (1971), a HP-UHP metamorphic belt, showing direction of increasing subduction depths and prograde blueschist-eclogite metamorphism (arrows), now recovered. The Ticino and Tauern thermal highs represent Miocene metamorphic culminations involving granitoids and kyanite-sillimanite recrystallization/annealing of the pre-existing units.

ROLE OF AQUEOUS FLUIDS IN SUBDUCTION-ZONE SETTINGS

General Statement

Consumption of an oceanic plate allows the subduction of entrained sediment and its basaltic basement. Rocks are either offloaded into the accretionary prism at shallow depths, as is most of the weak, low-density sedimentary prism, or returned to the upper mantle, as is most of the strong, high-density oceanic crust. Where microcontinental salients are entrained in the downgoing oceanic lithosphere, transport to the site of subduction leads to underflow, and continental crust may be carried beneath the non-subducted plate to considerable depths. Regardless of whether the descending materials are unconsolidated sediments or old, strong quartzofeldspathic crust, pressure within the slab rises with subduction depth, whereas temperature only gradually increases in most subduction zones. H_2O, and CO_2 may be added to relatively dry portions of the downgoing plate, and are driven off from the more volatile-rich parts (Peacock, 1995; Bebout, 1996). Shallow-level, pre-eclogitic stages of these reactions have been treated quantitatively by Frey, ed. (1987) and Ernst (1990). Attending deeper subduction of crustal lithologies, the remaining H_2O is sequestered exclusively in relatively refractory silicate phases (Schreyer et al., 1987; Poli and Schmidt, 1997; Ernst et al., 1998). During exhumation, volatiles gain access to ascending low-density masses, or diffuse away from them, depending on the composition, pressure-temperature trajectory, average grain size, permeability, and extent of shearing of the various units. Some expelled fluids rise into and through the overlying mantle wedge, whereas the rest migrates back up the conduit provided by the subduction channel (Cloos, 1984; Reck, 1987; Vrolijk, 1987; Vrolijk et al., 1988).

Evolution of H_2O and the Generation of Calcalkaline Arcs

Attending subduction, low-grade lithologies lose most of their volatiles at shallow depths during prograde recrystallization. At depths greater than ~50 km, clinoamphibole-bearing metabasaltic crust and the serpentinized peridotite underpinnings of the oceanic lithosphere comprise the most significant dehydrating rock types (Liu et al., 1996). Under equilibrium conditions, the devolatilization of Ca-amphiboles and serpentine minerals should begin at ~70–80 km depth; however, at low temperatures, reactions are sluggish on the time scale of plate descent, so fluid expulsion probably reaches a maximum at somewhat greater depths. Persistence of lower pressure phase assemblages during pressure overstepping

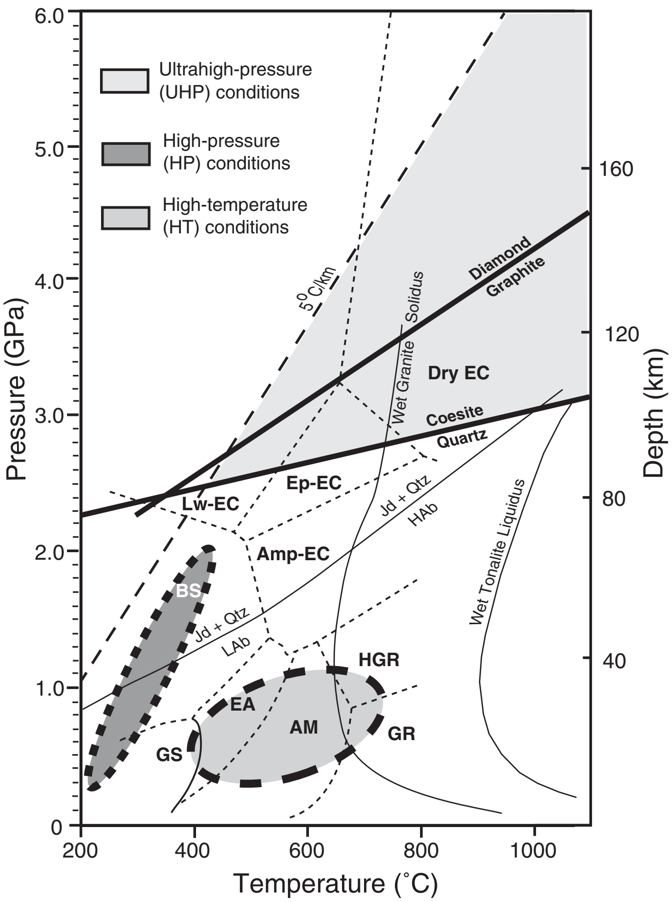


Figure 5. Petrogenetic grid for metabasaltic bulk-rock compositions, after Liou et al. (1998) and Okamoto and Maruyama (1999). The pressure-temperature realms for paired Pacific-type (HP + HT) and Alpine-type (HP-UHP) metamorphism are indicated. An extremely low subduction-zone geothermal gradient of 5 °C/km is also shown. Citations to the experimental phase equilibria are provided by Liou et al. (1998). Mineral abbreviations are: Jd—jadeite; Qtz—quartz; LAb—low albite; and Hab—high albite. Metamorphic-facies abbreviations are: AM—amphibolite; Amp-EC—amphibolite-eclogite; BS—blueschist; EA—epidote amphibolite; EC—eclogite; Ep-EC—epidote-eclogite; GR—sillimanite-bearing granulite; GS—greenschist; HGR—kyanite-bearing granulite; P—prehnite; PA—pumpellyite-actinolite; PP—prehnite-pumpellyite; and ZE—zeolite.

appears to be characteristic of some deeply subducted terranes where H_2O is absent (Austrheim, 1990, 1998). Thus, long-continued descent of thousands of kms of Pacific-type oceanic lithosphere may provide the greatest proportion of deep-seated aqueous fluid rising through the subduction channel, as well as diffusing into the overlying mantle wedge. Hydrous fluid-induced partial melting of the refertilized mantle hanging wall (and/or the eclogitic oceanic crust) evidently results in generation of the calcalkaline suite making up the massive volcanic-plutonic arc set back 100 ± 50 km from the convergent plate junction (Drummond and Defant, 1990; Kushiro, 1990; Hawkesworth et al., 1993; Morris, 1995; Clift et al., 2001; Hickey-Vargas et al., 2002). Concentrations of incompatible, large-ion-lithophile, and light rare earth elements, $^{87}Sr/^{86}Sr$ initial values, and epsilon Nd ratios in volatile-bearing arc volcanic and plutonic rocks argue for the partial fusion of garnet-bearing protoliths attended by an aqueous fluid.

Closure of a relatively small oceanic basin prior to continental subduction provides lesser amounts of volatiles derived from the descending oceanic lithosphere, explaining the general lack of H_2O-mediated generation of calcalkaline arc rocks in Alpine-type compressional belts. The fluid flux under UHP conditions is probably curtailed by the arrival, profound underflow, and suturing of sialic crust, because biotite and white mica—the principal hydrous phases present in metamorphosed quartzofeldspathic + pelitic rock types—remain stable at great depth, and do not devolatilize unless temperatures exceed ~800 °C. Accordingly, subduction is not expected to generate a substantial calcalkaline arc, but might involve partial melting of over-thickened continental crust, producing modest amounts of peraluminous, S-type granitoids as recycled material. Real continental growth—as opposed to the recycling of pre-existing sialic materials—appears to be the result of clinoamphibole ± serpentine dehydration within the descending oceanic lithosphere, followed by volatile-induced partial fusion of the metasomatized mantle wedge ± descending amphibolitic/eclogitic oceanic crust (Ernst, 1999).

The transition from oceanic to continental underflow is exemplified by the Indonesian Archipelago (Hamilton, 1979; Snyder et al., 1996). The strongly curved portion of the Australian-Eurasian suture between Timor and Seram-Irian Jaya is the site of underflow of old, cool continental crust; farther west along the Sumba-Java-Sumatra segment of the convergent boundary, oceanic lithosphere is diving beneath Indonesia. As evident from Figure 6, the Sunda-Banda inner volcanic arc is extremely active west of Timor, where oceanic lithosphere descends under Indonesia; volcanic activity declines eastward toward the Weber Deep, and the strongly curved portion of the arc is characterized by magmatic near-quiescence where Australian continental crust sinks beneath the Eurasian plate. In this easternmost part, the minor volumes of extrusive rock appear to be contaminated by assimilation of Australian passive margin sediments, as well as due to incorporation of continental crust (Charlton, 1991; Hilton et al., 1992; van Bergen et al., 1993). Generation of primary calcalkaline melts attending the subduction of hydrated oceanic crust-capped lithosphere in contrast to recycled volcanics associated with the downgoing, refractory micaceous sialic crust seems to explain the difference in volcanism laterally along the arc.

Cenozoic uplift and exposure of HP rocks in the eastern part of the suture zone reflect decoupling and ascent of subducted, largely quartzofeldspathic, low-density materials along the plate junction. As discussed in the section dealing with exhumation, the rise of sheet-like slabs of blueschist reflects rupturing and accelerated sinking of the oceanic lithosphere (Widiyantoro and van der Hilst, 1996); this ascent probably has been aided by a decrease in stress along the base of the buoyant, ductile continental material as it warmed within the upper mantle (Ernst et al., 1997).

TABLE 1. GENERALIZED LITHOLOGIC COMPARISON OF PHANEROZOIC SUBDUCTION-ZONE REGIMES

Protoliths	Alpine-type (high pressure–ultrahigh pressure)	Pacific-type (high pressure)
Shallow-marine strata	platform carbonates, orthoquartzites	reef (atoll) limestones
Clastic wedges	generally thin, well-stratified, multi-cycle siliciclastics, peraluminous shales	arc-derived, voluminous, first-cycle graywackes, muddy olistostromes
Deep-sea sedimentary rocks	uncommon deep-water carbonates	widespread bedded cherts, Mn-nodules, deep-water carbonates
Igneous rocks	mostly suprasubduction zone basalt + enriched-MORB	mostly normal-MORB + seamounts (OIB)
Basement	granitic gneiss complexes	oceanic lithosphere
Ore deposits	kuroko-type (massive sulfides)	mid-ocean ridge origin
Age of rock formations*	ancient to young	exclusively young
Tectonics	oceanward vergence of nappes, thrustfaults, late-stage backfolding	oceanward vergence of nappes, thrust faults. Rare antithetic thrusting
Rapid exhumation	during final collisional suturing	episodic, erratic

Petrology	Alpine-type (high pressure–ultrahigh pressure)	Pacific-type (high pressure)
Typical maximum pressure	2.6–4.0 GPa (ultrahigh-pressure)	0.6–1.8 GPa (high-pressure)
Associated coeval calcalkaline volcanic-plutonic belt	rare and small, or absent	outboard: absent or very minor; inboard: in all cases, huge
Degree of retrogression	ultrahigh pressure almost complete, high pressure incomplete	high pressure incomplete
Unaltered mantle fragments	garnet lherzolite	spinel ± plagioclase lherzolite, harzburgite, dunite
Associated, coeval serpentinite bodies	uncommon or common	outboard: ubiquitous inboard: uncommon or common
Coeval paired belts	absent	invariably present

*Young—generation of the lithologic section ~0–200 m.y. prior to time of underflow.

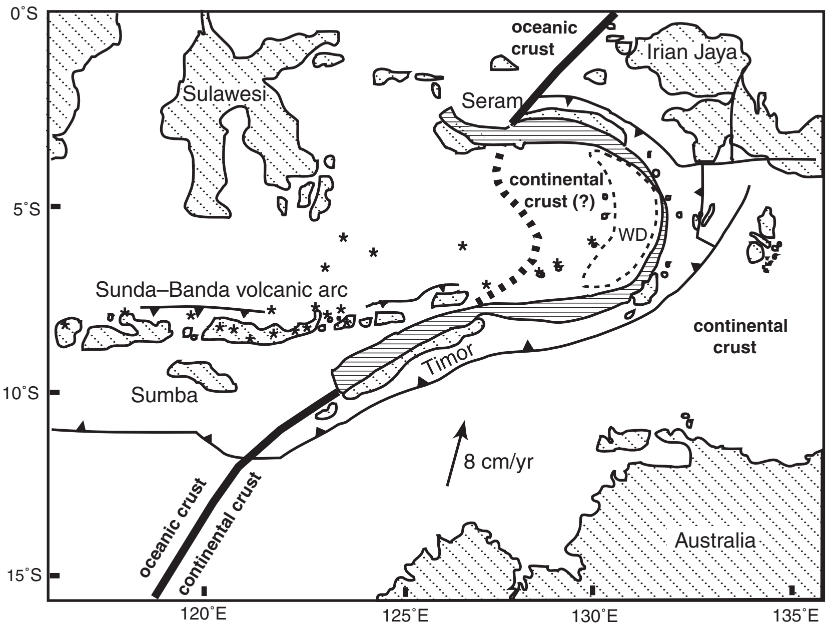


Figure 6. Eastern Sunda-Banda Arc, an example of convergence and exhumation of a transitional Alpine-Pacific-type belt, after Hamilton (1979) and Snyder et al. (1996) The plate-tectonic setting and exhumed blueschists (horizontal-lined pattern) are indicated. The 5 km isobath outlining the Weber Deep (WD), is shown by the closed dashed contour. Australian continental crust is subducting beneath the Timor-Seram-Irian Jaya section of the Indonesian suture zone; this eastern portion of the arc is typified by only minor calcalkaline igneous activity. The vigorous Sunda-Banda inner volcanic arc (asterisks—active volcanoes) lies chiefly west of Timor, where oceanic lithosphere of the Australian plate is descending beneath the Eurasian plate.

Kinetics of Metamorphic Hydration-Dehydration Reactions

Evidence of widespread disequilibrium during subduction-zone metamorphism (e.g., Frey et al., 1974; Rubie, 1990; Hacker, 1996; Austrheim, 1998) highlights the need for quantitative experimental data on reaction rates. Judging from the study of HP and UHP complexes, the presence or absence of aqueous fluid largely controls the rate at which reactions occur, and the extent to which they approach completion (Leech, 2001). Although the kinetic effect of H_2O is well known, and specific mechanisms for catalysis have been proposed (e.g., Rubie, 1986), little is known quantitatively about the dependence of reaction rates and mechanisms on fluid concentrations + chemistries in systems with very low fluid-rock ratios attending subduction of oceanic crust, an accretionary prism, or a microcontinental terrane.

The ease with which aqueous fluids gain access to, or egress from subducting lithosphere and ascending segments of low-density crustal material is a function of rock composition, permeabilities, deformation, grain size, and availability of volatiles. These parameters reflect the past geologic histories and dynamics of lithotectonic units moving along a convergent plate junction. Based on computational thermal modeling (Peacock, 1992, 1995; Ernst and Peacock, 1996; Hacker et al., 2003a) and laboratory phase-equilibrium studies (Vielzeuf and Holloway, 1988; Schreyer, 1995; Massone, 1995; Liu et al., 1996; Patiño Douce and McCarthy, 1998), the evolving thermal structure of a convergent plate junction, including subducting oceanic crust ± sedimentary load or continental material, as well as the pressure-temperature stability fields of the mineral assemblages for the major rock types are well understood. Almost unknown are the rates at which mineralogic transformations take place, and the conditions and tectonic realms under which volatile constituents are evolved and consumed. In the absence of aqueous fluid, low-pressure phase assemblages can be retained under prograde HP-UHP conditions (Austrheim, 1990; Zhang and Liou, 1997), and scattered HP-UHP relics can survive encased in unreactive container minerals under retrograde low-pressure conditions (Hirajima et al., 1993; Liou and Zhang, 1996).

EXHUMATION OF HIGH-PRESSURE–LOW-TEMPERATURE SUBDUCTION COMPLEXES

General Considerations

Most recognized HP and UHP terranes appear to be relatively tabular or sheet-like (Ernst et al., 1997). These tectonic slices have survived exhumation-induced decompression and recrystallization while retaining scattered relics of their high- to ultrahigh-pressure histories. The return toward shallow crustal levels occurs in response to one or more of several processes: tectonic contraction or wedge extrusion (Maruyama et al., 1994, 1996); buoyant body-force propulsion (Ernst, 1970, 1988; England and Holland, 1979; Hacker, 1996; Hacker et al., 2000); corner flow in front of a hanging wall backstop (Cowan and Silling, 1978; Cloos and Shreve, 1988a, 1988b; Cloos, 1993); and extensional or erosional collapse (Platt, 1986, 1987, 1993; Ring and Brandon, 1994, 1999). Because some relatively old, descending oceanic plates and deep-sea trenches appear to be retreating oceanward more rapidly than the encroaching nonsubducted lithosphere (Molnar and Atwater, 1978; Seno, 1985; Busby-Spera et al., 1990; Hamilton, 1995), compression of continental flakes in the jaws of a convergent junction cannot account for the ascent of subduction complexes. Moreover, although faulting associated with extensional collapse and/or erosion helps uncover formerly deeply buried terranes, this mechanism is incapable of explaining major pressure discontinuities observed across boundaries between subducted and nonsubducted lithologic units (Ernst, 1970; Ernst et al., 1970; Suppe, 1972), because differential uplifts exceeding the thickness of the continental crust would be required. However, buoyancy coupled with erosional decapitation and mass wastage, provides a viable mechanism for the exhumation of low-density sections carried to profound depths. Numerical simulations, laboratory scale models, and geologic field relationships demonstrate the operation of this process, as described farther on.

For both Pacific- and Alpine-type underflow of graywacke + shaley mélange, or a promontory of continental crust well bonded to the mantle lithosphere, entrance of increasing amounts of low-density material into the subduction zone reduces the negative buoyancy of the descending but coherent plate. This in turn may result in rupture and separation of the high-density oceanic lithosphere from the sialic crust at intermediate upper mantle depths—a realm where the lithosphere is in extension (Isacks et al., 1968). Breakoff of the oceanic slab (Sacks and Seacor, 1990; von Blanckenburg and Davies, 1995) increases the effective buoyancy of the up-dip quartzofeldspathic subduction complex; this rupture allows sialic sheets no longer attached to the oceanic lithosphere "anchor" to ascend back up the subduction channel (van den Beukel, 1992; Davies and von Blanckenburg, 1998). Exhumation also may be enhanced by a shallowing of the decoupled, buoyant, and rebounding continental lithosphere (Ernst et al., 1997). Also, the low-density continental lithosphere should rise as a consequence of the reduction of shear force acting along its base as the slab gradually warms in the upper mantle and passes through the brittle-ductile transition (Stöckhert and Renner, 1998). Devolatilization of the oceanic lithosphere would also produce embrittlement and weakening of the crustal section.

Previous studies (e.g., Ernst, 1971; Chopin, 1987) have demonstrated that deep subduction of low-density material accounts for the generation of Pacific- and Alpine-type metamorphic belts. A major petrotectonic problem consists of clarifying how these complexes have returned to shallow crustal levels while preserving relics of HP and UHP phase assemblages. The two-way movement of terranes along subduction zones was recognized long ago (Ernst, 1970; Suppe, 1972; Willett et al., 1993). Two end-member convergent plate junction configurations, both of which may involve large components of arc-parallel slip, are emphasized here: (1) subduction of a weak, Pacific-type graywacke + shale complex carried down on oceanic lithosphere; and (2) Alpine-type suturing of a relatively strong continent, microcontinent, or island arc beneath a nonsubducted lithospheric plate. The former gives rise to HP accretionary prisms that mark the Pacific Rim (Miyashiro, 1967). The latter involves underflow of salients or peninsulas of old continental crust, thoroughly imbedded in cool, oceanic lithospheric plates (Yin and Nie, 1993; Ernst and Liou, 1995). The rocks descend relatively rapidly, generating the characteristic HP-UHP mineralogy of contractional complexes (Peacock, 1995; Ernst et al., 1997). In a contrasting type of attempted subduction of muddy mélange, where the low-density materials are extremely incompetent and very poorly coupled to the descending lithosphere, upper plate collision/indentation occurs instead (Ellis, 1996); the East Taiwan ophiolite and Lichi mélange constitute an example of this type of aborted subduction (Liou et al., 1977; Page and Suppe, 1981; Ho, 1986).

The Thin-Slab Hypothesis

Rocks are good thermal insulators, hence it is exceedingly difficult for such materials to cool rapidly during exhumation. Because of this poor thermal conductivity, how can deeply buried but buoyant masses decompress rapidly without passing through more normal, low-pressure crustal pressure-temperature realms? All surviving HP-UHP complexes exhibit ubiquitous overprinting characteristic of granulite-, amphibolite-, and greenschist-facies conditions. In the presence of an aqueous fluid, adiabatic ascent would be expected to result in relatively high-temperature annealing and thorough obliteration of pre-existing HP and UHP mineral assemblages. Of course, lack of H_2O would decrease the rate of retrogression. Nevertheless, heat must be withdrawn from decompressing complexes as they are exhumed, or mineralogic evidence of their former HP and/or UHP configurations would not be retained in even fragmentary fashion.

The rare preservation of high- and ultrahigh-pressure relics is favored by continued subduction-induced refrigeration tectonically beneath the rising HP-UHP complex, and coeval extensional faulting against the overlying, cooler hanging-wall plate (Hacker and Peacock, 1995). In such cases, relatively thin slices of material would lose heat along both upper and lower surfaces by thermal conduction during ascent. Some subduction complexes rise virtually adiabatically, whereas others appear to have nearly retraced the prograde pressure-temperature trajectory during decompression (Rubie, 1984; Ernst, 1988; Ernst and Peacock, 1996). Proposed relationships, shown diagrammatically in Figure 7, apply to the exhumation of both HP and UHP terranes. Forces acting on a sheet of subducted low-density material are as follows (Platt, 1987): (A) Descent of the sialic slab occurs only if shear forces caused by underflow (F_s) overcome the combined effects of buoyancy (F_b) and frictional resistance along the upper wall of the subduction channel (F_r). In this case,

$$F_s > F_b \sin\theta + F_r. \quad (1)$$

(B) Ascent of a slice of the low-density material occurs in cases where buoyancy is positive and exceeds the combined effects of shearing along the slab base and resistance to movement along its upper surface. For this situation,

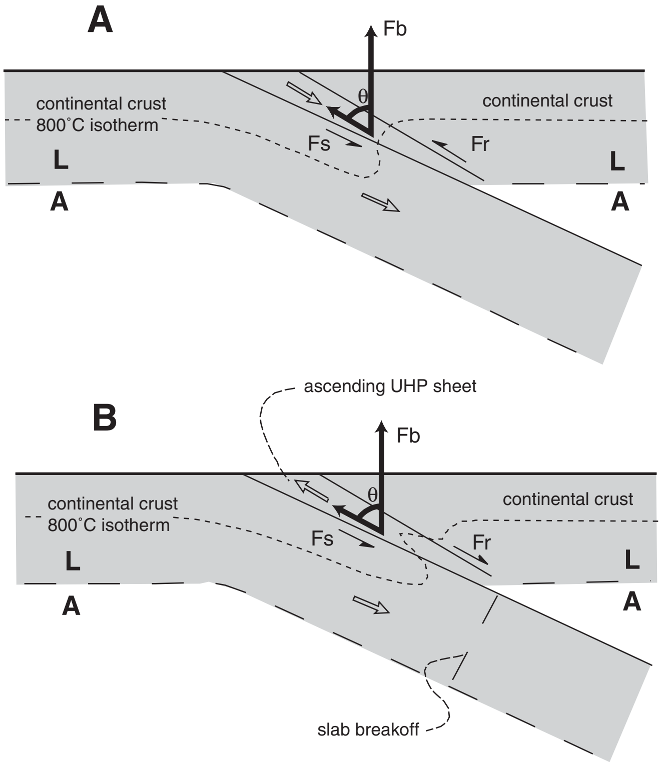


Figure 7. Schematic diagram portraying forces during active subduction, assuming structural integrity of the downgoing plate prior to slab breakoff, after Ernst et al. (1997). A: Deep burial and thermal structure of a subducted wedge of low-density material. B: Subsequent decompression and cooling of a rising slice of this buoyant HP-UHP material. Accompanying ascent of the thin HP-UHP sheet (thickness exaggerated for clarity), cooling of its upper margin takes place where it is juxtaposed against the lower temperature hanging-wall plate; cooling along the lower margin of the sheet takes place where it is in contact with the lower temperature, subducting-refrigerating lithospheric plate (see Fig. 1). Tectonic exhumation of low-density slices requires erosive denudation and/or gravitational collapse driven by the buoyant root at depth. The resolution of forces acting on the low-density slab in stages depicted in 7A and 7B are discussed in the text. Abbreviations are: A—asthenosphere; L—lithosphere.

$$F_b \sin\theta > F_s + F_r. \quad (2)$$

The hanging wall acts as a tectonic guide, so rising crustal materials are accreted seaward from the volcanic-plutonic arc.

Underflow of a basaltic crust-capped plate carrying a passive load of sediment, or closure of an oceanic basin, ultimately may result in the entrance of sialic material into the subduction zone. Heating and volatile expulsion cause a weakening of the subducted crust. Decoupling and ascent of a portion of this low-density section occurs provided buoyancy is positive, and exceeds the resistance to differential movement. For the HP and/or UHP mineral assemblages to be partly preserved on exhumation, the rising slab must be sufficiently thick to promote buoyancy-driven ascent, yet thin enough that heat is efficiently removed by thermal conduction across the sheet boundaries—the upper normal and lower reverse faults (Fig. 7). Such shear senses are required by observed structural relations and derived cross-sections, for example, in the Franciscan Complex (Ernst, 1970; Suppe, 1972; Platt, 1986; Jayko et al., 1987), the Western Alps (Henry, 1990; Compagnoni et al., 1995; Michard et al., 1995), the Sanbagawa Belt (Kawachi, 1968; Ernst et al., 1970; Banno and Sakai, 1989), the Kokchetav Massif (Kaneko et al., 2000; Ishikawa et al., 2000; Ota et al., 2000), and the Dabie-Sulu Belt (Hacker et al., 1995, 1996, 2000; Webb et al., 1999). A cross-section of the 1–2 km thick UHP sheet documented from the Western Alps is illustrated in Figure 8. Similar, remarkably thin allochthonous UHP sheets have been described from the Kokchetav Massif (Kaneko et al., 2000; Ishikawa et al., 2000; Maruyama and Parkinson, 2000; but see Theunissen et al., 2000), and the Western Gneiss Region of southwest Norway (Robinson and Terry, 1998; Terry et al., 2000a, 2000b).

A decrease in bulk density of the continental lithosphere after slab breakoff results in a shallowing of the subduction angle, and may be partly responsible for the late doming recognized in some exhumed convergent plate junctions. This late-stage exhumation also may be aided by continuing accretionary underplating, coupled with isostatic uplift and extensional collapse (Platt, 1986, 1987, 1993). Another unloading mechanism involves the antithetic faulting typical of some compressional orogens, in which double vergence is produced during terminal stages of the buoyant ascent of low-density crust and its erosional removal (e.g., Dal Piaz et al., 1972; Ring and Brandon, 1994, 1999; Beaumont et al., 1996, 1999).

Where thin HP-UHP slices (1–5 km thick, and tens to ≥100 km in lateral dimensions) are exhumed during continued subduction + refrigeration, the ascending sialic complex approximately follows the prograde metamorphic pressure-temperature path in reverse, but on its high-temperature side. Such pressure-temperature trajectories have been documented, for instance, in HP and UHP terranes of the California Coast Ranges and the Western Alps (e.g., Ernst, 1988; Chopin et al., 1991; Coleman and Wang, 1995). For thick, more nearly equidimensional ascending bodies (>10 km thick?), the ratio of cooling surface to mass is low, and interior portions probably remain sufficiently hot during decompression for the complete obliteration of all evidence of deep-seated metamorphism, and in some cases for partial melting to ensue; such exhumed masses would not retain precursor HP-UHP phases, and would not be recognized as ever having been deeply buried. Intermediate conditions between subduction-zone refrigeration and adiabatic exhumation evidently caused minor partial fusion in the ascending microdiamond-bearing Kokchetav Massif of northern Kazakhstan (Sobolev and Shatsky, 1990), and possibly in parts of several other UHP complexes (Cuthbert and Carswell, 1990; Carswell et al., 2000).

But are subduction complexes buoyant enough to overcome the traction of the oceanic plate carrying them downward? The one-atmosphere densities of unaltered oceanic crust, ~3.0, continental material, ~2.7, and anhydrous mantle, ~3.2, increase with elevated pressure, reflecting the progressive transformation of framework silicates to layer-, chain-, and orthosilicates. Typical HP and UHP mineralogic assemblages and computed ambient rock densities appropriate for burial depths of ~100 km (Ernst et al., 1997) are: metabasaltic eclogite, ~3.6; eclogitic quartzofeldspathic gneiss, ~3.0; and garnet peridotite, ~3.3. Completely transformed to a dense assemblage, K-feldspar + jadeite + coesite-bearing granitic gneiss nevertheless remains less dense than garnet or spinel lherzolite, whereas metabasaltic eclogite is considerably denser than the mantle. Thus, at any reasonable subduction depth, HP-UHP sialic crust is buoyant relative to the surrounding mantle and tends to rise, whereas eclogitized oceanic crust is negatively buoyant and continues to sink. This relationship explains why exhumed HP and UHP terranes worldwide consist of >85%–90% felsic materials, and contain only small proportions of mafic and anhydrous ultramafic lithologies. It also accounts for the volumetrically minor presence of ophiolitic complexes, except for thoroughly serpentinized masses, in exhumed subduction complexes.

The process illustrated in Figure 7 is geometrically somewhat similar to the slab-extrusion model that Maruyama et al. (1994) proposed to account for the Dabie-Sulu UHP Belt of east-central China, as well as tectonic models advanced for the Franciscan Complex, the Himalayas, and the Alps (e.g., Ernst, 1970; Burg et al., 1984; Burchfiel and Royden, 1985; Merle and Guillier, 1989; Wheeler, 1991). Explicit to the present scenario, however, is the dominance of buoyancy-driven return of the HP-UHP metamorphosed sheet of continental crust or accretionary prism back up the subduction zone (rather than compression), followed by extensional collapse and erosion (e.g., see; England and Molnar, 1993; Platt, 1986, 1987, 1993).

Numerical and Scale-Model Convergent Plate Junctions

The laboratory behavior of a sheet of low-density material resting on a dense, sinking slab has been experimentally modeled by Chemenda et al. (1995, 1996) employing proportional scaling factors combined with a simple three-layer convergent system. Underflow of the structurally coherent, continent-like sheet progresses until buoyancy exceeds the frictional resistance to decoupling from the downgoing plate; at this stage, the low-density material begins to return surfaceward along the subduction channel. The modeled subduction and exhumation processes are similar to the inferred dynamics of Alpine- and Pacific-type convergent margins illustrated in Figure 7. The simplified experiments of Chemenda et al. duplicate the overall imbricate architecture of the Himalayas and many other convergent plate junctions described in the literature. Finite-element computations of contractional orogens also produce familiar structures (Beaumont et al., 1996, 1999). Contrasting tectonic architectures reflect the variable extents of underplating and erosion-enhanced exhumation, as well as different physical and dynamic input parameters.

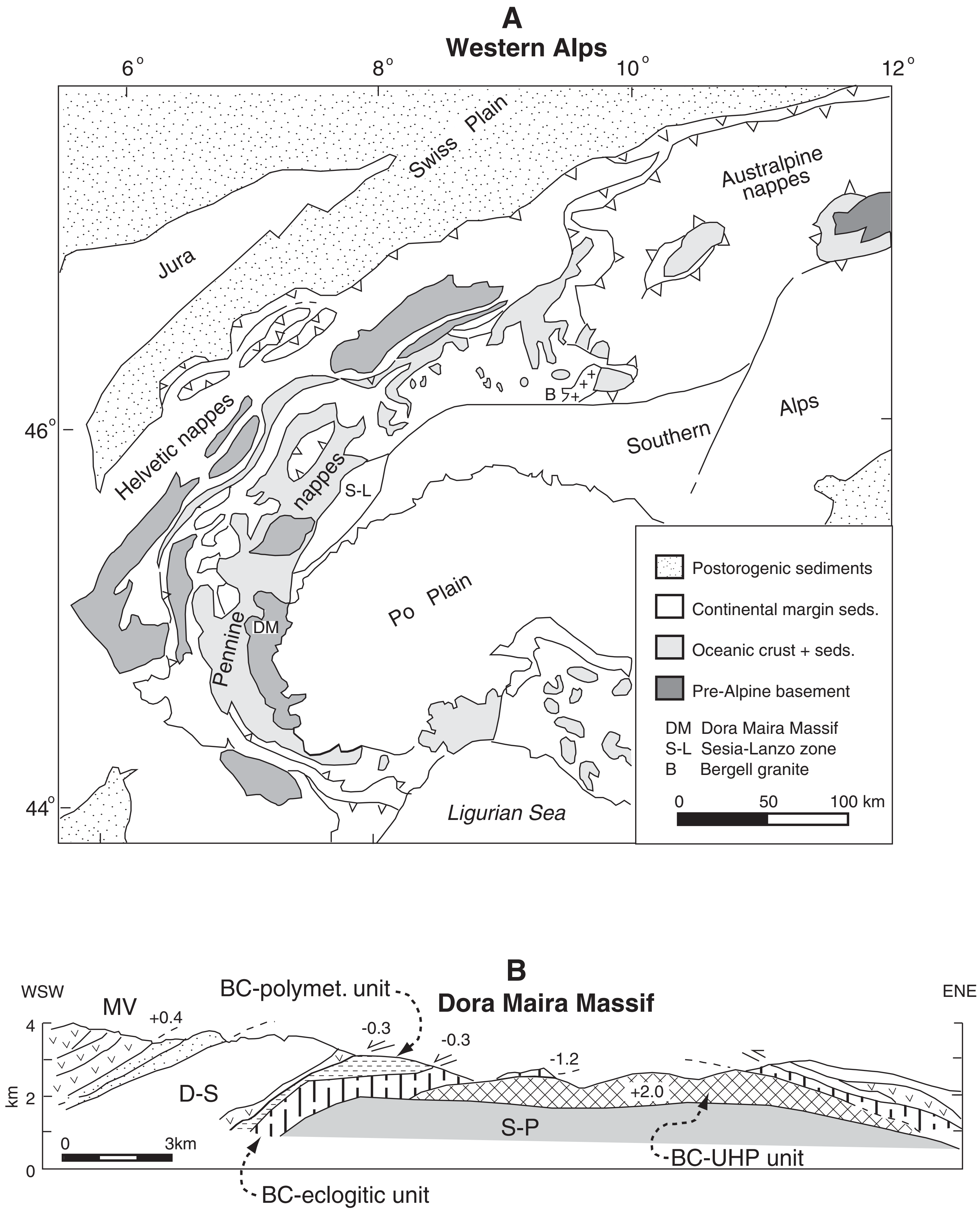


Figure 8. A: Regional geology and B: local structural + metamorphic relationships in the Dora Maira Massif of the Western Alps, simplified after Dietrich et al. (1974), Henry (1990), Compagnoni et al. (1995), Michard et al. (1995) and Coleman and Wang (1995). In the diagrammatic cross-section in the southern part of the Dora Maira Massif, numbers indicate the upward *change* in recorded pressure (GPa) relative to the adjacent underlying unit. Local nappe units are distinguished by different patterns in 8B, with abbreviations as follows: MV—Monviso meta-ophiolite and tectonically underlying serpentinitic mélange; D-S—Dronero-Sampeyre Permo-Triassic gneisses; BC—blueschistic and eclogitic basement complex; S-P—Sanfront-Pinerolo upper Paleozoic mica schists.

PETROTECTONIC CONTRASTS BETWEEN ALPINE- AND PACIFIC-TYPE METAMORPHIC BELTS

Petrologic and tectonic mechanisms proposed to explain the origin, plate-tectonic setting, and pressure-temperature evolution of Circumpacific and Alpine-type metamorphosed complexes must account for the wealth of observations regarding such terranes (Banno, 1964; Banno and Sakai, 1989; Bailey et al., 1964; Frey et al., 1974; Liou et al., 1994, 1995; Coleman and Wang, 1995; Dobretsov et al., 1995; Maruyama, 1997; Hacker et al., 2003a). Some of these differences are summarized in Table 2.

(1) Disrupted ophiolitic lithologies are present in both outboard Pacific- and Alpine-type belts. Although many exceptions occur, they consist chiefly of open-ocean N-MORBs + OIBs in Circumpacific subduction-zone terranes, and E-MORBs + IAT suprasubduction-zone complexes in Alpine-type belts (Dilek et al., eds., 2000).

(2) UHP metamorphic complexes are developed within old, relatively cool continental crust and are confined to intracontinental Alpine-type orogenic terranes, whereas HP metamorphic terranes frame the Pacific Rim, and are present in many intracratonic compressional sutures as well.

(3) Quartzofeldspathic ± pelitic lithologies constitute the most abundant rocks in both HP and UHP metamorphic belts. Pacific-type orogens consist of low metamorphic grade ophiolite + metagraywacke + metashale mélanges. High metamorphic grade continental equivalents, representing older protoliths, include para- and orthogneisses, paraschists, migmatites, and metagranitoids, followed by lesser amounts of metabasaltic rocks and metacalcareous platform strata characterize some Alpine-type orogens.

(4) Mafic and ultramafic SSZ rocks are of minor volumetric abundance in many but not all collisional orogens, whereas tectonized MORB + OIB ophiolites are ubiquitous in Circumpacific belts. In either case, similar to high- and ultrahigh-pressure metamorphic rocks, they mark the sites of convergent plate junctions.

(5) For UHP terranes, massive metamafic rocks contain most of the surviving relict ultrahigh-pressure silicate phases. Metacarbonates carry very rare UHP minerals; schistose metapelites and gneissose quartzofeldspathic lithologies generally lack UHP silicates, although exceedingly rare coesite and/or diamond micro-inclusions in garnet and zircon have been described (Liou and Zhang, 2002). For HP belts, metabasaltic and metagabbroic lithologies preserve minerals and phase assemblages indicating elevated pressures more completely than do quartzofeldspathic and pelitic lithologies; metacherts typically do not contain diagnostic HP phases, and if initially present in marbles, aragonite is rarely preserved.

(6) Postmetamorphic products of erosion are present but do not necessarily occur as giant sedimentary deposits adjacent to either Alpine- or Pacific-type mountain belts.

(7) Coeval calcalkaline volcanic-plutonic belts are conspicuously absent in Alpine-type terranes, but are ubiquitous,

TABLE 2. PRESSURE-TEMPERATURE-TIME HISTORIES OF HIGH- AND ULTRAHIGH-PRESSURE METAMORPHIC COMPLEXES*

Terrane Characteristic	Franciscan Complex, eastern belt	Sanbagawa Besshi + Oboke nappes	Dabie-Sulu Belt, coesite-eclogite unit	Kokchetav Massif, UHP unit	Dora Maira Massif, I. Venasca nappe	W. Gneiss Region, Fjordane Complex
protolith formation age	120–145 Ma	150–250 Ma	1.3–2.9 Ga	2.2–2.3 Ga	~300 Ma	1.6–1.8 Ga
temperature of metamorphism	250 ± 75 °C	300–625 °C	750 ± 75 °C	900 ± 75 °C	725 ± 50 °C	775 ± 75 °C
depth of metamorphism	15–35 km	20–70 km	90–125 km	~140 km	90–110 km	90–130 km
time of metamorphism	100–120 Ma	100 ± 10 Ma	235 ± 5 Ma	531 ± 3 Ma	35-40 Ma	400–410 Ma
upper crustal annealing	95 Ma (?)	70 ± 10 Ma	220 ± 5 Ma	525 ±3 Ma	30 Ma	~395 Ma
rise time to upper crust	15 ± 5 m.y.	30 ± 10 m.y.	15 ± 5 m.y.	~6 m.y.	3–4 m.y.	10 ± 5 m.y.
exhumation rate†	1–3 mm/yr	2–3 mm/yr	6–8 mm/yr	>18 mm/yr	>20 mm/yr	8–12 mm/yr
coesite inclusions	absent	absent	relatively abundant	rare	relatively abundant	rare
diamond inclusions	absent	absent	very rare	relatively abundant	absent	very rare
epidote blueschists	rare	common	present	rare	present	absent
lawsonite, aragonite, jadeite + quartz	law common, arag, jad + qtz rare	law rare, arag, jad + qtz absent	absent	absent	law, arag, jad + qtz rare	absent
areal extent	675 × 25 km	>700 × 35 km	>400 × 75 km	~120 × 10 km	225 × 60 km	350 × 70 km
max. thickness of HP or UHP units	5–10 km	>5 km	5 km (?)	1–3 km	1–2 km	>1 km (?)

*After Coleman and Wang (1995), Harley and Carswell (1995), Beane et al. (1995), Ernst and Peacock (1996), Hacker et al. (2000), and Rubatto and Hermann (2001).

†Average exhumation rates estimated by dividing depth of ultrahigh-pressure (UHP) metamorphism by time of ascent to 10–15 km crustal depth.

immense, and paired with an outboard subduction complex in Pacific-type belts.

(8) Rocks of the volcanic-plutonic arc may preserve a semicontinuous record of igneous activity marking landward HT belts of the Pacific Rim, whereas the exhumation of seaward blueschist-eclogite terranes in general is capricious and episodic in both Alpine- and Pacific-type subduction complexes.

(9) Well-dated Alpine-type terranes preserving scattered UHP relict phases have been exhumed to midcrustal levels at remarkably rapid ascent rates (Amato et al., 1998; Purchuk et al., 1998; Webb et al., 1999; Rubatto and Hermann, 2001; Hermann et al., 2001; Hacker et al., 2003b), approaching or exceeding 5–20 mm/yr. Radiometric data provide fewer constraints for the decompression of HP belts, but in general they also seem to have decompressed rapidly, although perhaps not as fast (1–3 mm/yr) as UHP terranes (Ernst, 1988; Itaya and Takasugi, 1988; Dallmeyer and Takasu, 1991).

DISCUSSION

How are the petrotectonic features of Alpine and Pacific-type metamorphic belts enumerated in the previous section accounted for by the inferred dynamic generation and exhumation histories of convergent plate junctions?

(1) Oceanic lithosphere is thrust into subduction complexes by convergent plate motion, and develops in continental margins or island arcs by back- and intra-arc spreading. These processes are similar in Circumpacific and contractional orogens, hence contrasts in the nature of associated ophiolites in HP and UHP metamorphic belts is a function of haphazard events. N-MORB and OIB suites seem to be most abundant in Pacific-type subduction zones, reflecting the sampling of an extensive tract of converging oceanic crust with its numerous lithospheric asperities, such as fracture zones, seamounts, hot spots, and spreading ridges. In contrast, consumption of a small ocean basin disfavors incorporation of abundant slices of oceanic crust + uppermost mantle because the brief underflow of oceanic lithosphere is limited by continental amalgamation; in such cases, SSZ ophiolites and E-MORBs can be as important as N-MORBs and OIBs. But, because of the tectonic imbrication of ophiolitic materials from both stable (nonsubducted), and descending plates, numerous contrary examples exist in consumptive suture zones.

(2) Mechanical analyses suggest that, provided it is well bonded to the downgoing lithosphere, sialic crust several km or more thick may be readily subducted if it enters a convergent plate junction (Molnar and Gray, 1979; England and Holland, 1979; Beaumont et al., 1996, 1999). A favorable geologic environment for ultrahigh-pressure metamorphism would involve insertion of a narrow tongue of continental crust into the subduction zone as an integral part of an old, thermally relaxed, largely oceanic slab (Ernst and Liou, 1995). The existence of UHP metagranitoids and quartzofeldspathic gneisses (e.g., Sobolev and Shatsky, 1990; Biino and Compagnoni, 1992; Wallis et al., 1997) demonstrates that low-density continental material may be carried to depths of at least 60–140 km. HP-UHP metamorphism is a consequence of this process, and is independent of lithology; however, the deep-seated sequestration of buoyant quartzofeldspathic rocks is a prerequisite for the later body-force-driven ascent of at least a portion of the HP-UHP terrane. Large, coherent masses of eclogitic oceanic crust remain negatively buoyant, so continue sinking into the deep mantle. Thus, resurrected UHP complexes essentially are restricted to zones of continental and microcontinental suturing—the plate-tectonic environment of Alpine-type subduction.

Pacific-type subduction of a quartzofeldspathic accretionary prism or shaley mélange involves the geologically simultaneous underflow of a longitudinal belt of low-density material. Insertion of a voluminous section of ductile graywacke ± shale into the convergent plate junction almost certainly would terminate subduction unless offloading and/or decoupling of the low-density material occurs. Because of weak bonding between the relatively incompetent sedimentary section and the sinking oceanic lithosphere, decoupling, ascent, and accretion would be expected to take place episodically at relatively shallow depths compared to UHP metamorphosed terranes.

(3) Lithospheric slabs descend to depths of 650 km or more along inclined Benioff-Wadati zones, so where underflow exceeds a few cm per year, HP and even UHP recrystallization are inevitable (Peacock, 1995); however, oceanic crust transformed to eclogite-facies mineral assemblages is denser than mantle peridotite, and garnet lherzolite is slightly denser than plagioclase- and spinel-bearing peridotite, so the oceanic crust + mantle will continue sinking after these phase transformations occur. In contrast, where a sufficiently large volume of low-density sialic material is subducted, buoyancy can overcome frictional resistance and permit ascent after disengagement from the downgoing plate. Accordingly, both recovered contractional UHP complexes and Circumpacific HP terranes consist chiefly of sialic bulk compositions, possessing an aggregate density considerably less than that of the mantle they displaced during subduction. Metamorphosed ophiolitic complexes represent a volumetrically minor portion of HP and UHP terranes because, if the latter contained a substantial complement of eclogitized oceanic crust, it would not be sufficiently buoyant to return to crustal levels (Ernst et al., 1997).

In support of this conclusion, all described UHP and HP terranes consist dominantly of low-density materials, with mafic ± anhydrous ultramafic rock types constituting <10%–15% by volume (Banno, 1964; Bailey et al., 1964; Frey et al., 1974; Coleman and Wang, 1995; Lennykh et al., 1995; Hacker et al., 1996; Maruyama et al., 1996; Leech, 2001). This reflects the buoyancy-driven ascent process that allows slices of profoundly subducted sialic terranes to be returned toward midlevels of the continental crust.

(4) The incompetence of shaley mélange + graywacke-rich, imbricated subduction complexes compared with old continental crust promotes the tectonic insertion of portions of the underlying oceanic crust ± serpentinized harzburgite basement into

downgoing Pacific-type terranes; many such mafic-ultramafic complexes have decoupled at shallow depths from the sinking oceanic lithosphere, and are sequestered along the inboard trench wall or nonsubducted continental margin. In contrast, the structural integrity of descending Alpine-type continental entities in some cases (but not the Western Alps) disfavors tectonic incorporation of disaggregated ophiolitic materials into the coherent HP-UHP complex. In both Alpine and Pacific types, variably hydrated peridotite of the overlying mantle wedge remains in a tectonically elevated position, and in some occurrences caps the subduction complex as an allochthonous sheet.

(5) Quartzofeldspathic + pelitic schists and gneisses contain abundant white mica ± biotite—rather refractory hydrous phases stable under UHP conditions (Hermann and Green, 2001). Such rocks in general are strongly foliated, whereas carbonates, cherts, and coarse-grained mafic igneous rocks are massive and nearly anhydrous. The former are relatively permeable to aqueous fluids compared to the latter. Thus, once formed, the retention of UHP relics is kinetically favored in massive, dry eclogites, impermeable siliceous schists, and a few marbles, but disfavored in more sheared, permeable, hydrated sialic units. The absence of H_2O, and closed-system recrystallization in situations where UHP relics are preserved, is supported by the anomalously low pre-subduction $\delta^{13}C$ and $\delta^{18}O$ values measured in Dabie-Sulu belt UHP coesite eclogites and their constituent minerals (Yui et al., 1995; Baker et al., 1997; Rumble, 1998; Zheng et al., 2000). Dry conditions are also suggested by laboratory kinetic studies of the transformation of coesite to quartz which indicate that, on decompression at moderate temperatures, H_2O contents of ~400 ppm in SiO_2 are sufficient to cause rapid, complete transformation to the low-pressure polymorph (Mosenfelder and Bohlen, 1997). For this reason, only very rare relict coesite has been discovered as micro-inclusions in zircons from Dabie-Sulu quartzofeldspathic gneisses (Tabata et al., 1998). The same situation holds for other UHP metamorphic terranes.

Blueschist belts have been subjected to pressure-temperature conditions less extreme than those attending UHP complexes, hence devolatilization is incomplete during prograde recrystallization, and retrogression is widespread attending decompression (Dal Piaz et al., 1972; Frey et al., 1974; Ernst, 1988; Banno and Sakai, 1989). Lower temperatures of HP metamorphism impede back-reaction, thus in many cases the low-pressure mineralogic overprint is incomplete. In contrast to silicate re-equilibration, the transformation of aragonite to calcite is exceedingly fast (Carlson and Rosenfeld, 1981), so orthorhombic $CaCO_3$ is only preserved in dry rocks subjected to very low-temperature retrograde paths.

(6) In order to elucidate possible decompression pressure-temperature trajectories allowing partial preservation of high- and ultrahigh-pressure relict phases, exhumations of both Alpine- and Pacific-type fault-bounded terranes have been numerically modeled (Ernst and Peacock, 1996) as extensional along the upper surface of a thin sheet while subduction-refrigeration continues along the lower thrust surface (Fig. 7). The process does not require the wholesale exhumation of a lithospheric plate, the entire continental crust, or even the full thickness of a quartzofeldspathic accretionary prism, and certainly not the structurally overlying mantle wedge. Thus, postmetamorphic erosional debris, although considerable in some cases (e.g., the Bengal fan and the Songpan-Ganze flysch basin), need not be voluminous in either Pacific- or Alpine-type orogens.

(7) Circumpacific subduction is a long-continued process involving thousands of kms of underflow of an oceanic plate, so sufficient time is available for the landward development of calcalkaline magmas at great depths, and maturation of the mantle hanging-wall plumbing system. The pressure-overstepped dehydration of abundant clinoamphiboles in the downgoing oceanic slab at depths exceeding 70–80 km (probably reaching a maximum near ~100 km due to sluggish devolatilization attending rapid subduction at low temperatures) would provide sufficient H_2O necessary to generate compositionally intermediate magmas through partial fusion of the oceanic crust and/or the undepleted mantle wedge (Drummond and Defant, 1990; Kushiro, 1990; Hawkesworth et al., 1993; Morris, 1995; Ernst, 1999). The generation and rise of these hydrous melts—apparently produced by this process—results in the construction of an andesitic-granitic arc inboard from the Pacific-type convergent plate junction on the stable, nonsubducted plate. In contrast, continental subduction in many cases involves relatively short-lived underflow of old, thermally relaxed oceanic lithosphere, so sufficient time may not have elapsed to develop a substantial volcanic-plutonic arc on the nonsubducted plate prior to amalgamation. During descent and suturing, layer silicates that dominate the sialic crust remain stable to subduction depths of at least ~140 km; thus, the arrival of continental crust at a convergent plate junction and its deep underflow would severely reduce the evolution of aqueous fluids at UHP depths—the pressure-temperature realm where calcalkaline magmas are generated.

(8) Long-sustained lithospheric underflow characteristic of Pacific-type subduction zones produces a massive, well-preserved andesitic-granitic arc typified by HT metamorphism in the spatially associated pre-existing crust, because magmas move up into the nonsubducted plate semicontinuously. In contrast, seaward subduction-zone metamorphic complexes of both Alpine- and Pacific-type descending plates disengage from the downgoing lithosphere episodically; return of low-density material to mid-crustal levels is a sensitive function of the changing geometry and physical properties of various units constituting the architecture of the convergent junction. Accordingly, only fragmentary portions of such blueschist-eclogite belts are erratically exhumed.

(9) The described petrotectonic features are compatible with the proposed formation, pressure-temperature evolution, and buoyancy-propelled tectonic exhumation + exposure through erosion and/or gravitational collapse of Alpine and Circumpacific terranes (e.g., Ernst, 1970; Platt, 1986, 1987, 1993; Maruyama, 1997), as well as the formation of massive calcalkaline arcs inboard from Pacific-type plate junctions. The kind of materials carried down subduction channels, the extent of deep-seated devolatilization, and the rates of transformation strongly influence

the nature of HP and UHP metamorphic belts. Exhumation of the subducted complexes to mid-crustal levels appears to be density driven, and the ascent in most cases is relatively fast. Because H_2O-rich Pacific-type subduction packages displace relatively small volumes of dense mantle ± serpentinized ultramafic material, they ascend at a few mm/yr—more slowly than do deeply subducted, rapidly exhumed Alpine-type complexes. Exhumation rates of 5–20 mm/yr, averaged over more than 5–20 m/yr, and seemingly required by UHP geochronologic data (Liou and Zhang, 1995; Dobretsov et al., 1995; Gebauer, 1996; Gebauer et al., 1997; Blythe, 1998; Purchuk et al., 1998; Grasemann et al., 1998; Lin and Roecker, 1998; Webb et al., 1999; Wheeler et al., 2001: Rubatto and Hermann, 2001) substantially exceed currently measured uplift and erosion rates in the Himalayan orogenic belt (Le Fort, 1996; Searle, 1996), but are marginally compatible with rates of exhumation of ~4 mm/yr calculated by Genser et al. (1996) for the Eastern Alps.

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REFERENCES CITED

Amato, J.M., Johnson, C., Baumgartner, L., and Beard, B., 1998, Sm-Nd geochronology indicates rapid exhumation of Alpine eclogites: Earth and Planetary Science Letters, v. 171, p. 425–438.

Anderson, R.N., DeLong, S.E., and Schwarz, W.M., 1978, Thermal model for subduction with dehydration in the downgoing slab: Journal of Geology, v. 80, p. 731–739.

Aoya, M., 2001, P-T-D path of eclogite from the Sanbagawa belt deduced from combination of petrological and microstructural analyses: Journal of Petrology, v. 42, p. 1225–1248.

Austrheim, H., 1990, The granulite-eclogite facies transition: A comparison of experimental work and a natural occurrence in the Bergen Arcs, western Norway: Lithos, v. 25, p. 163–169.

Austrheim, H., 1998, The influence of fluid and deformation on metamorphism of the deep crust and consequences for geodynamics of collision zones, *in* Hacker, B.R., and Liou, J.G., eds., When Continents Collide: Geodynamics and Geochemistry of Ultrahigh-Pressure Rocks: Dordrecht, Kluwer Academic Publishers, p. 297–323.

Bailey, E.H., Irwin, W.P., and Jones, D.L., 1964, Franciscan and related rocks, and their significance in the geology of western California: California Division of Mines and Geology Bulletin, v. 183, 177p.

Bailey, E.H., Blake, M.C., Jr., and Jones, D.L., 1970, On-land Mesozoic oceanic crust in California Coast Ranges: Washington, D.C., U.S. Geological Survey Professional Paper 700C, p. 70–81.

Baker, J., Matthews, A., Mattey, D., Rowley, D.B., and Xue, F., 1997, Fluid-rock interactions during ultra-high pressure metamorphism, Dabie Shan, China: Geochemica et Cosmochimica Acta, v. 61, p. 1685–1696.

Bally, A.W., 1981, Thoughts on the tectonics of folded belts, *in*: Thrust and Nappe Tectonics: Price, N.J., and McClay, K., eds.: London, Geological Society of London, Special Publication 9, p. 13–32.

Banno, S., 1964, Petrologic studies on Sanbagawa crystalline schists in the Bessi-Ino district, central Sikoku, Japan: Tokyo, University of Tokyo, Journal of the Faculty of Science, section 2, v. 15, p. 203–319.

Banno, S., and Sakai, C., 1989, Geology and metamorphic evolution of the Sanbagawa belt: London, Geological Society of London, Special Publication 43, p. 519–535.

Barton, M.D., Battles, D.A., Bebout, G.E., Capo, R.C., Christensen, J.N., Davis, S.R., Hanson, R.B., Michelson, C.J., and Trim, H.E., 1988, Mesozoic contact metamorphism in the western United States, *in* Ernst, W.G., ed., Metamorphic and Crustal Evolution of the Western United States: Englewood Cliffs, New Jersey, Prentice-Hall, Inc., p. 110–178.

Beane, R.J., Liou, J.G., Coleman, R.G., and Leech, M.L., 1995, Mineral assemblages and retrograde P-T path for high- to ultrahigh-pressure metamorphism in the lower unit of the Maksyutov Complex, Southern Ural Mountains, Russia: The Island Arc, v. 4, p. 254–266.

Beaumont, C., Ellis, S., Hamilton, J., and Fullsack, P., 1996, Mechanical model for subduction-collision tectonics of Alpine-type compressional orogens: Geology, v. 24, p. 675–678.

Beaumont, C., Ellis, S., and Pfiffner, A., 1999, Dynamics of sediment subduction-accretion at convergent margins: short-term modes, long-term deformation, and tectonic implications: Journal of Geophysical Research, v. 104, p. 17,573–17602.

Bebout, G.E., 1996, Volatile transfer and recycling at convergent margins: Mass-balance and insights from high P/T metamorphic rocks: Washington, D.C., American Geophysical Union Geophysical Monograph 96, p. 179–193.

Biino, G., and Compagnoni, R., 1992, Very high pressure metamorphism of the Brossasco coronite metagranite, southern Dora Maira massif, western Alps: Schweizerisches Mineralogisches und Petrografisches Mittelungen, v. 72, p. 347–362.

Blythe, A.E., 1998, Active tectonics and ultrahigh-pressure rocks, *in* Hacker, B.R., and Liou, J.G., eds., When Continents Collide: Geodynamics and Geochemistry of Ultrahigh-Pressure Rocks, Dordrecht, Kluwer Academic Publishers, p. 141–160.

Boudier, F., Bouchez, J.L., Nicolas, A., Cannat, M., Ceuleneer, G., Miseri, M., and Montigny, R., 1985, Kinematics of oceanic thrusting in the Oman ophiolites: model of plate convergence: Earth and Planetary Science Letters, v. 75, p. 215–222.

Boudier, F., Ceuleneer, G., and Nicolas, A., 1988, Shear zones, thrusts and related magmatism in the Oman ophiolite: initiation of thrusting on an oceanic ridge: Tectonophysics, v. 151, p. 275–296.

Burchfiel, B.C., and Royden, L.H., 1985, North-south extension within the convergent Himalayas region: Geology, v. 13, p. 679–682.

Burchfiel, B.C., Deng, Q., Molnar, P., Royden, L., Qang, Y., and Zhang, W., 1989, Intracrustal detachment within zones of continental deformation: Geology, v. 17, p. 448–452.

Burg, J.P., Brunel, M., Gapais, D., Chen, G.M., and Liu, G.H., 1984, Deformation of leucogranites of the crystalline Main Central Sheet in southern Tibet (China): Journal of Structural Geology, v. 6, p. 535–542.

Busby-Spera C.J., Mattinson, J.M., Riggs, N.R., and Schermer, E.R., 1990, The Triassic-Jurassic magmatic arc in the Mojave-Sonoran Deserts and the Sierran-Klamath region, *in* Harwood, D.S., and Miller, M.M., eds., Paleozoic and Early Mesozoic Paleogeographic Relations; Sierra Nevada, Klamath Mountains, and Related Terranes: Boulder, Colorado, Geological Society of America Special Paper 255, p. 93–114.

Carlson, W.D., and Rosenfeld, J.L., 1981, Optical determination of topotactic aragonite-calcite growth kinetics: metamorphic implications: Journal of Geology, v. 89, p. 615–638.

Carswell, D.A., Wilson, R. n., and Zhai, M., 2000, Metamorphic evolution, mineral chemistry, and thermobarometry of schists and orthogneisses hosting ultra-high pressure eclogites in the Dabieshan of central China: Lithos, v. 52, p. 121–155.

Castro, A., Fernandez, C., and Vigneresse, J.L., eds. 1999, Understanding Granites: Integrating New and Classical Techniques: London, Geological Society of London Special Publication, v. 168, 278p.

Charlton, P.R., 1991, Post collisional extension in arc-continent collision zones, eastern Indonesia: Geology, v. 19, p. 28–31.

Chemenda, A.I., Mattauer, M., Malavieille, J., and Bokun, A.N., 1995, A mechanism for syn-collisional rock exhumation and associated normal faulting: Results from physical modelling: Earth and Planetary Science Letters, v. 132, p. 225–232.

Chemenda, A.I., Mattauer, M., and Bokun, A.N., 1996, Continental subduction and a new mechanism for exhumation of high-pressure metamorphic rocks: new modelling and field data from Oman: Earth and Planetary Science Letters, v. 143, p. 173–182.

Chopin, C., 1984, Coesite and pure pyrope in high-grade blueschists of the Western Alps. A first record and some consequences: Contributions to Mineralogy and Petrology, v. 86, p. 107–118.

Chopin, C., 1987, Very-high-pressure metamorphism in the western Alps: implications for subduction of continental crust: Philosophical Transactions of the Royal Society of London, ser. A, no. 1557, p. 183–197.

Chopin, C., Henry, C., and Michard, A., 1991, Geology and petrology of the coesite-bearing terrain, Dora-Maira massif, Western Alps: European Journal of Mineralogy, v. 3, p. 263–291.

Clift, P.D., Rose, E.F., Shimizu, N., Layne, G.D., Draut, A.E., and Regelous, M., 2001, Tracing the evolving flux from the subducting plate in the Tonga-Kermadec arc system using boron in volcanic glass: Geochimica et Cosmochimica Acta, v. 65, p. 3347–3364.

Cloos, M., 1984, Landward-dipping reflectors in accretionary wedges: Active dewatering conduits?: Geology, v. 12, p. 519–522.

Cloos, M., 1993, Lithospheric buoyancy and collisional orogenesis: Subduction of oceanic plateaus, continental margins, island arcs, spreading ridges, and seamounts: Geological Society of America Bulletin, v. 105, p. 715–737.

Cloos, M., and Shreve, R. l., 1988a, Subduction-channel model of prism accretion, melange formation and subduction erosion at convergent plate margins, 1, Background and description, *in* Ruff, L., and Kanamori, H., eds., Subduction Zones: Pure and Applied Geophysics: Basel, Switzerland, Birkhauser, v. 128, p. 455–500.

Cloos, M., and Shreve, R. l., 1988b, Subduction-channel model of prism accretion, melange formation and subduction erosion at convergent plate margins, 2, Implications and discussion, *in* Ruff, L., and Kanamori, H., eds., Subduction Zones: Pure and Applied Geophysics: Basel, Switzerland, Birkhauser, v. 128, p. 501–545.

Coleman, R.G., 1977, Ophiolites, Ancient Oceanic Lithosphere?: Springer-Verlag, New York, 229p.

Coleman, R.G., and Wang, X., 1995, Overview of the geology and tectonics of UHPM, *in* Coleman, R.G., and Wang, X., eds., Ultrahigh Pressure Metamorphism: New York, Cambridge University Press, p. 1–32. .

Compagnoni, R., Hirajima, T., and Chopin, C., 1995, UHPM metamorphic rocks in the Western Alps, *in* Coleman, R.G., and Wang, X., eds., Ultrahigh Pressure Metamorphism: New York, Cambridge University Press, p. 206–243.

Coney, P.J., Jones, D.L., and Monger, J.W. H., 1980, Cordilleran suspect terranes: Nature, v. 288, p. 329–333.

Cowan, D.S., and Silling, R.M., 1978, A dynamic, scaled model of accretion at trenches and its implications for the tectonic evolution of subduction complexes: Journal of Geophysical Research, v. 83, p. 5389–5396.

Cuthbert, S.J., and Carswell, D.A., 1990, Formation and exhumation of medium-temperature eclogites in the Scandinavian Caledonides, *in* Carswell, D.A., ed., Eclogite Facies Rocks: Glasgow, Scotland, Blackie & Son, Ltd, p. 180–203.

Dallmeyer, R.D., and Takasu, A., 1991, Tectonometamorphic evolution of the Sebadani eclogitic metagabbro and the Sanbagawa schists, central Shikoku, Japan: ^{40}Ar/^{39}Ar mineral age constraints: Journal of Metamorphic Geology, v. 9, p. 605–618.

Dal Piaz, G.V., Hunziker, J.C., and Martinotti, G., 1972, La zona Sesia-Lanzo e l'evoluzione tettonico-metamorfica delle Alpi nordoccidentali interne: Memoir Soc. Geol. Italy, v. 11, p. 433–460.

Davies, J.H., and von Blanckenburg, F. (1998) Thermal controls on slab breakoff and the rise of high-pressure rocks during continental collisions, *in* Hacker, B.R., and Liou, J.G., eds., When Continents Collide: Geodynamics and Geochemistry of Ultrahigh-Pressure Rocks: Dordrecht, Kluwer Academic Publishers, Dordrecht, p. 97–115.

DePaolo, D.J., 1981, A neodymium and strontium isotopic study of Mesozoic calc-alkaline granite batholiths of the Sierra Nevada and Peninsular Ranges, California: Journal of Geophysical Research, v. 86, p. 10,470–10,488.

Dewey, J.F., and Bird, J.M., 1970, Mountain belts and the new global tectonics: Journal of Geophysical Research, v. 75, p. 2625–2647.

Dickinson, W.R., 1971, Clastic sedimentary sequences deposited in shelf, slope and trench settings between magmatic arcs and associated trenches: Pacific Geology, v. 3, p. 1–14.

Dickinson, W.R., 1972, Evidence for plate-tectonic regimes in the rock record: American Journal of Science, v. 272, p. 551–576.

Dickinson, W.R., 1976, Sedimentary basins developed during evolution of Mesozoic-Cenozoic arc-trench systems in western North America: Canadian Journal of Earth Science, v. 13, p. 1268–1289.

Dietrich, V., Vuagnat, M., and Bertrand, J., 1974, Alpine metamorphism of mafic rocks: Schweizerisches Mineralogische und Petrografisches Mittelungen, v. 54, p. 291–333.

Dilek, Y., Moores, E.M., Elthon, D., and Nicolas, A., eds., 2000, Ophiolites and oceanic crust: new insights from field studies and the ocean drilling program: Boulder, Colorado, Geological Society of America Special Paper 349, 552p.

Dobretsov, N.L., Shatsky, V.S., and Sobolev, N.V., 1995, Comparison of the Kokchetav and Dabie Shan metamorphic complexes: coesite- and diamond-bearing rocks and UHP-HP accretional-collisional events: International Geology Review, v. 37, p. 636–656.

Drummond, M.S., and Defant, M.J., 1990, A model for trondhjemite-tonalite-dacite genesis and crustal growth via slab melting: Archean to modern comparisons: Journal of Geophysical Research, v. 95, p. 21,503–21,521.

Ellis, S., 1996, Forces driving continental collision: Reconciling indentation and mantle subduction tectonics: Geology, v. 24, p. 699–702.

England, P.L., and Holland, T.J. B., 1979, Archimedes and the Tauern eclogites: the role of buoyancy in the preservation of exotic eclogitic blocks: Earth and Planetary Science Letters, v. 44, p. 287–274.

England, P.L., and Molnar, P., 1993, Cause and effect among thrust and normal faulting, anatectic melting and exhumation in the Himalaya: London, Geological Society of London, Special Publication no. 74, p. 401–411.

Ernst, W.G., 1970, Tectonic contact between the Franciscan melange and the Great Valley sequence, crustal expression of a Late Mesozoic Benioff zone: Journal of Geophysical Research, v. 75, p. 886–901.

Ernst, W.G., 1971, Metamorphic zonations on presumably subducted lithospheric plates from Japan, California and the Alps: Contributions to Mineralogy and Petrology, v. 34, p. 43–59.

Ernst, W.G., 1988, Tectonic histories of subduction zones inferred from retrograde blueschist P-T paths: Geology, v. 16, p. 1081–1084.

Ernst, W.G., 1990, Thermobarometric and fluid-expulsion history of subduction zones: Journal of Geophysical Research, v. 95, p. 9047–9053.

Ernst, W.G., 1992, Metamorphism of the western Cordillera, and its relationship to tectonics, *in* Burchfiel, B.C., Lipman, P.W., and Zoback, M.L., eds., The Cordilleran Orogen; Conterminous United States: Boulder, Colorado, Geological Society of America, The Geology of North America, v. G3, p. 515–538.

Ernst, W.G., 1999, Hornblende, the continent maker—Evolution of H_2O during circum-Pacific subduction versus continental collision: Geology, v. 27, p. 675–678.

Ernst, W.G., and Liou, J.G., 1995, Contrasting plate-tectonic styles of the Qinling-Dabie-Sulu and Franciscan metamorphic belts: Geology, v. 23, p. 353–356.

Ernst, W.G., and Peacock, S., 1996, A thermotectonic model for preservation of ultrahigh-pressure mineralogic relics in metamorphosed continental crust: Washington, D.C., American Geophysical Union Geophysical Monograph 96, p. 171–178

Ernst, W.G., Seki, Y., Onuki, H., and Gilbert, M.C., 1970, Comparative Study of Low-grade Metamorphism in the California Coast Ranges and the Outer Metamorphic Belt of Japan: Boulder, Colorado, Geological Society of America Memoir 124, 276p.

Ernst, W.G., Maruyama, S., and Wallis, S., 1997, Buoyancy-driven, rapid exhumation of ultrahigh-pressure metamorphosed continental crust: Proceedings of the National Academy of Sciences, v. 94, p. 9,532–9,537.

Ernst, W.G., Mosenfelder, J.L., Leech, M.L., and Liu, J., 1998, H_2O recycling during continental collision: phase-equilibrium and kinetic considerations, *in* Hacker, B.R., and Liou, J.G. eds., When Continents Collide: Geodynamics and Geochemistry of Ultrahigh-Pressure Rocks: Dordrecht, Kluwer Academic Publishers, p. 275–295.

Fitch, T.J., 1972, Plate convergence, transcurrent faults, and internal deformation adjacent to Southeast Asia and the Western Pacific: Journal of Geophysical Research, v. 77, p. 4432–4460.

Frey, M., ed., 1987, Low Temperature Metamorphism: Glasgow, Scotland, Blackie Publishing, 351p.

Frey, M., Hunziker, J.C., Frank, W., Bocquet, J., Dal Piaz, G.V., Jäger, E., and Niggli, E., 1974, Alpine metamorphism of the Alps: Schweizerische Mineralogisches und Petrografisches Mittelungen, v. 54, p. 248–290.

Gebauer, D., 1996, A P-T-t path for an (ultra?-) high-pressure ultramafic/mafic rock-association and its felsic country-rocks based on SHRIMP-dating of magmatic and metamorphic zircon domains. Example: Alpe Arami (central Swiss Alps): Washington, D.C., American Geophysical Union Geophysical Monograph 95, p. 307–329.

Gebauer, D., Schertl, H.P., Briz, M., and Schreyer, W., 1997, 35 Ma old ultrahigh-pressure metamorphism and evidence for very rapid exhumation in the Dora Maira Massif, Western Alps: Lithos, v. 41, p. 5–24.

Genser, J., van Wees, J.D., Cloetingh, S., and Neubauer, F., 1996, Eastern Alpine tectono-metamorphic evolution: constraints from two-dimensional modeling: Tectonics, v. 15, p. 584–604.

Gnos, E., Immenhauser, A., and Peters, T., 1997, Late Cretaceous/early Tertiary convergence between the Indian and Arabian plates recorded in ophiolites and related sediments: Tectonophysics, v. 271, p. 1–19.

Grasemann, B., Ratschbacher, L., and Hacker, B.R. (1998) Exhumation of ultrahigh-pressure rocks: thermal boundary conditions and cooling history, *in* Hacker, B.R., and Liou, J.G., eds., When Continents Collide: Geodynamics and Geochemistry of Ultrahigh-Pressure Rocks: Dordrecht, Kluwer Academic Publishers, p. 117–139.

Hacker, B.R., 1996, Eclogite formation and the rheology, buoyancy, seismicity, and H_2O content of oceanic crust: Washington, D.C., American Geophysical Union Geophysical Monograph 96, p. 171–178.

Hacker, B.R., and Peacock, S.M., 1995, Creation, preservation and exhumation of UHPM rocks, *in* Coleman, R.G., and Wang, X., eds., Ultrahigh Pressure Metamorphism: New York, Cambridge University Press, p. 159–181.

Hacker, B.R., Ratschbacher, L., Webb, L., and Dong, S., 1995, What brought them up? Exhuming the Dabie Shan ultrahigh-pressure rocks: Geology, v. 23, p. 743–746.

Hacker, B.R., Wang, X., Eide, E.A., and Ratschbacher, L., 1996, The Qinling-Dabie ultrahigh-pressure collisional orogen, *in* Harrison, T.M., and Yin, A., eds., The Tectonic Development of Asia: New York, Cambridge University Press, p. 345–370.

Hacker, B.R., Ratschbacher, L., Webb, L., McWilliams, M.O., Ireland, T., Calvert, A., Dong, S., Wenk, H-R., and Chateigner, D., 2000, Exhumation of ultrahigh-pressure continental crust in east central China: Late Triassic-Early Jurassic tectonic unroofing: Journal of Geophysical Research, v. 105, p. 13,339–13,364.

Hacker, B.R., Abers, G.A., and Peacock, S.M., 2003a, Subduction factory 1. Theoretical mineralogy, density, seismic wave speeds, and H_2O content: Journal of Geophysical Research, v. 108, no. B1, 10.1029/2001Jb001127.

Hacker, B.R., Calvert, A.T., Zhang, R.Y., Ernst, W.G., and Liou, J.G., 2003b, Ultra-rapid exhumation of ultrahigh pressure diamond-bearing metasedimentary rocks of the Kokchetav Massif: Lithos (in press).

Hamilton, W., 1970, The Uralides and the motion of the Russian and Siberian platforms: Geological Society of America Bulletin, v. 81, p. 2553–2576.

Hamilton, W., 1979, Tectonics of the Indonesian region: Washington, D.C., U.S. Geological Survey Professional Paper 1078, 345p.

Hamilton, W., 1995, Subduction systems and magmatism, *in* Smellie, ed., Volcanism Associated with Extension at Consuming Plate Margins: London, Geological Society of London Special Publication no. 81, p. 3–28.

Harley, S.L., and Carswell, D.A., 1995, Ultradeep crustal metamorphism: A prospective review: Journal of Geophysical Research, v. 100, p. 8367–8380.

Hashimoto, M., Igi, S., Seki, Y., Banno, S., and Kojima, G., 1970, Metamorphic facies map of Japan: Tokyo, Geological Survey of Japan, scale 1:2 000 000.1 sheet.

Hawkesworth, C.J., Gallagher, K., Hergt, J.M., and McDermott, F., 1993, Mantle and slab contributions in an arc magma: Annual Review of Earth and Planetary Sciences, v. 21, p. 175–204.

Henry, C., 1990, L'unite a coesite du massif Dora-Maira dans son cadre petrologique et structural (Alpes occidentales, Italie) [thesis]: Paris, Université de Paris VI, 453p.

Hermann, J., and Green, D.H., 2001, Experimental constraints on high pressure melting in subducted crust: Earth and Planetary Science Letters, v. 188, p. 149–168.

Hermann, J., Rubatto, D., Korsakov, A., and Shatsky, V.S., 2001, Multiple zircon growth during fast exhumation of diamondiferous, deeply subducted continental crust (Kokchetav Massif, Kazakhstan): Contributions to Mineralogy and Petrology, v. 141, p. 66–82.

Hickey-Vargas, R., Sun, M., Lopez-Escobar, L., Moreno-Roa, H., Reagan, M.K., Morris, J.D., and Ryan, J.G., 2002, Multiple subduction components in the mantle wedge: Evidence from eruptive centers in the Central Southern volcanic zone, Chile: Geology, v. 30, p. 199–202.

Hilton, D.R., Hoogewerff, J.A., van Bergen, M.J., and Hammerschmidt, K., 1992, Mapping magma sources in the east Sunda-Banda arcs, Indonesia: Constraints from helium isotopes: Geochimica et Cosmochimica Acta, v. 56, p. 851–859.

Hirajima, T., Wallis, S., Zhai, R., and Ye, K., 1993, Eclogitized metagranitoid from the Su-Lu ultrahigh-pressure (UHP) province, eastern China: Tokyo, Proceedings of the Japan Academy, v. 69, section B, p. 249–254.

Ho, C.S., 1986, A synthesis of the geological evolution of Taiwan: Tectonophysics, v. 125, p. 1–16.

Howell, D.G., ed., 1985, Tectonostratigraphic Terranes of the Circum-Pacific Region: Houston, Texas, Circum-Pacific Council for Energy and Mineral Resources, 581p.

Irwin, W.P., 1972, Terranes of the western Paleozoic and Triassic belt in the southern Klamath Mountains, California: Washington, D.C., U.S. Geol. Survey Prof. Paper 800C, p. 103–111.

Isacks, B., Oliver, J., and Sykes, L.R., 1968, Seismology and the new global tectonics: Journal of Geophysical Research, v. 73, p. 5855–5899.

Ishikawa, M., Kaneko, Y., and Yamamoto, H., 2000, Subhorizontal boundary between ultrahigh-pressure and low-pressure metamorphic units in the Sulu-Tjube area of the Kokchetav Massif, Kazakhstan: The Island Arc, v. 9, p. 317–328.

Itaya, T., and Takasugi, H., 1988, Muscovite K-Ar ages of the Sanbagawa schists, Japan, and argon depletion during cooling and deformation: Contributions to Mineralogy and Petrology, v. 100, p. 281–290.

Jayko, A.S., Blake, M.C., and Harms, T., 1987, Attenuation of the Coast Range ophiolite by extensional faulting, and nature of the Coast Range "thrust," California: Tectonics, v. 6, p. 475–488.

Jones, D.L., 1983, Recognition, character, and analysis of tectonostratigraphic terranes in western North America, *in* Hashimoto, M., and Uyeda, S., eds., Accretion Tectonics of the Circum-Pacific Regions: Tokyo, Terrapub, p. 21–36.

Kaneko, Y., Terabayashi, M., Yamamoto, H. et al., 2000, Geology of the Kokchetav ultrahigh-pressure—high-pressure metamorphic belt, north-eastern Kazakhstan: The Island Arc, v. 9, p. 264–283.

Kawachi, Y., 1968, Large-scale overturned structure in the Sanbagawa metamorphic zone in central Shikoku, Japan: Geological Society of Japan Journal, v. 74, p. 607–616.

Kushiro, I., 1990, Partial melting of mantle wedge and evolution of island arc crust: Journal of Geophysical Research, v. 95, p.15, 929–15,939.

Leech, M.L., 2001, Arrested orogenic development; eclogitization, delamination, and tectonic collapse: Earth and Planetary Science Letters, v. 185, p. 149–159.

Le Fort, P., 1996, Evolution of the Himalaya, *in* Yin, A., and Harrison, T.M., eds., The Tectonic Evolution of Asia: New York, Cambridge University Press, p. 95–109.

Lennykh, V.I., Valizer, P.M., Beane, R., Leech, M., and Ernst, W.G., 1995, Petrotectonic evolution of the Maksyutov Complex, southern Urals, Russia: Implications for ultrahigh-pressure metamorphism: International Geology Review, v. 37, p. 584–600.

Lin, C.H., and Roecker, S.W., 1998, Active crustal subduction and exhumation in Taiwan, *in* Hacker, B.R., and Liou, J.G., eds., When Continents Collide: Geodynamics and Geochemistry of Ultrahigh-Pressure Rocks: Dordrecht, Kluwer Academic Publishers, p. 1–25.

Liou, J.G., and Zhang, R.Y., 1995, Significance of ultrahigh-pressure talc-bearing eclogite assemblages: Mineralogical Magazine, v. 59, p. 93–102.

Liou, J.G., and Zhang, R.Y., 1996, Occurrences of intergranular coesite in ultrahigh-P rocks from the Sulu region, eastern China: Implications for lack of fluid during exhumation: American Mineralogist, v. 81, p. 1217–1221.

Liou, J.G., and Zhang, R.Y., 2002, Ultrahigh-pressure metamorphic rocks: Encyclopedia of Physical Science and Technology: San Diego, Academic Press, v. 17, p 227–244.

Liou, J.G., Lan, C.Y., Suppe, J., and Ernst, W.G., 1977, The Eastern Taiwan Ophiolite, its occurrence, petrology, metamorphism, and tectonic setting: Taipei, Taiwan, Mining Research and Service Organization, Special Report No. 1, 212 p.

Liou, J.G., Zhang, R. and Ernst, W.G., 1994, An introduction to ultrahigh-pressure metamorphism: The Island Arc, v.3, p. 1–24.

Liou, J.G., Banno, S., and Ernst, W.G., 1995, Ultrahigh-pressure metamorphism and tectonics: The Island Arc, v. 4, p. 233–239.

Liou, J.G., Zhang, R.Y., Wang, X., Eide, E.A., Ernst, W.G., and Maruyama, S., 1996, Metamorphism and tectonics of high-pressure and ultrahigh-pressure belts in the Dabie-Sulu region, China, *in* Yin, A., and Harrison, T.M., eds., The Tectonic Evolution of Asia: New York, Cambridge University Press, p. 300–344.

Liou, J.G., Zhang, R.Y., Ernst, W.G., Rumble, D. III, and Maruyama, S., 1998, High pressure minerals from deeply subducted metamorphic rocks: Reviews in Mineralogy, v. 37, p. 33–96.

Liu, J., Bohlen, S.R. and Ernst, W.G., 1996, Stability of hydrous phases in subducting oceanic crust: Earth and Planetary Science Letters, v. 143, p. 161–171.

Maruyama, S., 1997, Pacific-type orogeny revisited: Miyashiro-type orogeny proposed: The Island Arc, v. 6, p. 91–120.

Maruyama, S., and Parkinson, C.D., 2000, Overview of the geology, petrology and tectonic framework of the HP-UHP metamorphic belt of the Kokchetav Massif, Kazakhstan: The Island Arc, v. 9. P. 439–455.

Maruyama, S., Liou, J.G., and Zhang, R., 1994, Tectonic evolution of the ultrahigh-pressure (UHP) and high-pressure (HP) metamorphic belts from central China: The Island Arc, v. 3, p. 112–121.

Maruyama, S., Liou, J.G., and Terabayashi, M., 1996, Blueschists and eclogites of the world, and their exhumation: International Geology Review, v. 38, p. 485–594.

Massone, H.J., 1995, Experimental and petrogenetic study of UHPM, *in* Coleman, R.G., and Wang, X., eds., Ultrahigh Pressure Metamorphism: New York, Cambridge University Press, p. 33–95.

Merle, O., and Guillier, B., 1989, The building of the Central Swiss Alps: An experimental approach: Tectonophysics, v. 165, p. 41–56.

Michard, A., Henry, C., and Chopin, C., 1995, Structures in UHPM rocks: A case study from the Alps, *in* Coleman, R.G., and Wang, X., eds., Ultrahigh Pressure Metamorphism: New York, Cambridge University Press, p. 132–158.

Miller, J.M., Gray, D.R., and Gregory, R.T., 1998, Exhumation of high-pressure rocks in northeastern Oman: Geology, v. 26, p. 235–238.

Miyashiro, A., 1961, Evolution of metamorphic belts: Journal of Petrology, v. 2, p. 277–311.

Miyashiro, A., 1967, Orogeny, regional metamorphism, and magmatism in the Japanese islands: Meddelelser fra Dansk Geologisk Forening, v. 17, p. 390–446.

Molnar, P., and Atwater, T., 1978, Interarc spreading and cordilleran tectonics as alternates related to the age of subducted oceanic lithosphere: Earth and Planetary Science Letters, v. 41, p. 330–340.

Molnar, P., and Gray, D., 1979, Subduction of continental lithosphere: Some constraints and uncertainties: Geology, v. 7, p. 58–62.

Molnar, P., and Tapponnier, P., 1975, Cenozoic tectonics of Asia; effects of a continental collision: Science, v. 189, p. 419–426.

Molnar, P., Burchfiel, B.C., Liang, K., and Zhao, Z., 1987, Geomorphic evidence for active faulting in the Altyn Tagh and northern Tibet and quantitative estimates of its contribution to the convergence of India and Eurasia: Geology, v. 15, p. 249–253.

Moores, E.M., 1970, Ultramafics and orogeny, with models for the U.S. Cordillera and the Tethys: Nature, v. 228, p.837–842.

Morris, P.A., 1995, Slab melting as an example of Quaternary volcanism and aseismicity in southwest Japan: Geology, v. 23, p. 395–398.

Mosenfelder, J.L., and Bohlen, S.R., 1997, Kinetics of the coesite to quartz transformation: Earth and Planetary Science Letters. v.153, p. 133–147.

Nishimura, Y., 1998, Geotectonic subdivision and areal extent of the Sangun belt, Inner Zone of Southwestern Japan: Journal of Metamorphic Geology, v. 16, p. 129–140.

Okamoto, K., and Maruyama, S., 1999, The high pressure synthesis of lawsonite in the MORB + H_2O system: American Mineralogist, v. 84, p. 362–373.

Ota, T., Terabayashi, M., Parkinson, C.D., and Masago, H., 2000, Thermobarometric structure of the Kokchetav ultrahigh-pressure—high-pressure massif deduced from a north-south transect in the Kulet and Saldat-kol regions, northern Kazakhstan: The Island Arc, v. 9, p. 328–357.

Oxburgh, E.R., and Turcotte, D.L., 1971, Origin of paired metamorphic belts and crustal dilation in island arc regions: Journal of Geophysical Research, v. 76, p. 1315–1327.

Page, B.M., and Suppe, J., 1981, The Pliocene Lichi Melange of Taiwan: its plate tectonic and olistostromal origin: American Journal of Science, v. 281, p. 193–227.

Patiño Douce, A.E., and McCarthy, T.C., 1998, Melting of crustal rocks during continental collision and subduction, *in* Hacker, B.R., and Liou, J.G., eds., When Continents Collide: Geodynamics and Geochemistry of Ultrahigh-Pressure Rocks: Dordrecht, Kluwer Academic Publishers, p. 27–55.

Peacock, S.M., 1990, Fluid processes in subduction zones: Science, v. 248, p. 329–337.

Peacock, S.M., 1992, Blueschist-facies metamorphism, shear heating, and P-T-t paths in subduction shear zones: Journal of Geophysical Research, v. 97, p. 17,693–17,707.

Peacock, S.M., 1995, Ultrahigh-pressure metamorphic rocks and the thermal evolution of continent collision belts: The Island Arc, v. 4, p. 376–383.

Platt, J.P., 1986, Dynamics of orogenic wedges and the uplift of high-pressure metamorphic rocks: Geological Society of America Bulletin, v. 97, p. 1037–1053.

Platt, J.P., 1987, The uplift of high-pressure, low-temperature metamorphic rocks: Philosophical Transactions of the Royal Society of London, v. 321, p. 87–103.

Platt, J.P., 1993, Exhumation of high-pressure rocks: a review of concepts and processes: Terra Nova, v. 5, p. 119–133.

Poli, S., and Schmidt, M.W., 1997, The high-pressure stability of hydrous phases in orogenic belts: an experimental approach on eclogite-forming processes: Tectonophysics, v. 273, p. 169–184.

Perchuk, A.L., Yaspaskurt, V.O., and Podlesskii, S.K., 1998, Genesis and exhumation dynamics of eclogites in the Kokchetav Massif near Mount Sulu-Tyube, Kazakhstan: Geochemistry International, v. 36, p. 877–885.

Reck, B.H., 1987, Implications of measured thermal gradients for water movement through the northeast Japan accretionary prism: Journal of Geophysical Research, v. 92, p. 3683–3690.

Ring, U., and Brandon, M.T., 1994, Kinematic data for the Coast Range fault and implications for the exhumation of the Franciscan subduction complex: Geology, v. 22, p. 735–738.

Ring, U., and Brandon, M.T., 1999, Ductile deformation and mass loss in the Franciscan subduction complex—Implications for exhumation processes in accretionary wedges: London, Geological Society of London Special Publication no. 154, p. 180–203.

Robinson, P., and Terry, M.P., 1998, Evolution of amphibolite-facies structural features during transition from convergence to extensional collapse, Western Gneiss Region, Norway: International Workshop on UHP Metamorphism and Exhumation, Stanford University, p. A79-A83.

Rubatto, D., and Hermann, J., 2001, Exhumation as fast as subduction?: Geology, v. 29, p. 3–6.

Rubie, D., 1984, A thermal-tectonic model for high-pressure metamorphism in the Sesia zone, Western Alps: Journal of Geology, v. 92, p. 21–36.

Rubie, D.C., 1986, The catalysis of mineral reactions by water and restrictions on the presence of aqueous fluid during metamorphism: Mineralogical Magazine, v. 50, p. 399–415.

Rubie, D.C., 1990, Role of kinetics in the formation and preservation of eclogites, *in* Carswell, D.A., ed., Eclogite Facies Rocks: New York, Chapman and Hall, p. 111–140.

Rumble, D., 1998, Stable isotope geochemistry of ultrahigh-pressure rocks, *in* Hacker, B.R., and Liou, J.G., eds., When Continents Collide: Geodynamics and Geochemistry of Ultrahigh-Pressure Rocks: Dordrecht, Kluwer Academic Publishers, p. 241–259.

Sacks, P.E., and Secor, D.T., Jr., 1990, Delaminations in collisional orogens: Geology, v. 18, p. 999–1002.

Schreyer, W., 1995, Ultradeep metamorphic rocks: The retrospective viewpoint: Journal of Geophysical Research, v. 100, p. 8353–8366.

Schreyer, W., Massone, H.J., and Chopin, C., 1987, Continental crust subducted to depths near 100 km: Implications for magma and fluid genesis in collision zones, *in* Mysen, B.O., ed., Magmatic Processes: Physicochemical Principles: University Park, Pennsylvania, The Geochemical Society Special Publication no. 1, p. 155–163.

Searle, M.P., 1996, Cooling history, erosion, exhumation, and kinetics of the Himalaya-Karakorum-Tibet orogenic belt, *in* Yin, A., and Harrison, T.M., eds., The Tectonic Evolution of Asia: New York, Cambridge University Press, p. 110–137.

Searle, M.P., Hacker, B.R., and Bilham, R., 2001, The Hindu Kush seismic zone as a paradigm for the creation of ultrahigh-pressure diamond- and coesite-bearing continental rocks: Journal of Geology, v. 109, p. 143–153.

Seno, T., 1985, Age of subducting lithosphere and back-arc basin formation in the western Pacific since the middle Tertiary, *in* Nasu, N., Kobayashi, K., Uyeda, S., Kushiro, I., and Kagami, H., eds., Formation of Active Ocean Margins: Tokyo, Terrapub, p. 469–481.

Shreve, R.L., and Cloos, M., 1986, Dynamics of sediment subduction, melange formation, and prism accretion: Journal of Geophysical Research, v. 91, p. 10,229–10,245.

Smith, D.C., 1984. Coesite in clinopyroxene in the Caledonides and its implications for geodynamics: Nature, v. 310, p. 641–644.

Snyder, D.B., Prasetyo, H., Blundell, D.J., Pigram, C.J., Barber, A.J., Richardson, A., and Tjokosaproetro, S., 1996, A dual doubly vergent orogen in the Banda Arc continent-continent collision zone as observed on deep seismic reflection profiles: Tectonics, v. 15, p. 34–53.

Sobolev, N.V., and Shatsky, V.S., 1990, Diamond inclusions in garnets from metamorphic rocks: Nature, v. 343, p. 742–746.

Stöckhert, B., and Renner, J., 1998, Rheology of crustal rocks at ultrahigh pressure, in Hacker, B.R., and Liou, J.G., eds., When Continents Collide: Geodynamics and Geochemistry of Ultrahigh-Pressure Rocks, Dordrecht, Kluwer Academic Publishers, p. 57–95.

Stüwe, K., and Barr, T.D., 1998, On uplift and exhumation during convergence: Tectonics, v. 17, p. 80–88.

Suppe, J., 1972, Interrelationships of high-pressure metamorphism, deformation, and sedimentation in Franciscan tectonics, U.S.A.: International Geological Congress, 24th, Montreal, Reports, sec. 3, p. 552–559.

Tabata, H., Yamauchi, K., Maruyama, S., and Liou, J.G., 1998, Tracing the extent of a UHP metamorphic terrane: mineral-inclusion study of zircons in gneisses from the Dabie Shan, *in* Hacker, B.R., and Liou, J.G., eds., When Continents Collide: Geodynamics and Geochemistry of Ultrahigh-Pressure Rocks: Dordrecht, Kluwer Academic Publishers, p. 261–273.

Tapponnier, P., Peltzer, G., Le Dain, A.Y., and Armijo, R., 1982, Propagating extrusion tectonics in Asia: new insights from simple experiments with plasticine: Geology, v. 10, p. 611–617.

Terry, M.P., Robinson, P., and Krogh Ravna. E.J., 2000a, Kyanite eclogite thermobarometry and evidence of thrusting of UHP over HP metamorphic rocks, Nordoyane, Western Gneiss Region, Norway: American Mineralogist, v. 85, p. 1637–1650.

Terry, M.P., Robinson, P., Hamilton, M.A., and Jercinovic, M.J., 2000b, Monazite geochronology of UHP and HP metamorphism, deformation, and exhumation, Nordoyane, Western Gneiss Region, Norway: American Mineralogist, v. 85, p. 1651–1664.

Theunissen, K., Dobretsov, N.L., Travin, A., Shatsky, V.S., Korsakov, A., Smirnova, L., and Boven, A., 2000, Two contrasting petrotectonic domains in the Kokchetav megamelange (north Kazakhstan): difference in exhumation mechanisms of ultrahigh-pressure crustal rocks, or a result of subsequent deformation?: The Island Arc, v. 9, p. 284–303.

Thompson, A.B., and Ridley, J.R., 1987, Pressure-temperature-time (P-T-t) histories of orogenic belts: Philosophical Transactions of the Royal Society of London, ser. A, v. 321, p. 27–45.

Turcotte, D.L., and Oxburgh, E.R., 1972, Mantle convection and the new global tectonics: Annual Review of Fluid Mechanics, v. 4, p. 33–68.

van Bergen, M.J., Vroon, P.Z., and Hoogewerff, J.A., 1993, Geochemical and tectonic relationships in the east Indonesian arc-continent collision region: Implications for the subduction of the Australian passive margin: Tectonophysics, v. 223, p. 97–116.

van den Beukel, J., 1992, Some thermomechanical aspects of the subduction of continental lithosphere: Tectonics, v. 11, p. 316–329.

van den Beukel, J., and Wortel, R., 1988, Thermo-mechanical modelling of arc-trench regions: Tectonophysics, v. 154, p. 177–193.

Vielzeuf, D., and Holloway, J.R., 1988, Experimental determination of the fluid-absent melting relations in the pelitic system. Consequences for crustal differentiation: Contributions to Mineralogy and Petrology, v. 98, p. 257–276.

von Blanckenburg, F., and Davies, J.H., 1995, Slab break off: A model for syncollision magmatism and tectonics in the Alps: Tectonics, v. 14, p. 120–131.

Vrolijk, P.J., 1987, Tectonically driven fluid flow in the Kodiak accretionary complex, Alaska: Geology, v. 15, p. 466–469.

Vrolijk, P.J., Meyers, G., and Moore, J.C., 1988, Warm fluid migration along tectonic melanges in the Kodiak accretionary complex, Alaska: Journal of Geophysical Research, v. 93, p. 10,313–10,324.

Wallis, S.R., Ishiwatari, A., Hirajima, T., Ye, K., Guo, J., Nakamura, D., Kato, T., Zhai, M., Enami, M., Cong, B., and Banno, S., 1997, Occurrence and field relationships of UHP meta-granitoid and coesite eclogite in the Su-Lu terrane, Eastern China: Journal of the Geological Society of London, v. 154, p. 45–55.

Webb, L.E., Hacker, B.R., Ratschbacher, L., McWilliams, M.O., and Dong, S., 1999, ^{40}Ar/^{39}Ar thermochronologic constraints on deformation and cooling history of high and ultrahigh-pressure rocks in the Qinling-Dabie orogen: Tectonics, v. 18, p. 621–638.

Wheeler, J., 1991, Structural evolution of a subduction continental sliver: the northern Dora-Maira massif, Italian Alps: Journal of the Geological Society of London, v. 148, p. 1101–1113.

Wheeler, J., Reddy, S.M., and Cliff, R.A., 2001, Kinematic linkage between internal zone extension and shortening in more external units in the NW Alps: Journal of the Geological Society of London, v. 158, p. 439–443.

Widiyantoro, S., and van der Hilst, R., l996, Structure and evolution of lithospheric slab beneath the Sunda Arc, Indonesia: Science, v. 271, p. 1566–l570.

Willett, S., Beaumont, C., and Fullsack, P., 1993, Mechanical model for the tectonics of doubly vergent compressional orogens: Geology, v. 21, p. 371–374.

Yin, A., and Nie, S., 1993, An indentation model for the north and south China collision and the development of the Tan-lu and Honam fault systems, eastern Asia: Tectonics, v. 12, p. 801–813.

Yui, T.F., Rumble, D., and Lo, C.H., 1995, Unusually low ^{18}O ultrahigh-pressure metamorphic rocks from the Sulu terrain, eastern China: Geochemica et Cosmochimica Acta, v. 59, p. 2859–2864.

Zhang, R.Y., and Liou, J.G., 1997, Partial transformation of gabbro to coesite-bearing eclogite from Yangkou, the Sulu terrane, eastern China: Journal of Metamorphic Geology, v. 15, p. 183–202.

Zheng, Y.F., Gong, B., Li, Y., Wang, Z., and Fu, B., 2000, Carbon concentrations and isotopic ratios of eclogites from the Dabie and Sulu terranes in China: Chemical Geology, v. 168, p. 291–305.

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