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TECTONICS AND PROGRADE VERSUS RETROGRADE P-T TRAJECTORIES OF HIGH-PRESSURE METAMORPHIC BELTS **

ABSTRACT. — Relatively high-pressure metamorphic belts evidently form within subduction zone environments. Extensive underflow, such as has taken place in the circumpacific region, results in the development of a contemporaneous calc-alkaline volcanic-plutonic+high-temperature metamorphic belt surmounting the stable, non-subducted plate; where small amounts of closure are indicated, such as in Mesozoic Tethys, only an incipient volcanic+high-temperature metamorphic arc has been produced. Glaucophane schist terranes are characterized by recumbent, isoclinal and ptygmatic folds which show tectonic transport directions towards the oceanic basin of the downgoing plate, and by thrust faults which dip beneath the continent or island arc of the stable, non-subducted lithospheric plate. The generation of blueschists and eclogites in petrotectonic association with ophiolitic rocks, deep-sea sediments and olistostrome deposits reflects the accumulation of protoliths in an oceanic rather than a continental setting. Plate tectonic frameworks and relatively high-pressure phase assemblages are very briefly described for both circumpacific and Alpine blueschist belts.

Observed mineral parageneses include laumontite and analcime at lowest grades, and successively more thoroughly recrystallized sections typified by pumpellyite (±prehnite), lawsonite, albite, glaucophane, aragonite and jadeite, generally coexisting with quartz and an aqueous fluid. Highest grade rocks include eclogites and albite amphibolites. Experimental studies demonstrate that such parageneses form at low temperatures and relatively high pressures. Most of the lower grade rocks apparently have been subjected to high H_2O activities and low values of a_{CO_2}, whereas eclogitic occurrences probably require moderate or rather low attendant a_{H_2O} values for their development instead of amphibolites. Maximum recovered subduction depths are approximately 30-45 km (i.e., 9-13 kb) for blueschist belts from Japan, California and the Alps, with highest temperatures on the order of 450-550° C.

Computed thermal models for convergent plate boundaries demonstrate that appropriate prograde P-T trajectories would be realized only within subduction zone environments. Buoyant return of decoupled packets of rock after subduction terminated would provide a retrograde P-T path which would ensure partial or complete conversion of the high-pressure assemblages to greenschists, as in the Alps, depending on reaction rates and the speed of ascent. Where underflow continued, blueschistic sections could migrate slowly back up the convergent plate junction (acting as a stress guide), essentially following the prograde metamorphic path in reverse; this process would avoid the back-reaction of the early, relatively high-pressure assemblages to more « normal » greenschistic phase compatibilities, as in western California.

Virtually all glaucophane schist belts exhibit the obscuring effects of profound post-metamorphic deformation, including transcurrent and overthrust faulting, and oroclinal bending. Thus, although the preserved mineral assemblages bear witness to both prograde and retrograde metamorphic P-T paths, post-recrystallization tectonism has disrupted and complicated the spatial relationships.

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Major tectonic and petrologic features of circumpacific blueschist belts

The border of the Pacific Ocean is framed in large part by island arcs and trenches. Such regimes constitute the active sites of present-day orogenic zones. They provide two distinctive, contrasting petrotectonic settings for various groups of sedimentary and volcanic rocks and, by inference from the examination of older, now eroded mountain belts, for plutonic igneous and metamorphic lithologies as well: (1) Volcanic continental margins and island arcs are the locus of basaltic + + calc-alkaline volcanism and plutonism. Country rocks have been faulted and thrown into chiefly open folds, and metamorphosed under high-temperature, relatively low-pressure conditions. Contemporaneous sedimentary rocks tend to be rich in volcanic detritus, and for the most part have been deposited in stable shelf, slope and continental rise environments. (2) The open ocean and more

TABLE 1

Contrasting general characteristics of circumpacific paired metamorphic belts

	Feature	High-Pressure Oceanward Terrane	High-Temperature Landward Terrane
	presumed location	trench	volcanic front
	breadth	narrow, about 30-150 km wide	broader, about 100-250 km wide
	basement	oceanic crust	transitional or continental crust
	folds	ptygmatic, recumbent predominant, with oceanward vergence; most intense deformation towards the continentalward side of the belt	broad, open predominant; tectonic disruption not pervasive
	faults	low-angle abundant, dipping towards continent	high-angle abundant
roughly coeval with metamorphism	sedimentary rocks	trench mélange and/or continental rise prism; olistostromes; widespread but thin deep-sea deposits	continental shelf and slope section; abundant in situ shallow-water clastic deposits*
	volcanic rocks	fine-grained mafic pyroclastic debris; pillow lavas	coarse-grained calc-alkaline pyroclastic debris ubiquitous*
	plutonic igneous rocks	cold, alpine-type peridotites + associated gabbros, tectonically inserted	abundant hypabysally intruded quartz diorites + granodiorites*
	metamorphic facies	zeolite, prehnite-pumpellyite, blueschist-greenschist, albite amphibolite, eclogite	zeolite, prehnite-pumpellyite, greenschist, almandine amphibolite, granulite and/or pyroxene hornfels*
	inferred unroofing rate	very rapid rise and erosion (?)	moderately rapid uplift and erosion (?)
	post-metamorphic plate motion	largely horizontal (= transform?) along strike-slip faults; arcuate bending of most belts	large-scale horizontal motion not uncommon

*Note: older igneous, metamorphic and sedimentary rocks are characteristic of continental margins and mature island arcs.

landward trench complex receive the clastic overflow from the sialic margin, in large part as turbidite and olistostrome deposits, as well as thin layers of pelagic sediment from the deep ocean basin. These are tectonically mixed during recumbent folding and underthrusting within the subduction zone itself; the same process causes oceanic crust and its mantle underpinnings (= ophiolite) to be incorporated in the mélange by shearing. The trench complex characteristically is overprinted by a relatively high-pressure, low-temperature metamorphic recrystallization.

As is now known, these two contrasting petrotectonic environments are a reflection of convergent lithospheric plate motions (ISACKS et Al., 1968; DEWEY and BIRD, 1970; DICKINSON, 1970). The effects of this plate consumption are especially evident in Phanerozoic — especially Late Mesozoic — terranes, and have given rise, among other things, to paired metamorphic belts of differing P-T conditions. MIYASHIRO (1961, 1967) was the first to clearly recognize these contrasting paired metamorphic belts, and ZWART (1967) showed that representatives of the various types are not confined to the circumpacific region.

Systematic differences in these roughly synchronous circumpacific paired petrotectonic belts are listed in Table 1. Important contrasts between individuals of a paired metamorphic terrane also exist, but these appear to reflect local geologic relationships and unique convergence histories. In this category belong: the total volume and nature of the sedimentary section deposited on the downgoing slab; the retention or tectonic obliteration of the arc-trench gap section which initially must have separated the parallel members of a paired belt sequence; the extent and time of decoupling of subducted sections; the collision of continental masses; the impaction of a spreading center with a trench, and so forth. As is clear from the work of MIYASHIRO (1961) as well as from Table 1, blueschist belts are located seaward of the volcanic-plutonic arc, or at least were so situated at the time of metamorphism. The distinctive phase assemblages, lithologies and structural characteristics of blueschist belts are thought to be due to relatively high-pressure, low-temperature subduction zone recrystallization (ERNST, 1975 a). Other explanations involving tectonic overpressures, metastable crystallization or metasomatism have been advanced to account for aspects of these terranes, but none seems capable of explaining the plate tectonic setting, petrologic associations and observed mineral parageneses as completely as the subduction zone hypothesis.

Highly generalized structural, geologic and metamorphic features of five circumpacific blueschist belts, (1) southweastern Japan, (2) southern Alaska, (3) South Island, New Zeland, (4) western California, and (5) west-central Chile, will now be summarized briefly. Other blueschist belts, including eastern Papua (DAVIES, 1968; DAVIES and SMITH, 1971; ROD, 1974), New Caledonia (BROTHERS, 1970; LILLIE and BROTHERS, 1970; BROTHERS and BLAKE, 1973) and Taiwan (YEN, 1966; BIQ, 1971; CHAI, 1972; LIOU et Al., 1975) exhibit most of the relationships now to be described, but they have been less thoroughly studied, hence are not discussed here. The general directions of increasing metamorphic grade, ages of deposition and recrystallization, and directions of inferred descent of the Pacific lithospheric plate in all examples are towards the original convergent plate junction; the overturning of recumbent folds — or tectonic transport direction — is in the opposite sense. (Here « Pacific lithospheric plate » refers to one or more ancient oceanic crust-capped plates located central to the girdling circumpacific sialic crust-capped plates, and not specifically to the present-day Pacific lithospheric plate).

Areal relations for the relatively high-pressure Sanbagawa belt of southweastern Japan have been presented by HASHIMOTO et Al. (1970), as part of the Metamorphic Map of Japan. The original rocks seem to have been deposited in a continental margin setting rather than a trench (KIMURA, 1974). The Late Mesozoic, relatively high-temperature, low-pressure Ryoke metamorphic terrane is situated on the Asiatic side of the transcurrent Median Tectonic Line, along which this belt is juxtaposed against the essentially coeval blueschist belt. The Fossa Magna is located at the « great bend » of the central portion of Honshu and apparently represents a major inflection in the convergent plate junction. Farther to the northeast, beyond the Fossa Magna, the Sanbagawa belt is faulted against the more continentalward high-temperature, low-pressure Abukuma terrane (MIYASHIRO, 1961).

A map of the Kenai-Chugach Mid to Late Mesozoic volcanic + argillite belt of southern Alaska has been provided by King, compiler (1969); more recent studies have been undertaken by CLARK (1973), FORBES and LANPHERE (1973), MOORE (1973, 1974), CONNELLY et Al. (1976) and CARDEN et Al. (1977). This relatively high-pressure, low-temperature metamorphic belt is juxtaposed against the Alaskan-Aleutian Range calc-alkaline volcanic-plutonic belt along the Border Ranges Fault (MACKEVETT and PLAFKER, 1973). Older portions of the high-pressure terrane lie just to the southeast of this major structural break, whereas successively younger sections are exposed progressively seaward (ERNST, 1975 b). The roughly contemporaneous landward igneous belt has undergone relatively high-temperature, low-pressure recrystallization in the vicinity of the volcanic front. Another strand of the Border Ranges Fault is the Denali-Fairweather system; the latter curves around the northern and eastern portions of southern Alaska and displays strike slip.

The geology of the Mesozoic Alpine or Torlesse-Haast belt of South Island, New Zeland has been elucidated by LANDIS and COOMBS (1967), LANDIS and BISHOP (1972), BLAKE and LANDIS (1973), BLAKE et Al. (1974), and COOMBS et Al. (1976). Highest grade, albite amphibolitic metamorphic rocks occur along the later, transcurrent Alpine Fault; such rocks tend to give young metamorphic ages, presumably reflecting post subduction cooling dates. Lawsonite-bearing lower grade rocks occur adjacent to the Livingstone-MacPherson Fault System. To the west of this break — here speculatively interpreted as a now overturned thrust fault (see also COOMBS et Al., 1976) — lies the roughly contemporaneous Hokonui arc-trench gap sequence, and continental crust of Fiordland and Nelson. Calc-alkaline plutonic rocks of the latter area intrude country rocks which display a relatively high-temperature, low-pressure paragenesis.

Areal relations of the Late Mesozoic Franciscan belt of western California were presented by BAILEY et Al. (1964, 1970), PAGE (1966) and ERNST (1971 b), among others. The more westerly trench complex has been brought into contact with coeval Klamath + Sierra Nevada + Salinia granitic basement and intervening arc--trench gap strata of the Great Valley along the Coast Range Thrust. The Franciscan complex shows a very high-pressure, low-temperature recrystallization sequence, whereas Sierran country rocks have been subjected to conditions of relatively shallow burial and high temperatures of metamorphism. The Late Mesozoic continental margin has been duplicated to the southwest by Cenozoic strike slip along the San Andreas Fault.

Geologic relations of the Western Series metamorphic belt of west-central Chile have been elucidated by AGUIRRE et Al. (1972), HERVÉ et Al. (1974), and KATO (1976). This Late Paleozoic, relatively high-pressure, low-temperature recrystallized subduction complex is juxtaposed against the apparently contemporaneous Coast Range batholith and adjacent high-temperature, low-pressure metamorphic rocks along a problematic transcurrent fault or shear zone termed the Coast Range Suture (ERNST, 1975 b).

The major aspects of such belts have been discussed previously (ERNST, 1971 a, 1975 b), so will be only briefly mentioned here. In each case, within the relatively high-pressure belt, metamorphic grade increases passing from the Pacific Basin towards continental crust, although in parts of South Island, New Zealand, it decreases again before reaching, the inferred plate junction. In southweastern Japan, South Island of New Zeland and western California, the grade reaches a maximum of albite amphibolite ± eclogite facies, whereas intermediate blueschist-greenschist facies rocks represent the culmination of metamorphism in southern Alaska and west-central Chile. Both the primary depositional age and the age of recrystallization also increase inland, with the possible exception of Chile, where data are sparse, and South Island, New Zealand, where the situation is complicated. These overall progressions probably reflect the direction of inferred increase in (now recovered) subduction depth.

All five described terranes are typified by the presence of serpentinized peridotites, the solid-state emplacement of which is attested to by intense shearing and the lack of thermal aureoles in the surrounding country-rocks. To differing degrees, these ultramafic rocks have been transported into the relatively high-pressure terranes, but in some cases the peridotites closely mark the initial convergent plate junctions. The original natures of the ultramafic rocks have been obscured by later alteration and metamorphism, but in addition to harzburgitic protoliths, parental peridotites in some occurrences include lherzolites of relatively deep derivation. For each composite terrane, a major fault separates the relatively high-pressure belt from lower pressure strata of the arc-trench gap or from the volcanic-plutonic arc in regions in which the arc-trench gap section is missing. The most deeply buried rocks of the arc-trench gap section (Matanuska series of southern Alaska; Hokonui facies of South Island, New Zeland; and Great Valley series of central California) have developed very low-grade, zeolitic mineral assemblages (e.g., see Coombs, 1960; Dickinson et Al., 1969; Bailey and Jones, 1973).

In general, the direction of tectonic transport — and in simple cases, the vergence of folds — is towards the oceanic realm within the relatively high-pressure belt (opposite to the direction of increasing metamorphic grade); the overall dip of thrust surfaces is towards the continental margin. This is exactly the sense of shearing that would be expected within a subduction zone inclined beneath an island arc or continental margin (Ernst, 1975 b; Moore and Karig, 1976). The increasing metamorphic grade within a blueschist terrane is thought to indicate the depth of underflow for individual packets of rock which, on decoupling, presumably have returned towards the surface, at least in part driven by buoyancy forces. Evidently the successively younger, imbricated units were subducted to somewhat shallow depths prior to their release from the downgoing slab — or at least the presently exposed levels of subduction are progressively less profound proceeding towards the Pacific Basin. Thus with the possible exception of west-central Chile, where insufficient stratigraphic and radiometric age data are available, each of the five metamorphic belts just described appears in general to have accreted seaward with time.

Structure of convergent plate margins

Gross structural aspects of the hypothesis of subduction zone metamorphism rest in large part on geophysical studies of modern trench complexes and their landward extensions (Beck, 1972; Grow, 1973; Seely et Al., 1974; Hussong et Al., 1976). Simplified relationships are shown in Fig. 1. The important point to be noted here is that sedimentary debris derived from the volcanic front and its environs appears to be partly trapped within the arc-trench gap, but a portion of this material is transported beyond the convergent plate junction and deposited on the downgoing plate. These latter units and the underlying ophiolitic sections (+ the thin veneer of pelagic sediments) are swept beneath the non-subducted slab where some of the complex eventually breaks free from the descending lithosphere and is accreted to the overlying stable plate. During the course of time such an imbricated section grows, and the more landward packets rise due to buoyancy of the tectonically thickened portions. Concomitant erosion therefore tends to expose the oldest, most deeply subducted — hence highly metamorphosed — section of rocks at the initial plate junction, with successively younger, more feebly recrystallized, less intensely deformed packets of rock disposed progressively nearer to the Pacific Ocean. Composite imbrication of the trench complex — or, in the case of Japan, the subducted continental margin section — is evident in many of these belts, complicating the relatively simple picture just presented. Moreover, post-metamorphic thrusting in some of these terranes such as western California, New Caledonia (and the eastern Alps, to be discussed in the following section) has further obscured the relationship between initial structure and metamorphism.

Finally, it should be observed that each of these blueschist belts is bounded or transected by a post-metamorphic transcurrent fault of great displacement (including Tawan, New Caledonia and eastern Papua, as well as the areas just summarized). In each case it seems plausible that the return towards the surface of the subducted complex accompanied a profound change of plate motion from consumptive to conservative. This apparent change in lithospheric dynamics, which would enhance the rebound of a subducted complex, may have been a consequence of the destruction of a spreading center at a convergent margin (e.g., see Atwater, 1970; Uyeda and Miyashiro, 1974). Another manifestation of this post metamorphic change in plate motions appears to be the oroclinal bending or rotation evident in many circumpacific belts. Clearly, blueschist belts have been subjected to much post-metamorphic deformation, complicating and confusing the geometric relationships which attended recrystallization.

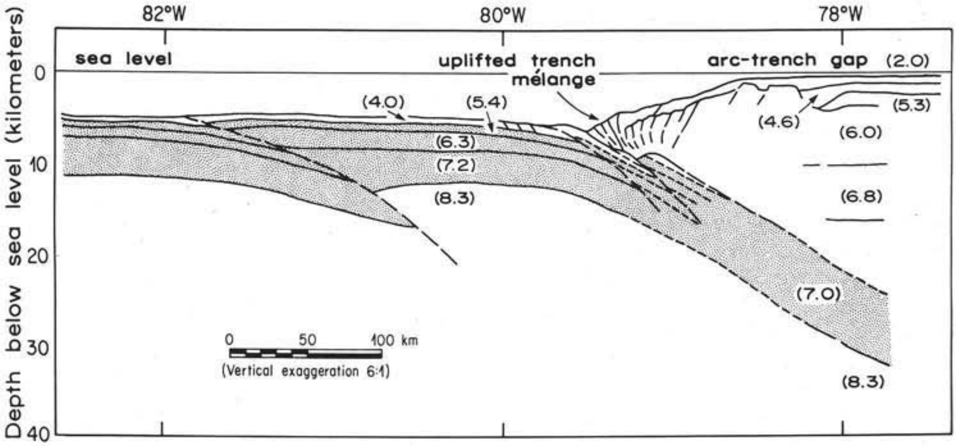


Fig. 1. — Composite crustal cross section across the Chile-Peru trench between latitudes 8-12° S, after Hussong et Al. (1976, Figs. 12, 13). Oceanic crust of the Pacific (=Nazca) plate is stippled. The South American lithospheric slab probably is capped by continental crust just landward of the trench complex. P wave velocities determined by Hussong et Al. are indicated for the various reflectors. Note imbrication of oceanic crust within the subduction zone, offscraping, rotation and buoyant uplift of the trench complex, with older, most deeply subducted section disposed closest to the initial plate junction.

Major tectonic and petrologic features of the Early Alpine high-pressure metamorphic terrane

Comparison of the circumpacific blueschist belts described above (and in Table 1) with the early, glaucophanic metamorphic paragenesis of the Alps reveals many similarities, even though there are major contrasts in plate tectonic setting (e.g., see Dal Piaz, 1974 a, b). Regional relations are presented in Fig. 2.

In spite of the lack of a broadly contemporaneous volcanic-plutonic arc and associated high-temperature metamorphic terrane, the Alpine blueschist belt shows evidence of having been deposited partly on Tethyan oceanic crust (Piemonte zone), it exhibits external (i.e., European foreland-directed) overturning of recumbent folds and internally dipping décollement surfaces, and it contains dismembered ophiolite suites (Steinmann, 1926; Bearth, 1967; Dietrich et Al., 1974) tectonically inserted in the section and associated with mélange deposits.

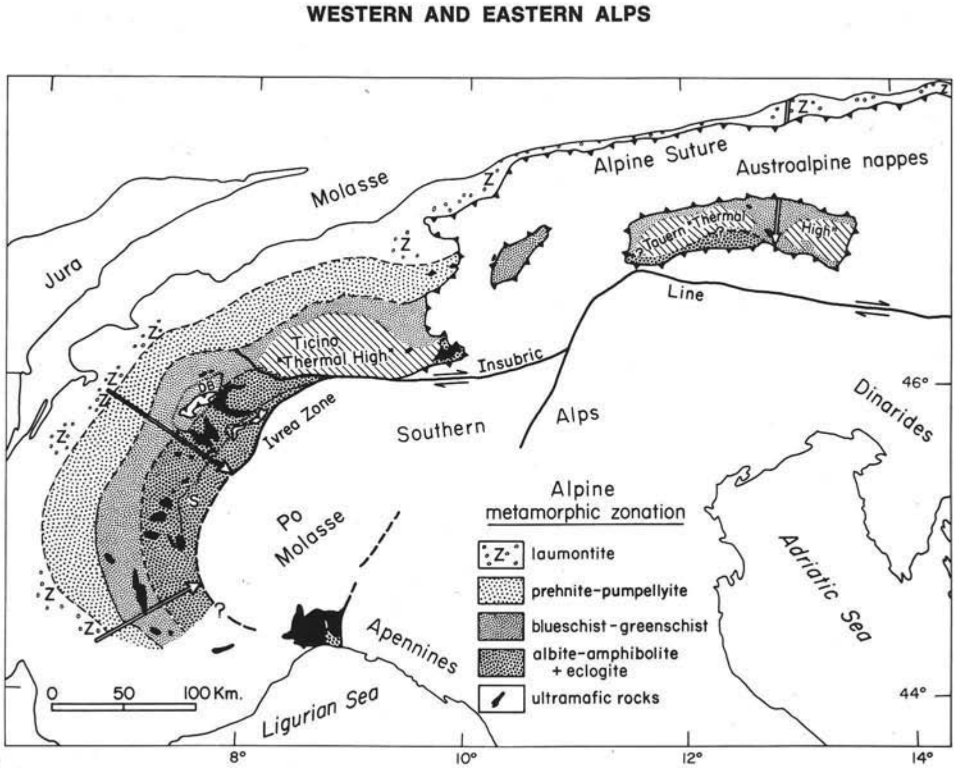


Fig. 2. — Late Cretaceous-Early Tertiary relatively high-pressure metamorphic zonation in the Alps, after Ernst (1971 a), Niggli, general coordinator (1973) and Frey et Al. (1974). The general direction of increasing metamorphic grade, ages of deposition and recrystallization, and direction of inferred descent of the Mesozoic Tethyan-European plate are indicated by the arrows; the transport direction of recumbent folds is in the opposite sense. The original plate junction — termed the Alpine Suture by Ernst (1973) — separates the more external subduction complex on the north and west from the stable, tectonically higher Southern Alps + Austroalpine nappes on the south and east. Contemporaneous arc-trench gap sedimentary rocks are represented by shallow water Mesozoic strata occurring in the Southern Alps + Austroalpine nappes (e.g., see Dietrich, 1976). DB = Dent Blanche; S = Sesia-Lanzo realm.

The relatively high-pressure, imbricated metamorphic terrane, which grades from an internal, albite amphibolite + eclogite zone through successively more external portions consisting of blueschists and greenschists, prehnite-pumpellyite facies rocks and a peripheral laumontite zone (Niggli, 1960; Niggli, general coordinator, 1973; Ernst, 1973; Frey et Al., 1974; Hunziker, 1974) shows an overall decrease in age of deposition and of recrystallization analogous to the circumpacific blueschist belts (ERNST, 1975 b). The early, high-pressure mineral assemblages have been pervasively overprinted by a later prasinitic recrystallization, and, especially in the Lepontine and Tauern gneiss regions, thoroughly obliterated by the Late Alpine thermal event (JÄGER et Al., 1967; NIGGLI, 1970; WENK, 1970) which outlasted the deformation. Finally, post-metamorphic, apparent strike slip along the Insubric Line (GANSSER, 1968; LAUBSCHER, 1971 a, b) seems to have rather closely reproduced the geometric situation of blueschist belts marginal to the Pacific Ocean. The pronounced arcuate curvature of the western Alps is also analogous to the oroclinal bending of many circumpacific glaucophanic terranes.

Evidently the closure of Mesozoic Tethys (DEWEY et Al., 1973; see also TRÜMPY, 1960, 1975), a small oceanic seaway in contrast to the great Pacific plate, resulted in the repeated southward and eastward, internally directed subduction of oceanic crust and portions of the European foreland. Eclogitic assemblages in the Sesia-Lanzo zone indicate that portions of the southern plate were sheared off and began moving with the tectonically underlying Tethyan-European plate. Different times and loci of high-pressure metamorphism reflect a complex imbrication of structural units; individual members probably were sutured to one another during a series of convergence events (DAL PIAZ et Al., 1972; DIETRICH, 1976). This complex event in certain respects may be regarded as a large-scale analogue to the sorts of processes which produced the trench structures illustrated in Fig. 1.

The virtual absence of the continentalward member of a paired belt sequence in the Southern Alps is probably a consequence of the fact that, unlike circumpacific subduction, in which the underflow of several thousands of kilometers of oceanic crust-capped lithosphere has been documented (e.g., see HAMILTON, 1969; UYEDA and MIYASHIRO, 1974), destruction of Mesozoic Tethys involved the consumption of only a rather small ocean basin. In this latter case, only minor amounts of partial melting at mantle depths would be expected, hence little or no advective heat transfer (upward migration of melts) would be proved to higher levels of the nonsubducted southern plate. For a description of the minor calc-alkaline volcanism in the Austroalpine realm, see GATTO et Al., 1976.

Prograde paragenetic sequences in blueschistic terranes

Generalized, relatively well documented high-pressure mineral parageneses for mafic schists and for pelitic + quartzofeldspathic schists are presented in Figs. 3-5 for southweastern Japan, western California and the western Alps, respectively. Solid lines indicate the common occurrence, dashed lines the sporadic occurrence of minerals in each zone. These diagrams are compilations of numerous petrologic studies (some of which are noted in the figure legends), and exhibit numerous mineralogic similarities for the three belts. Other circumpacific terranes referred to in this report also share many paragenetic relationships with these progressive

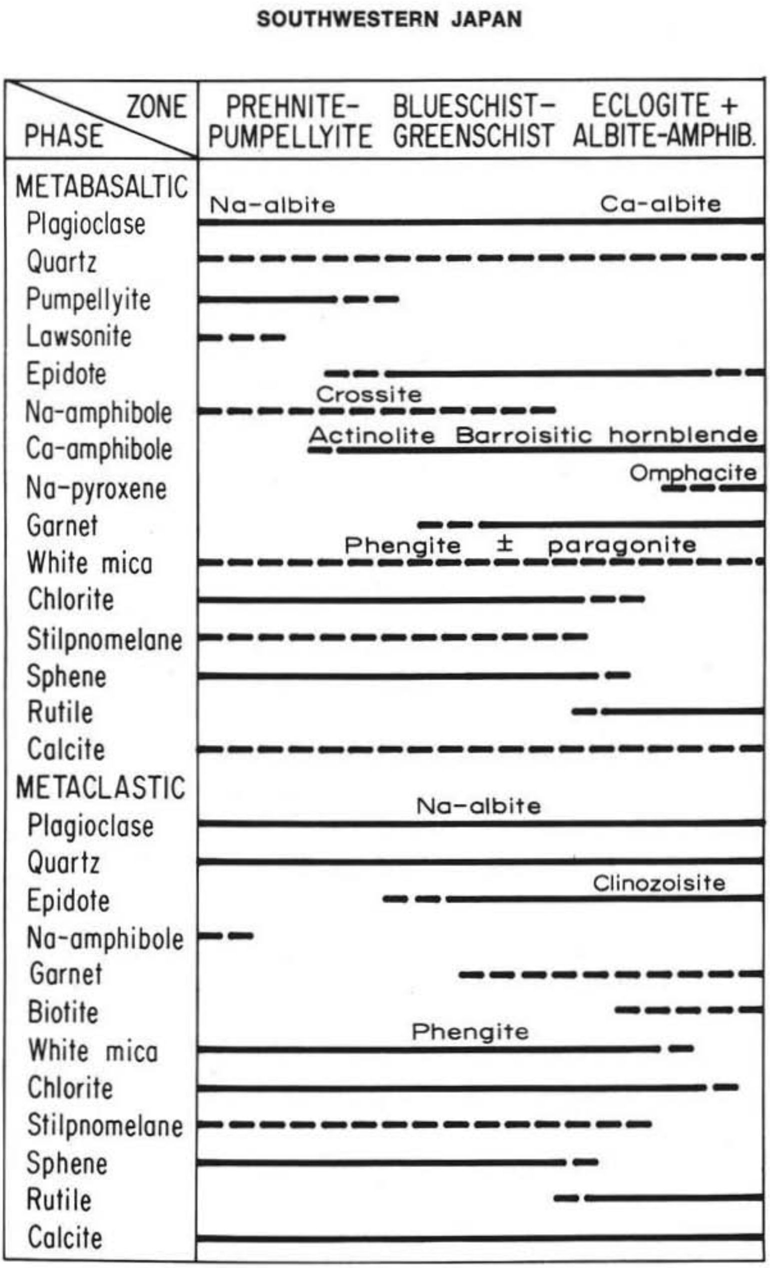
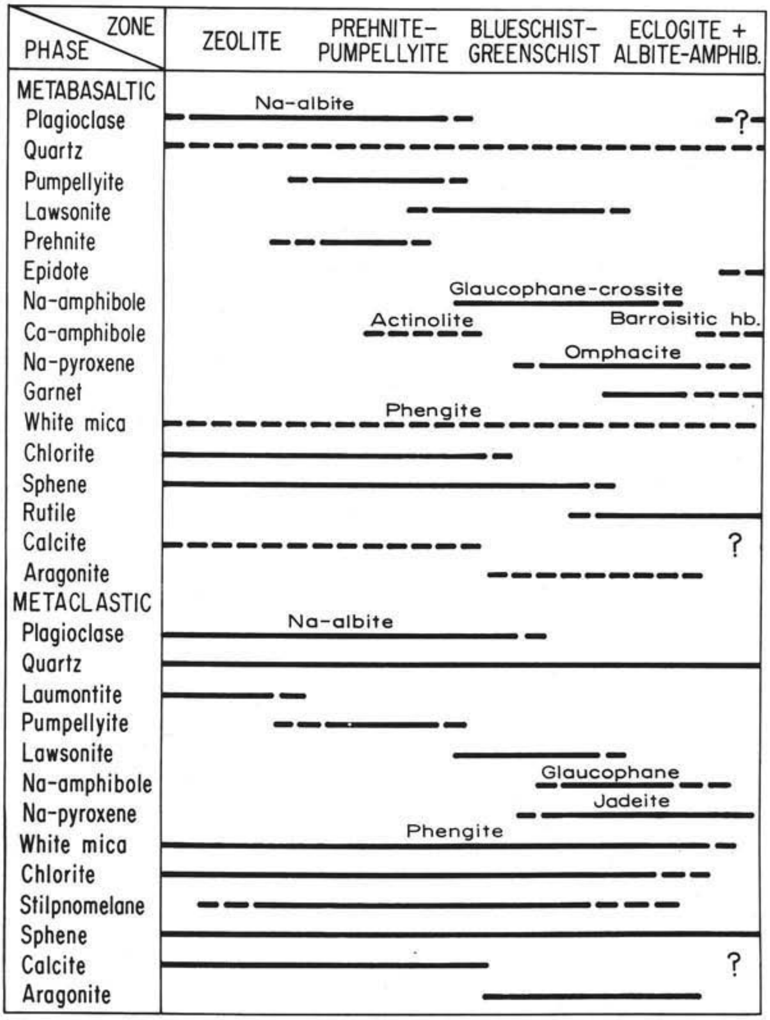


Fig. 3. — Schematic progressive metamorphic sequences of phases in the Sanbagawa belt of southwestern Japan, largely after Iwasaki (1963), Banno (1964), Ernst et Al. (1970) and Hashimoto et Al. (1970).

metamorphic sequences. Of course, to some extent each belt is unique, and its controlling physical conditions have varied with time; moreover, systematic contrasts in phase assemblage sequences along the extent of any one belt exist too, indicating



WESTERN CALIFORNIA

Fig. 4. — Schematic progressive metamorphic sequence of phases in the Franciscan complex of western California, chiefly after Coleman and Lee (1963), Blake et Al. (1969), Ernst et Al. (1970), Suppe (1973) and Platt (1975).

that P-T conditions varied laterally. However, metamorphic aragonite has been preserved on a broad scale only in western California (and New Caledonia — e.g., see Brothers and Blake, 1973). In all areas, grade increases from zeolite facies (not shown for the Sanbagawa belt because of the paucity of phase assemblage data) through prehnite-pumpellyite and blueschist or glaucophanic greenschist facies into the highest grade rocks. In Japan and the Alps, these latter consist of albite amphibolites containing lenses and zones of eclogite and glaucophane- or

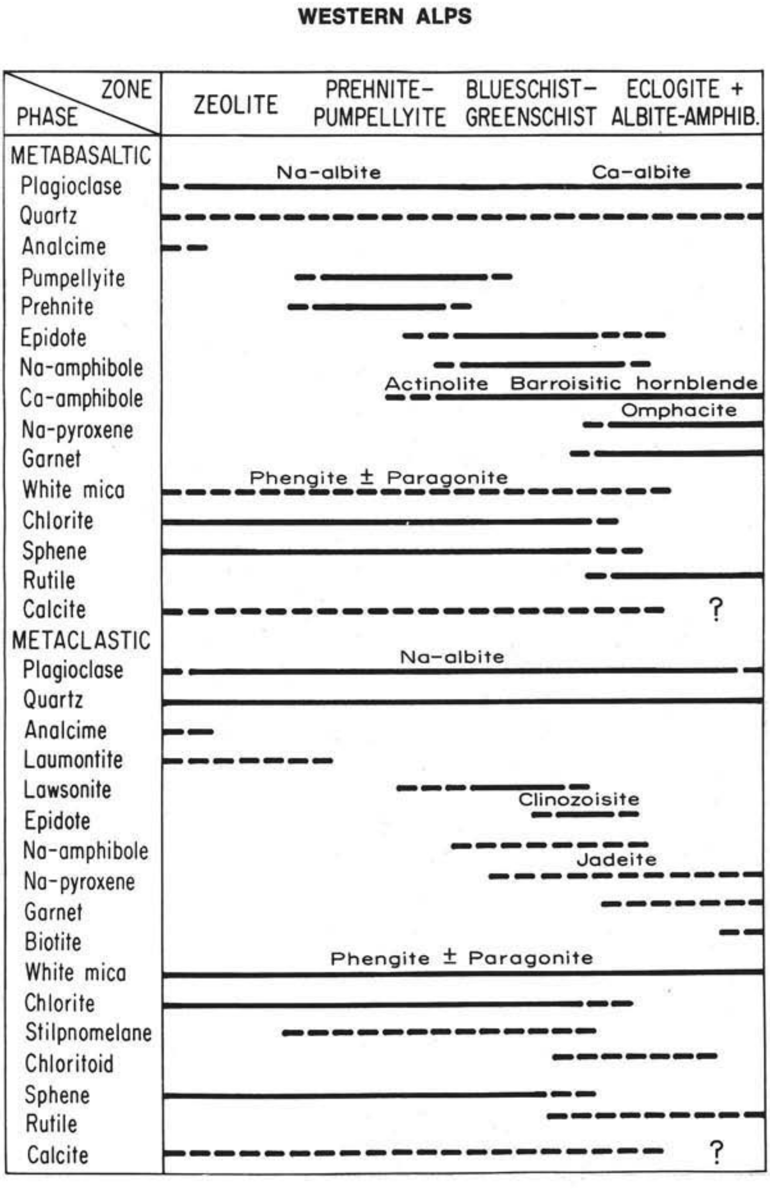


Fig. 5. — Schematic progressive metamorphic sequence of phases in the western Alps, after NIGGLI (1960, 1970), BEARTH (1962, 1966), WENK (1962, 1970), WENK and KELLER (1969), BOCQUET (1971), ERNST (1973) and FREY et Al. (1974).

hornblende-bearing eclogite, whereas in the Franciscan terrane such high-grade rocks occur principally as isolated tectonic blocks. Na-pyroxene is absent from lower grade schists of the Sanbagawa terrane except for the Kanto Mountains, investigated by SEKI (1958); unlike the other belts, biotite does not occur in the Franciscan, except for the Catalina greenschists and amphibolites (PLATT, 1976).

The prograde sequence in all three areas has produced more ferric iron-rich phases in the metabasaltic units compared to the metasedimentary schists, reflecting both lower iron contents and lower values of oxygen fugacity in the carbonaceous metaclastic rocks compared to the mafic igneous rocks.

The generalized prograde parageneses illustrated in Figs. 3-5 represent the areal disposition of metamorphic zones as they exist today. From the proceding section, it is evident that these terranes bear witness to relatively high-pressure, low-temperature recrystallization histories; by inference from the previous discussions, it seems likely that such sequences reflect progressively greater depoisitional + metamorphic ages and greater amounts of subduction, now recovered. These parageneses might also provide a model for the mineralogic path followed by successively higher grade assemblages; e.g., blueschists, eclogites and amphibolites probably passed through earlier stages of zeolitic and prehnite-pumpellyite facies recrystallization, these lower grade assemblages having been nearly totally obliterated as temperature and pressure increased. The rare preservation of relics of lower grade phases, such as blue amphibole grains encased in garnet and albite porphyroblasts, and widespread garnet zoning in Shikoku amphibolites (ERNST et Al., 1970; KURATA and BANNO, 1974) may attest to this prograde metamorphic path. Therefore, the abscissas in Figs. 3-5 may be tentatively regarded as depicting a model for syncronously increasing metamorphic grade.

However, deposition and metamorphic ages of these belts vary systematically across strike. Considering the facts that rocks are poor thermal conductors, and plate convergence rates allow the rapid descent of material coupled to the downgoing slab (e.g., to 10-50 km depth or more in a million years, depending on the plate velocities and the subduction angles), the subducted lithologic packets may follow nearly isothermal prograde P-T trajectories before decoupling from the downgoing plate. This means that each tectonically coherent unit may have suffered a subduction-induced elevation of pressure, then an increase in temperature specific to that mass, later being thrust against other unts characterized by different attending P-T conditions. However, the more or less regular change in metamorphic grade across these high-pressure belts suggests that seaward sections were never as deeply subducted as those tectonic units disposed closer to the initial plate junction.

Retrograde paragenetic sequences in blueschistic terranes

The only retrograde Franciscan metamorphism appears to have been the partial conversion of preexisting eclogites and anphibolitic rocks to lower grade glaucophane-lawsonite phase compatibilities (e.g., see ERNST et Al., 1970).

Although western California appears to be a notable exception, many subduction zone complexes show evidence of extensive retrograde reaction. Nowhere is this better displayed than in the Alpine high-pressure belt, where early eclogites and high rank glaucophane schists have been converted to amphibolitic and greenschistic (prasinitic) phase compatibilities (Bearth, 1959; Van der Plas, 1959). Obviously this represents a time sequence. As an example, the paragenesis developed in the Ligurian eclogites (Cortesogno et Al., 1977) is presented as Fig. 6. Here rocks characteristic of a zone which reached the metamorphic maximum have back-reacted to form a temporal series of successively lower pressure, and probably slightly lower temperature assemblages (to the right along the abscissa). The mineral paragenesis developed in the Ligurian eclogites is remarkably similar to sequences of phase compatibilities described from Zermatt, Valtournanche and the Tauern window (Bearth, 1970; Miller, 1974; Dal Piaz, 1974 a, b, and in progress). This close similarity suggests that large portions of the Alpine terrane were subjected to comparable P-T histories during and subsequent to the subduction events.

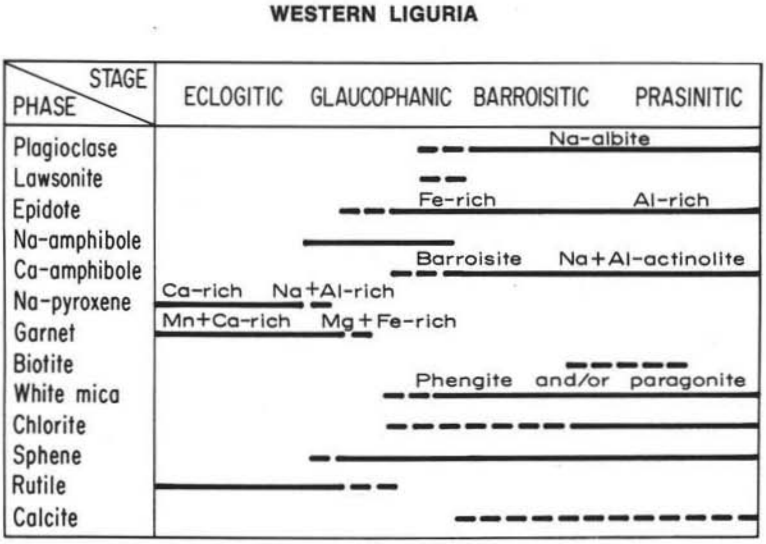


Fig. 6. — Paragenetic sequence of metagabbroic lenses in serpentinized peridotite, Gruppo di Voltri, western Liguria (Cortesogno et Al., 1977). All rocks of this complex have passed through an early high-pressure stage, and have been variably overprinted by later, lower grade mineral assemblages. Thus, although Figs. 3-5 each may model a roughly synchronous metamorphic event, this figure shows a definite time sequence of recrystallization.

Pertinent experimental phase equilibrium studies

The relatively high-pressure, low-temperature nature of blueschists was clearly recognized by Eskola (1939), based on the ubiquitousness of remarkably dense phases and, consequently, the high specific gravities of such rocks compared to other low-grade lithologies. This conclusion has been abundantly corroborated by more recent laboratory phase equilibrium investigations. Most such studies have concerned the elucidation of stability relations for a particular phase in a system of the same composition. Some of the critical equilibria will be presented below. Where devolatilization is involved, such as in the decomposition of lawsonite or analcime, depicted phase relations are for systems in which $P_{fluid} = P_{total}$.

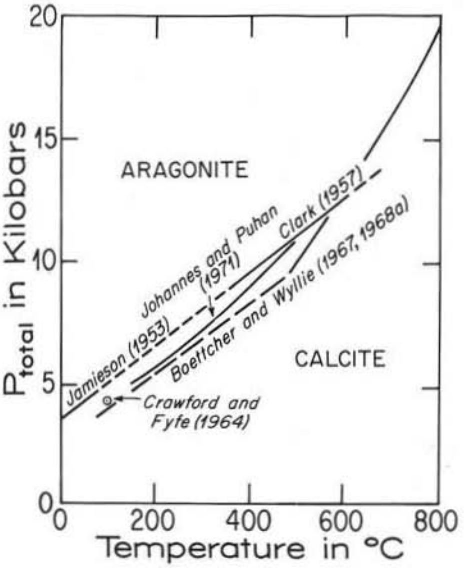


Fig. 7. — Experimental phase equilibrium studies in the system $CaCO_3$. Because the transformation involves only solid phases, the activities of volatile components are unimportant in this equilibrium. However, the presence of H_2O does accelerate the rate of recrystallization.

Oxygen isotopic data, calculations and experimental studies (Taylor and Coleman, 1968; Ernst, 1972; Nitsch, 1972, 1974) all suggest that except for the highest grade, eclogitic rocks, observed blueschistic assemblages have been generated in the presence of a fluid phase characterized by a high value of a_{H_2O}. Apparently lower activities of H_2O are required to stabilize the omphacite + garnet pair relative to amphibolitic assemblages (Yoder and Tilley, 1962; Green and Ringwood, 1967; Fry and Fyfe, 1971; Ghent and Coleman, 1973).

Figure 7 shows experimental data for the polymorphism of $CaCO_3$. Equilibrium P-T values for this transition published by Jamieson (1953), Clark (1957), Crawford and Fyfe (1964), Boettcher and Wyllie (1967, 1968 a), and Johannes and Puhan (1971) are in excellent agreement. It is clear that aragonite is stable only at relatively high pressures and low temperatures compared to calcite. Where analyses of natural materials are available (Coleman and Lee, 1962; Ernst et Al., 1970), Franciscan orthorhombic carbonates have been demonstrated to be virtually pure calcium carbonate. The back-reaction of aragonite to calcite is extremely rapid (Brown et Al., 1962; Davis and Adams, 1965), hence the orthorhombic polymorph is only preserved at the Earth's surface (where it is metastable) under favorable circumstances.

Remarkable interlaboratory agreement regarding the conversion of the assemblage jadeite + quartz to albite is also evident from an examination of Fig. 8. Experimental determinations of the P-T locations of this reaction by Birch and Le Comte (1960), M. S. Newton and Kennedy (1968), Boettcher and Wyllie (1968 b), Johannes et Al. (1971) and Hays and Bell (1973) lie within two kb total pressure of one another. Moreover, employing natural jadeitic pyroxene containing small amounts of iron and calcium, R. C. Newton and Smith (1967) proved that the high-pressure stability limit of albite is lowered only about one kb compared to the P-T curve for the pure $Na_2O \cdot Al_2O_3 \cdot 6SiO_2$ system (see also WICKSTRÖM, 1970). HLABSE and KLEPPA (1968) pointed out that the structural state of albite influences the P-T location of this reaction, but only to a relatively minor extent. As is also shown in Fig. 8, at low pressures and in situations where P_{fluid} equals P_{total}, the association analcime + quartz replaces albite + H_2O, according to laboratory work by LIOU (1971 a) and THOMPSON (1971); however, at pressures approaching 4-5 kb, analcime (± quartz) dehydrates to form the condensed assemblage jadeite (± quartz) as demonstrated by MANGHNANI (1970), hence in quartzose rocks this zeolite is confined to very low temperatures and rather low pressures. Of course, lowered a_{H_2O} would also disfavor analcime relative both to the higher temperature and higher pressure equivalent assemblages.

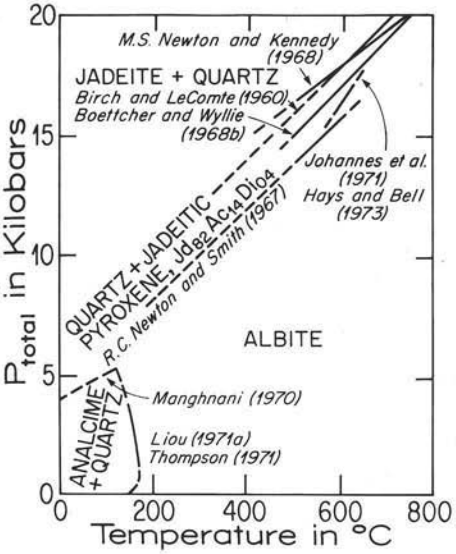


Fig. 8. — Experimental phase equilibrium studies in the system $Na_2O \cdot Al_2O_3 \cdot 4SiO_2$-$SiO_2$-$H_2O$. Fluid ($H_2O$) pressure is equal to total pressure in the P-T region where the assemblage analcime + + quartz is stable.

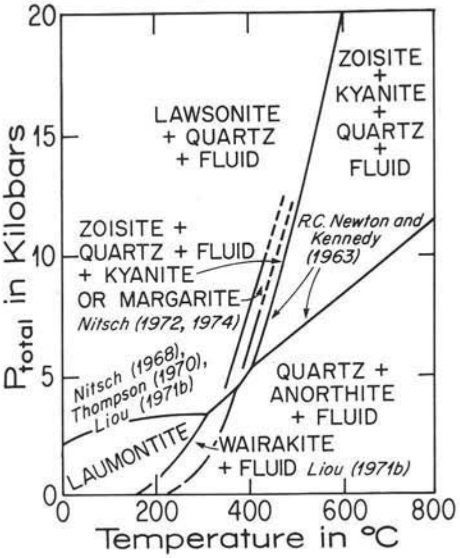


Fig. 9. — Experimental phase equilibrium studies in the pseudoternary system $CaO \cdot Al_2O_3 \cdot 2SiO_2$-$SiO_2$-$H_2O$. Fluid ($H_2O$) pressure is equal to total pressure.

A great deal of work has been performed on the rather recalcitrant system $CaO \cdot Al_2O_3 \cdot 2SiO_2$-$SiO_2$-$H_2O$, as shown in Fig. 9. Phase relations among laumontite, lawsonite, zoisite and related phases have been elucidated by R. C. NEWTON and KENNEDY (1963), NITSCH (1968, 1972, 1974), THOMPSON (1970) and LIOU (1971 b). Laumontite is restricted to pressures and temperatures below three kb and 300° C in the case in which fluid pressure equals total pressure; where the activity of H_2O is reduced, the stability field of this phase is encroached upon by that for lawsonite +

+ quartz + fluid in the higher pressure region, and wairakite + fluid in the higher temperature region. At elevated pressures, the lawsonite + quartz assemblage dehydrates to form the higher temperature condensed phase compatibility zoisite + + quartz + kyanite, pyrophyllite or margarite, according to investigations by R. C. NEWTON and KENNEDY (1963), and NITSCH (1972, 1974) (see also CHATTERJEE, 1976). Of course, decreased a_{H_2O} would disfavor the hydrous minerals with respect to the P-T stability fields illustrated in Fig. 9. For example, NITSCH (1972) showed that where a_{CO_2} achieves even rather low values, the lawsonite + quartz + CO_2 assemblage is replaced by calcite + pyrophyllite + H_2O; an analogous relationship limiting the stability of laumontite has been demonstrated experimentally by IVANOV and GUREVICH (1975) (see also THOMPSON, 1970). ERNST (1972) arrived a similar conclusion for SANBAGAWA and FRANCISCAN mineral parageneses from thermochemical calculations. It is important to recognize that all these phase equilibrium studies have shown that lawsonite is confined to a high-pressure, low-temperature region, whereas laumontite is stable at only very low pressures as well as low

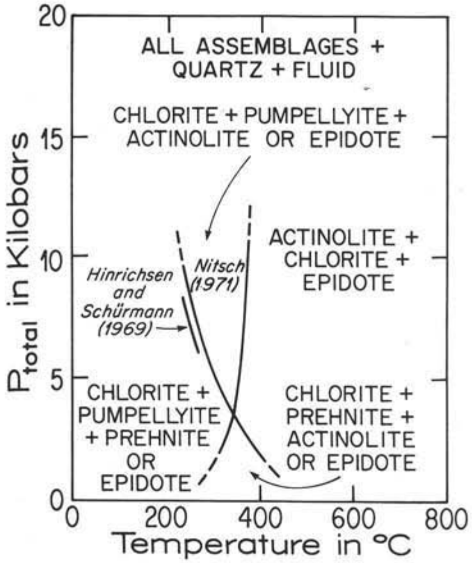


Fig. 10. — Experimental investigation of complex iron- and magnesium-bearing Ca-Al hydrous silicates, employing synthetic (HINRICHSEN and SCHÜMANN, 1969), and natural (NITSCH, 1971) starting materials. The latter equilibria are multivariant, hence P-T curves illustrated actually mark the medial portions of transition zones of finite P-T band width. Fluid (H_2O) pressure is equal to total pressure.

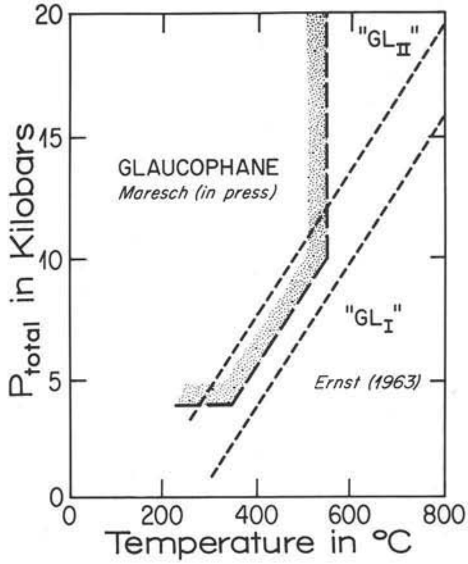


Fig. 11. — Experimental phase equilibrium studies in the system $Na_2O \cdot 3MgO \cdot Al_2O_3 \cdot 8SiO_2$-$H_2O$ (see also: GILBERT and POPP, 1973; CARMAN, 1974). Fluid (H_2O) pressure is equal to total pressure. Recent experimental studies by Maresch (stippled) have shown that the so-called polymorphism of glaucophane may actually reflect compositional variation of the synthetic sodic amphiboles rather than the order-disorder relationship claimed by ERNST.

temperatures — even where the rock bulk composition closely approaches that of the system An-Q-H_2O. The actual bulk chemistries of most rocks of concern include normative plagioclase more sodic than calcic, hence the thermal stability ranges of all these phases would be displaced to even lower temperatures for a given pressure.

Figure 10 presents reconnaissance experiments on the reactions prehnite + + chlorite + fluid = pumpellyite + actinolite + fluid (Nitsch, 1971). Natural Fe-Mg-Al solid solutions were employed in Nitsch's hydrothermal experiments, so the phase boundaries for the various assemblages are actually P-T bands over which the phases change proportions and compositions. Recent experiments on synthetic Mg-pumpellyite by Schiffman and Liou (in press), however, are compatible with the upper thermal stability limit presented by Nitsch (1971). In the presence of chlorite, the prehnite-pumpellyite (+ quartz) compatibility evidently is stable only up to rather low temperatures and pressures (345 ± 20° C at two kb P_{fluid}; 260 ± 20° C at seven kb P_{fluid}). This mineral association certainly is strongly dependent on rock bulk composition, so temperature and pressure values quoted above must be viewed as tentative only, and do not apply to chlorite-absent assemblages.

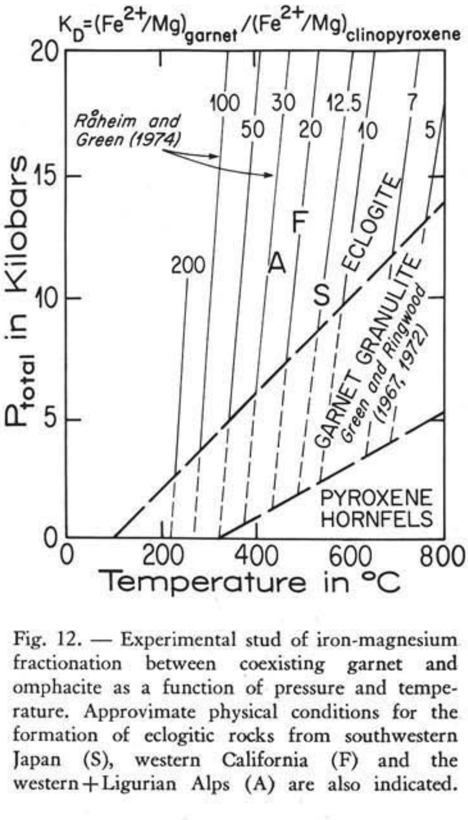


Fig. 12. — Experimental stud of iron-magnesium fractionation between coexisting garnet and omphacite as a function of pressure and temperature. Approvimate physical conditions for the formation of eclogitic rocks from southwestern Japan (S), western California (F) and the western + Ligurian Alps (A) are also indicated.

Experimental phase equilibrium studies of glaucophane (see Fig. 11) have been summarized recently by Maresch (in press); he demonstrated that earlier works actually produced amphiboles divergent from the pure $Na_2Mg_3Al_2Si_8O_{22}(OH)_2$ end member — and some of these may represent metastable crystallization. Maresch investigated iron-poor natural glaucophane under conditions where P_{fluid} = = P_{total} and concluded that this amphibole is not stable below four kb fluid pressure; it does appear to have a field of stability — or at least persistance — at pressures exceeding four kb P_{fluid} at 350° C, and ten kb P_{fluid} at 550° C. Thus the presence of glaucophane itself indicates relatively high pressures of formation for rocks in which it occurs, as shown by Fig. 11.

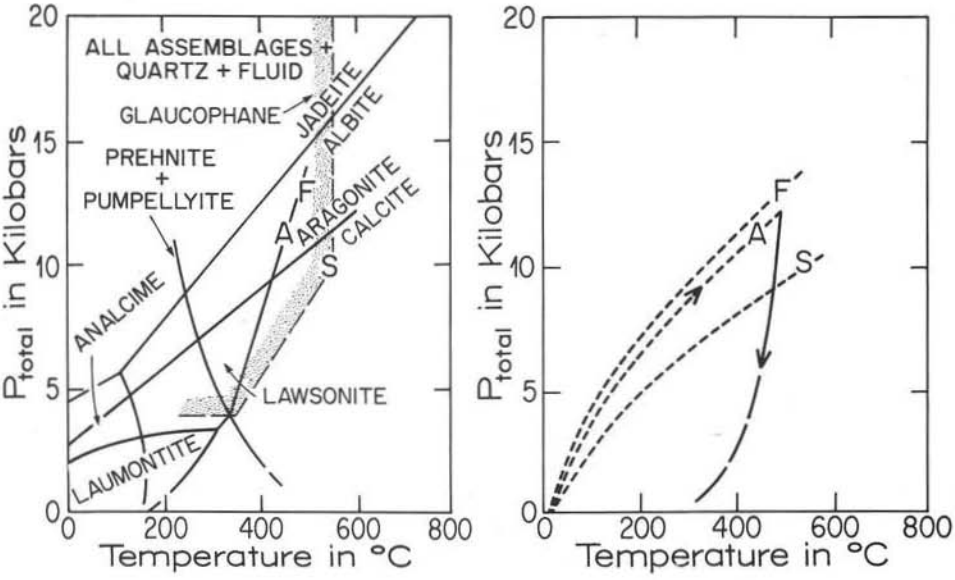
The disproportionation of ferrous iron and magnesium in eclogitic garnet + + omphacite pairs has been studied experimentally by Raheim and Green (1974).

Values for the equilibrium partitioning, $K_D = (Fe^{2+}/Mg)_{garnet}/(Fe^{2+}/Mg)_{clinopyroxene}$, are presented as a function of temperature and pressure in Fig. 12, along with the extrapolated garnet-granulite transition zone of GREEN and RINGWOOD (1967, 1972; see also: ITO and KENNEDY, 1971; RINGWOOD, 1975). Analyzed garnet + omphacite pairs from Shikoku, the Franciscan terrane and the western and Ligurian Alps (COLEMAN et Al., 1965; BANNO, 1970; ERNST et Al., 1970; ERNST, 1976) yield K_D averages of approximately 12-15, 23-26 and 21-30, respectively. Coupled with oxygen isotopic data from the eclogites of western California (TAYLOR and COLEMAN, 1968), which yield equilibration temperatures of about 500° C, it seems probable that the Franciscan eclogitic assemblages crystallized at confining pressures exceeding 10 kb. The Sanbagawa lenses in albite amphibolite apparently are higher grade ($\sim 550 \pm$ $\pm 50°$ C) than somewhat analogous masses in the western and Ligurian Alps (~ 450-$500 \pm 50°$ C). Because of the presence of widespread jadeitic pyroxene and aragonite in the Franciscan terrane, and relics of preserved Na-rich clinopyroxene in the western Alps and Liguria, the associated eclogites are thought to have been subjected to relatively higher pressures than the Shikoku portion of the Sanbagawa metamorphic terrane, as is indicated in Fig. 12 (see also Figs. 7 and 8).

Prograde metamorphic trajectories

Critical phase relations are projected into a single P-T framework in Fig. 13 a. Inferred prograde metamorphic paths as deduced from the similar but slightly contrasting mineral assemblages are shown in Fig. 13 b. In all cases, minimum pressures dictated by the phase assemblages have been selected. The illustrated prograde path for Early Alpine metamorphism reflects the fact that in many — but not all — portions of this terrane, albite was stable rather than the assemblage jadeite + quartz; the latter association does occur in portions of the Pennine and Sesia-Lanzo realms (e.g., see COMPAGNONI and MAFFEO, 1973), so obviously different portions of a metamorphic belt must have been characterized by contrasting P-T trajectories. Probably it would be more realistic to show the prograde metamorphic geothermal gradient as a band of finite P-T width, but for clarity and simplicity this is not done.

Lowered a_{H_2O} would disfavor highly aqueous minerals such as analcime and other zeolites compared to the P-T stability fields illustrated in Fig. 13 a, but in addition, very low temperatures of equilibration for such phases probably are reflected in slow growth rates — hence metastable persistance of precursor assemblages is to be expected. In any case, it is clear that for the Sanbagawa, Franciscan and Alpine blueschist belts, and other circumpacific high-pressure terranes as well, the observed progressive metamorphic sequences are in good agreement with experimentally determined phase equilibrium studies: most feebly recrystallized rocks belong to the zeolite metamorphic facies, whereas prehnite-pumpellyite, glaucophane schist or high-pressure greenschist and eclogite facies rocks constitute successively higher pressure, higher temperature assemblages. As shown by YODER and TILLEY (1962), ESSENE et Al. (1970), LAMBERT and WYLLIE (1970, 1972) and FRY and FYFE (1971), the activity of H_2O influences whether metabasaltic protoliths recrystallize to amphibolitic or eclogitic phase compatibilities — higher values of a_{H_2O} favoring the generation of barroisitic hornblende at crustal and uppermost mantle pressures, whereas low a_{H_2O} tends to stabilize the garnet + omphacite pair.



(*a*) (*b*)

Fig. 13. — (*a*) Composite phase diagram for experimentally determined equilibria pertinent to blueschist belts (Figs. 7-12). Note that only in the presence of chlorite is the prehnite + pumpellyite compatibility defined by the illustrated P-T curve. (*b*) Progressive metamorphic P-T trajectories for southwestern Japan (S), western California (F) and the western + Ligurian Alps (A), and the retrograde depressurization path described for the latter (ERNST, 1976).

The prograde P-T trajectories shown in Fig. 13 b indicate that the Sanbagawa terrane was characterized by a slightly lower P/T ratio during metamorphism compared to Alpine and Franciscan subduction zone complexes; this is also suggested by the interlayering of blue and green schists in southwestern Japan, by the general scarcity of lawsonite and jadeitic pyroxene, and by the rarity of eclogitic rocks. In the Alps, later prasinitization has effectively destroyed most of the early high-pressure assemblages (e.g., see Fig. 6), but relict jadeite has been preserved locally in quartzose metasedimentary and metagranitic rocks, indicating a rather high P/T ratio for the Early Alpine event; the nearly total lack of Alpine metamorphic aragonite presumably is due to its retrograde conversion to calcite during the ubiquitous prasinitization. In the Alps, the prograde paragenesis is thus much obscured by later thermal events.

Thermal structure during subduction zone metamorphism

It is evident from the preceding descriptions of relatively high-pressure metamorphic belts, observed mineral parageneses, and the applicable experimental phase equilibrium studies, that blueschist terranes characteristically are situated marginal to the continents in a low-temperature thermal regime. Oceanic trenches are the loci of abnormally low heat flow values such as would be expected of the appropriate blueschist environment. These regions are also the sites of enormous negative gravity anomalies, and unusually high efficiencies of earthquake energy transmission (high seismic Q values). Correlation of these latter features, plus the well-known continentalward inclination of Benioff-Wadati seismic shear zones, and the physical contrasts in uppermost mantle compared to material within and below the low--velocity zone, with new magnetic data concerning sea-floor spreading + continental drift led to the unifying concept of plate tectonics (e.g., see ISACKS et Al., 1968, for geophysical data and pertinent references).

Relatively high-pressure metamorphic belts are regarded as an important manifestation of consumptive lithospheric plate motion. Their sense of penetrative, pervasive deformation, lithologic association with ophiolites and deep-sea sediments, lack of associated coeval calc-alkaline volcanism within the high-pressure belt, and location peripheral to sialic crust all are compatible with the hypothesis that such terranes formed within subduction zones and, on resurrection, now mark the positions of former convergent plate boundaries. The mineral parageneses reflect unusually high pressures and low temperatures attending the prograde metamorphism. This too is explicable in the light of plate tectonics, as will now be discussed.

Models of thermal structures at convergent lithospheric plate junctions have been computed by numerous authors employing different input parameters and assumption (e.g., MACKENZIE, 1969; HASEBE et Al., 1970; OXBURGH and TURCOTTE, 1970, 1971; TOKSÖZ et Al., 1971, 1973; GRIGGS, 1972; TURCOTTE and OXBURGH, 1972; and TURCOTTE and SCHUBERT, 1973; see also: OXBURGH and TURCOTTE, 1974; ERNST, 1974; PLATT, 1975; GRAHAM and ENGLAND, 1976). A typical example is presented as Fig. 14. The major feature which all calculated models share is the pronounced downwarp of the isotherms in the upper portion of the descending slab, and in the trench complex itself. Therefore, subducted trench mélanges and adjacent units, as well as the underlying oceanic crust, apparently are subjected to recrystallization under relatively high-pressure, low-temperature conditions provided by such a subduction zone geothermal gradient. As long as lithospheric plate underflow continues, the thermal structure illustrated in Fig. 14 will be preserved. Accordingly, sections of rock which have decoupled from the downgoing slab can accumulate along the plate junction without significant temperature increment. Once convergence ceases, however, a return to isostatic equilibrium and a static, uniform thermal regime is to be expected.

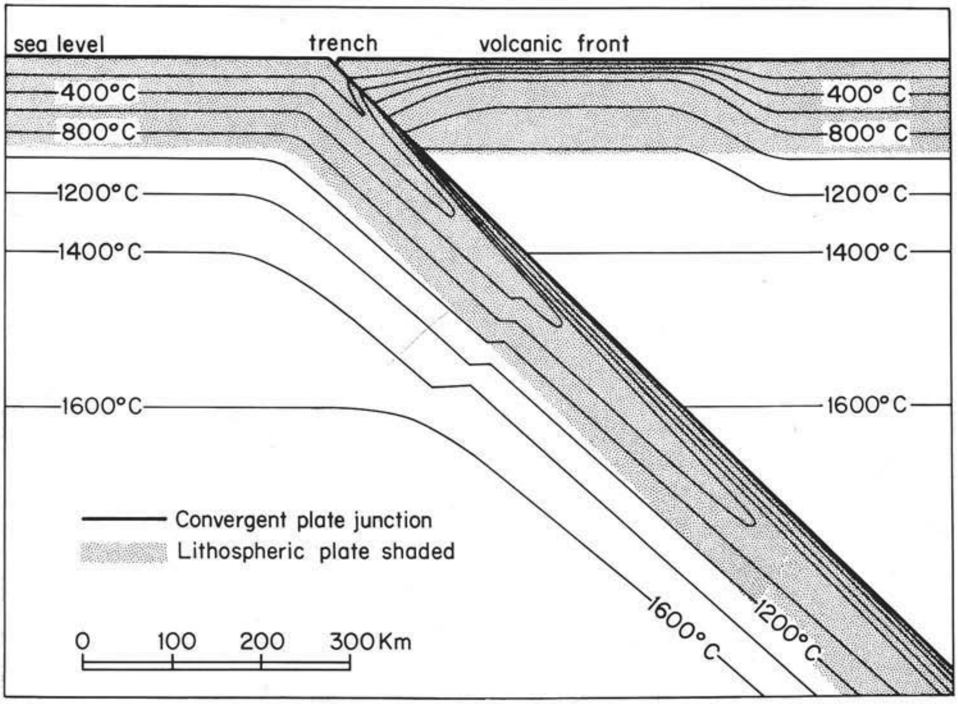


Fig. 14. — Calculated thermal structure of a convergent plate junction and its environs, after Turcotte and Oxburgh (1972); dissipative shear along the inclined contact between the slabs has been assumed, and this additional term accounts for the thermal bulge in the nonsubducted plate. Heat transfer through the ascent of buoyant melts has not been considered. The heat dome is centered about the volcanic-plutonic arc and surrounding high-temperature, low-pressure metamorphic terrane, whereas the plate suture zone is the locale of relatively high-pressure, low-temperature recrystallization. Horizontal and vertical scales are the same. Lithospheric slabs stippled are shown as about 100 km thick, regardless of the attending thermal structure. Note that the scale is different from that of Fig. 1. Inflections in the isotherms result from the olivine-spinel transitions, a P-T band of finite width (not shown).

Retrograde metamorphic trajectories

Historically, petrologic and geophysical attention has focused on the prograde mineral parageneses and thermal structures developed during active subduction. Where uplift of these high-pressure complexes takes place after the cessation of underflow, if buoyant return towards the surface has been rapid, the effects of retrograde metamorphism should not be as pronounced as situations in which the uplift was long delayed or proceeded more slowly. In any case, however, the P-T paths followed on depressurization would bring the relatively high-pressure assemblages through thermally equivalent but successively lower pressure, more « normal » environments where back-reactions would be anticipated (As a matter of fact, nearly vertical rise of subducted, low-T, high-P sections of rock might be attended by early heating, as evident from the thermal model of a convergent plate junction shown in Fig. 14). The retrograde prasinitization of Ligurian eclogites is illustrated in Fig. 13 b as an essentially adiabatic P-T path accompanying an inferred buoyant rise towards the surface.

Similar to the Alps, most circumpacific terranes (including the Sanbagawa belt of Japan) exhibit widespread effects of the partial obliteration of the early, relatively high-pressure parageneses; for such belts we may assume that depressurization occurred at nearly constant temperature. Such a retrograde trajectory could be virtually adiabatic, and the extent of back-reaction therefore would be a function of reaction rates and the speed with which the uplift of the subduction complex was accomplished. Structural, sedimentological, geochronologic and heat flow data (CLARK and JÄGER, 1969) indicate that the buoyant rise of the Alps was relatively rapid, so it may be concluded tentatively that the ubiquitous Alpine prasinitization was a function of the fact that the more internal, deeply subducted sections had attained a fairly high temperature (e.g., 350-500° C), allowing extensive recrystallization during the relatively rapid depressurization. As is presumed for the Ticino and Tauern « thermal highs », total obliteration of the Early Alpine high-pressure recrystallization would be expected in subducted sections which remained at depth long after convergence ceased; on heating, these complexes eventually would begin their rise towards the surface. Such P-T histories are not illustrated in Fig. 13 b, but presumably, subsequent to the early prograde subduction zone metamorphism, substantial isobaric heating must have occurred, followed by an adiabatic depressurization accompanying diapiric rise towards upper levels of the Earth's crust.

In contrast, the Franciscan terrane shows neither evidence of widespread retrogression nor rapid unloading. Conceivably, decoupled imbricate slabs of this terrane may have moved back towards the Earth's surface during continued subduction of the more seaward sections HSÜ, 1971; ERNST, 1971 c; SUPPE, 1972, 1973). This process would allow maintenance of the pronounced downward deflection of the isotherms in the vicinity of the convergent plate junction shown in Fig. 14. Hence, driven by gravitational forces, relatively cold, high-pressure packets of rock could have moved back upwards along the plate junction which evidently acted as a stress guide, following in reversed direction the Franciscan prograde P-T trajectory of Fig. 13 b. Such a change in physical conditions is reflected in higher-grade Franciscan eclogitic and hornblendic rocks which have been partly converted to glaucophane + lawsonite phase assemblages.

Conclusions

Relatively high-pressure metamorphic belts apparently form within the suture zones between pairs of convergent lithospheric plates. The unusually low geothermal gradient in the subduction complex itself is a consequence of the rapid descent of a thick slab of lithosphere (a poor thermal conductor). This underflow results in a pronounced downward deflection of the isotherms in the subducted plate. The abundance of ophiolitic rocks and deep-sea pelagic sedimentary units in blueschist belts reveals the latter's associations with oceanic crust adjacent to the continental margins. The direction of increasing metamorphic grade in such belts and the opposite sense of fold overturning and « younging » of depositional packets of rocks indicate the attitude (polarity) of the inclined convergent plate junction. Observed mineral assemblages and paragneneses in blueschist belts are systematic, internally consistent, and in excellent accord with experimental and calculated phase equilibria; taken together, the phase associations bear unequivocal testimony to relatively high-pressure, low-temperature metamorphism. Tectonic transport directions and the imposed thermal regime strongly argue for a subduction zone stage of deformation and concomitant recrystallization. The retrograde P-T path followed by portions of a subduction complex on return to upper crustal levels depends on the speed of uplift and whether buoyant rise takes place during continued subduction or subsequent to termination of underflow. Different high-pressure terranes exhibit the mineralogic effects of contrasting depressurization paths.

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