



Tectonic mechanisms associated with P – T paths of regional metamorphism: alternatives to single-cycle thrusting and heating

John Wakabayashi*

Wakabayashi Geologic Consulting, 1329 Sheridan Lane, Hayward, CA 94544, USA

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Abstract

Metamorphic pressure (P)–temperature (T) paths are commonly used as tools to interpret the tectonic history of orogenic belts, those deformed belts of rocks that record past activity along active plate margins. Many studies and reviews relating P – T path development to tectonics have focused on thrusting–thermal relaxation cycles, with special emphasis on collisional processes. Other studies have assumed that P – T paths resulted from a single tectono-metamorphic event that accounted for the entire burial–exhumation history of the rocks. In many cases, such assumptions may prove invalid.

This paper speculates on the relationship of tectonic processes other than thrusting–heating to P – T path development. The processes discussed herein include subduction initiation, triple-junction interactions, initiation and shut off of arc volcanism, subcontinental delamination, and hot spot migration. All of these processes may leave a signature in the metamorphic rock record. Examples are presented from a number of localities, most of which are from the Pacific Rim. Although thrusting–heating cycles have influenced metamorphic evolution in many orogenic belts, the potential impact of other types of tectonic mechanisms should not be overlooked.

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Keywords: P – T paths; Tectonics; Orogenic belts; Subduction initiation; Triple-junction migration; Magmatic arcs

1. Introduction

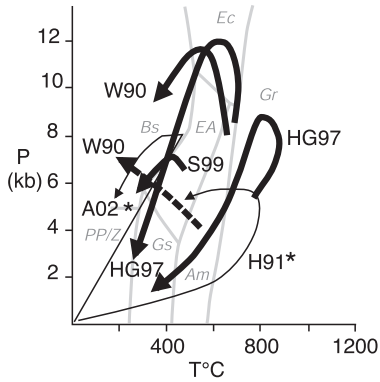
The study of ancient, exhumed continental margins commonly focuses on deformed belts of rocks known as orogenic belts, because these regions formed as a consequence of active plate margin tectonics (e.g., Dewey and Bird, 1970; Moores, 1970). Within orogenic belts, geoscientists use the spatial distribution of different rock types, their ages, and their structural and metamorphic history, to better understand the tectonics of ancient plate boundaries.

Studies linking tectonic environments to types of metamorphic rocks, with key examples from the Pacific Rim and Alpine regions, were published as plate tectonic theory became widely accepted (e.g., Miyashiro, 1967, 1973; Ernst, 1971). Oxburgh and Turcotte (1974) conducted pioneering thermal modeling of pressure (P)–temperature (T)–time (t) paths that represent the progressive metamorphic evolution of rocks. Oxburgh and Turcotte (1974) based the thermal models on a process that involved thrusting, that buried rocks faster than they can equilibrate with the ambient geothermal gradient, followed by thermal relaxation, which reestablished the ambient geothermal gradient in underthrust rocks. The thrusting–

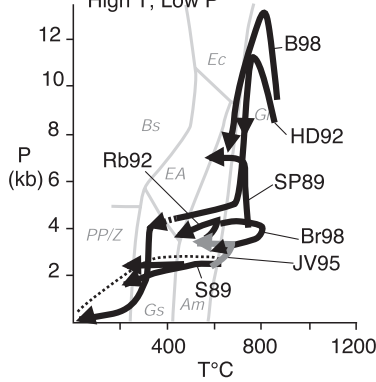
* Fax: +1-510-887-2389.

E-mail address: wako@tdl.com (J. Wakabayashi).

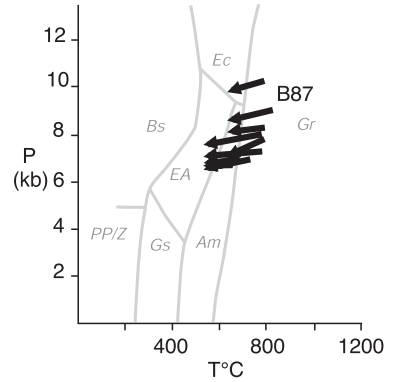
A Anticlockwise: Subduction Complexes and Metamorphic Soles



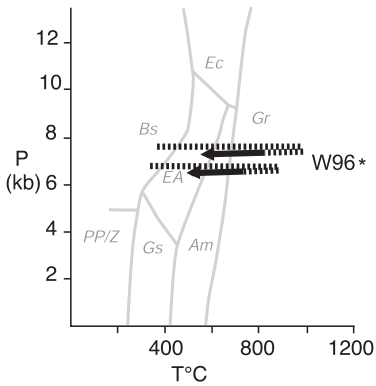
B Anticlockwise, isobaric cooling, or "near isobaric hairpin": including High T, Low P



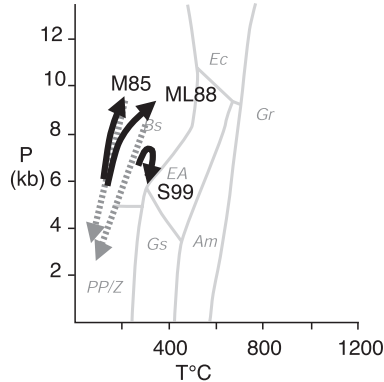
C Isobaric cooling: Granulites



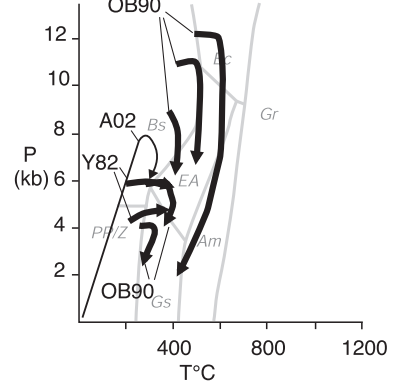
D Near isobaric cooling: Roots of Arc; Deep parts of subduction-transform transition or ridge-trench interaction



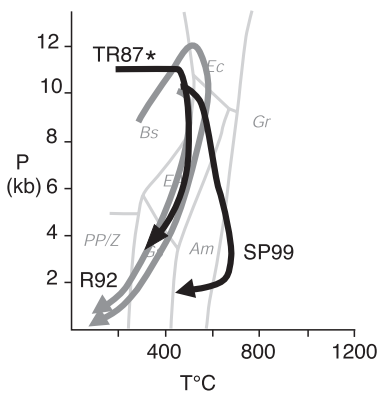
E Weakly clockwise or hairpin: Subduction Complexes



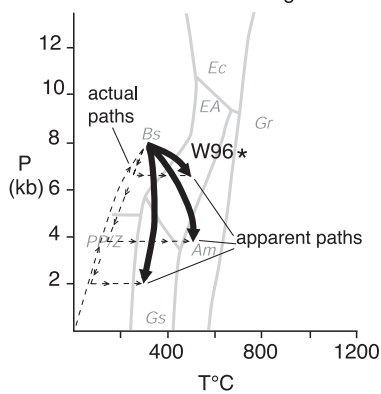
F Clockwise: Subduction Complexes



G Clockwise: Collisional



H Clockwise apparent paths: Subduction-Transform, shallow levels or lateral margins



thermal relaxation cycle was linked to subduction followed by collision. Subsequent researchers refined thermal models based on thrusting–thermal relaxation cycles and evaluated clockwise (P on the positive y axis) P – T paths of orogenic belts in this context (e.g., England and Thompson, 1984; Thompson and England, 1984; Thompson and Ridley, 1987; Spear and Peacock, 1989) (Fig. 1G). Since the late 1980s, an increasing number of studies have interpreted P – T paths that differ significantly from clockwise P – T loops (Fig. 1, Table 1). These studies include those of some types of granulites (e.g., Bohlen, 1987; Harley, 1989) (Fig. 1C), low- P /high- T metamorphism (e.g., Clarke et al., 1987; Grambling, 1988; Rubenach, 1992; Sisson and Pavlis, 1993; Johnson and Vernon, 1995; Brown, 1998a,b) (Fig. 1B), subduction–transform transition (Wakabayashi, 1996) (Fig. 1D, H), and of rocks associated subduction initiation (e.g., Wakabayashi, 1990; Hacker, 1991; Parkinson, 1996; Hacker and Gnos, 1997) (Fig. 1A).

This paper focuses on evaluation of P – T paths formed by mechanisms other than thrusting–thermal relaxation. The mechanisms reviewed in this paper are overlooked in many analyses of P – T paths. Fig. 1 shows examples of some of the types of P – T paths that I will discuss in the paper. These and other P – T paths are listed in tabular form in Table 1. The first sections of the paper discuss some general definitions and concepts related to tectonic interpretations of P – T paths. Following the general sections, I will speculate on specific tectonic settings of P – T path development. Most of the examples used in these discussions are from the Pacific Rim region, with particular emphasis on western North America. This paper is not intended as a comprehensive review of P – T paths and tectonics. My goal is merely to point out that P – T paths we interpret from rocks are likely generated by a greater variety of tectonic processes than commonly proposed.

2. Partial P – T paths and ‘apparent’ P – T paths

2.1. Partial versus complete P – T loops

Mineral growth recording a P – T path will not reflect the complete burial and exhumation history of a rock. This is because metamorphic minerals do not grow during the lowest grade parts of the burial and exhumation paths, and because successive recrystallization may erase earlier formed assemblages. Collisional thrusting–exhumation, and subduction with syn-subduction exhumation can account for an entire burial–exhumation cycle of a rock (Fig. 2A to J). Basinal sedimentation followed by basin inversion may also result in a complete burial–exhumation cycle, but the maximum depths of burial are much less than in collisional and subduction settings (e.g., Cooper and Williams, 1989). For other tectonic mechanisms, the rocks that record P – T paths associated with the mechanism may be at significant depth when the tectonothermal event begins and ends (Fig. 2K–U). Multiple tectonic events must occur in order to complete a burial–exhumation cycle for such rocks. If there is no metamorphic record of exhumation and initial burial, however, the P – T path recorded in such rocks may be the product of a single metamorphic event (Fig. 2K–U).

2.2. Time dependence and ‘apparent’ P – T paths

P – T paths recorded by overprinting mineral assemblages, inclusions, and mineral zoning are generally interpreted to result from a single evolving tectono-metamorphic event (e.g., Oxburgh and Turcotte, 1974; England and Thompson, 1984; Thompson and England, 1984; Ernst, 1988). However, the different stages of metamorphic mineral growth in rocks can result from metamorphic events separated by long periods of time and related to different tectonic events (e.g., Getty et al., 1993; Hand et al.,

Fig. 1. Examples of different P – T path types. Most examples are P – T paths determined from field-based studies. Modeled P – T paths are denoted by an asterisk after the acronym. Labels for P – T paths correspond to the following references: A02*: Aoya et al. (2002); B87: Bohlen (1987); B98: Baba (1998); H91*: Hacker (1991); HD92: Henry and Dokka (1992); HG97: Hacker and Gnos (1997); M85: Maruyama et al. (1985); ML88: Maruyama and Liou (1988); JV95: Johnson and Vernon (1995); OB90: Otsuki and Banno (1990); R92: Ring (1992); Rb92: Rubenach (1992); S89: Sisson et al. (1989); S99: Smith et al. (1999); SP89: Stüwe and Powell (1989); SP99: Soto and Platt (1999); TR87*: Thompson and Ridley (1987); W90: Wakabayashi (1990); W96*: Wakabayashi (1996); Y82: Yardley (1982); P – T paths in ‘D’ from Wakabayashi (1996). Facies abbreviations are Am: Amphibolite, Bs: Blueschist, EA: Epidote amphibolite, Ec: Eclogite, Gr: Granulite, Gs: Greenschist, PP/Z: Prehnite–pumpellyite and Zeolite. Facies boundaries from Takasu (1984).

Table 1
Examples of P – T paths generated by processes other than thrusting–thermal relaxation^a

P – T path type	Location	Reference
Anticlockwise: inception of subduction	High-grade blocks, Franciscan Complex, California, USA	Wakabayashi (1990), Krogh et al. (1994)
	Eclogites, Yukon–Tanana terrane, Canada	Perchuk et al. (1999)
	Structurally highest part of Shuksan Suite, Washington, USA	Brown et al. (1982) (y)
	Raspberry Schist, Alaska, USA	Roeske (1986) (y)
	Tetagouche Group, New Brunswick, Canada	Trzcinski et al. (1984), van Staal et al. (1990) (y)
	Structurally highest unit of Villa de Cura belt, Venezuela	Smith et al. (1999)
	High-grade blocks, Coastal Chile	Kato and Godoy (1995)
	Anglesey blueschists, Wales	Gibbons and Gyopari (1986)
	Early stages of metamorphism, structurally highest part of Sanbagawa Belt, Japan	Hara et al. (1990) (y); Wintsch et al. (1999)
	Kamuikotan zone, Hokkaido, Japan	Ishizuka et al. (1983) (y); Maekawa (1986) (y)
	Ballantrae Complex, Scotland	Bloxam and Allen (1960) (y)
	Metamorphic sole of Oman ophiolite	Hacker and Gnos (1997)
	Metamorphic sole beneath Kiziltepe ophiolitic nappe, Turkey	Dilek and Whitney (1997)
	Metamorphic sole, Kaynarca area, Tavsanlı Zone, Turkey	Önen and Hall (2000)
	High grade blocks, Sulawesi	Parkinson (1996)
Fragments from Marianas serpentinite seamounts	Maekawa et al. (1992) (y)	

Table 1 (continued)

P – T path type	Location	Reference
Anticlockwise: inception of subduction	Platta nappe, upper Engadine Valley, Switzerland Alps.	Phillip (1982) (y), Deutsch (1983) (y)
Anticlockwise (acw) or isobaric cooling (ibc), medium to high P granulites	Granulites, many locations in listed references (mostly ibc, some acw) Kohistan Arc, Pakistan (acw) Lewisian Complex, Outer Hebrides, Scotland (acw) Early metamorphism, Mojave extensional belt, California, USA (acw)	Bohlen (1987), Harley (1989) Yamamoto (1993) Baba (1998) Henry and Dokka (1992)
Anticlockwise (acw), isobaric cooling (ibc), isobaric hairpin (ibh), and other complex paths: mostly high T , low P	Chugach Complex, Alaska, USA (ibh) Ryoke Belt, Japan (ibh) Cooma Complex, Australia (acw) Mount Isa Inlier, Queensland, Australia (acw) Olary Block, Australia (acw) Bungler Hills, Antarctica (acw) Later metamorphism, Mojave extensional belt, California, USA (ibc)	Sisson et al. (1989); Sisson and Pavlis (1993) Brown (1998a,b) Johnson and Vernon (1995) Rubenach (1992) Clarke et al. (1987) Stüwe and Powell (1989) Henry and Dokka (1992)
Clockwise apparent paths, arc-related	Overprint on blueschists, Sierra Nevada, California, USA	Hacker (1993)
	Overprint on blueschists, Queensland, Australia	Little et al. (1992)
Clockwise apparent paths: subduction–transform transition	Sanbagawa Belt, Japan Haast Schists, New Zealand Mid-crustal levels, California Coast Ranges, USA	Otsuki and Banno (1990) (z) Yardley (1982) (z) Wakabayashi (1996) (hypothetical)

1994; Christensen et al., 1994; Barton et al., 1994; Hensen et al., 1995). I will use the term “actual P – T path” to refer to P – T paths that result from a single tectonic event. I will refer to P – T paths that may be the result of multiple tectonic events as “apparent P – T ” paths. Depending on the grade of metamorphism, the closure temperature of geochronologic systems, and the temporal separation of tectonic events, the distinction between actual and apparent P – T paths can be blurred. For example, if the peak metamorphic temperature is high enough, geochronologic ‘clocks’ may be reset, erasing information on the timing of the pre-peak metamorphism. Multiple tectonic events can occur so quickly that superimposed metamorphism might be interpreted as a single event, even if the isotopic systems were not reset by peak metamorphism. The southwest Pacific provides good examples of rapid tectonic transitions. In this region, at least three separate events of subduction cessation, subduction polarity reversal, and arc development have occurred within the last 25 million years (Hall, 1996). Some researchers have suggested that the southwest Pacific is a modern analog of the western North American Cordillera (e.g., Silver and Smith, 1983; Moores, 1998), so similar complexity of metamorphic evolution might be expected in the latter region. Although apparent P – T paths do not reflect a single tectonothermal event, they still provide information on the thermal evolution of a region or package of rocks. Many regions from which P – T paths have been determined lack sufficiently detailed geochronologic data. Interpretations of single event tectonic histories derived from such P – T paths should be viewed with caution.

3. Stage of observation and P – T path preservation: the link between earth processes and the rock record

Many tectonic processes may cause changes in geothermal gradient and consequent changes in P/T ratio recorded in metamorphic rocks. Although Earth processes may produce a variety of P – T paths, the rock record we observe is governed by preservation of the P – T path formed by a given process and the stage in the geologic evolution of a metamorphic terrane represented by present field exposures (e.g., Wakabayashi, 1996). Although a rock may physically experience a P – T path, whether such a P – T path is observed in the rock record depends on several factors including:

- Whether the P – T path survives thermal perturbations associated with exhumation.
- The amount of time elapsed since the metamorphic event.
- The different exhumation rates and consequent time scales characteristic of a given tectonic setting.
- The P/T ratio of the metamorphism.

Mineral reaction kinetics favor recording of counterclockwise P – T paths or isobaric cooling because the defining parts of such paths occur under conditions of decreasing temperature and reaction rates, favoring the preservation of earlier formed metamorphic phases. However, exhumation of rocks is commonly associated with events in which the geothermal gradient increases (slab breakoff, lithospheric delamination, thermal relaxation following thrusting, extension). Exhumation processes may preferentially produce or preserve clockwise P – T paths while erasing anticlockwise P – T paths.

The level of exposure may influence what type of P – T paths are preserved from the same tectonic setting. The level of exposure is a function of the amount of exhumation that has occurred and time that has elapsed since the metamorphic event. As an example, consider an area where the geothermal gradient increased and then decreased. In such an area, shallow to intermediate crustal levels may record a prograde P – T path or an apparent P – T path. Retrograde metamorphism may be too feeble to result

Notes to Table 1:

^aReferences listed for anticlockwise P – T paths marked as (“y”) do not include calculated P – T paths. I have interpreted anticlockwise type P – T paths from these works based on the mineral assemblages described therein. For the references marked (“z”), Wakabayashi (1996) interpreted the P – T paths as possible examples of apparent clockwise paths resulting from subduction-transform transition, a different interpretation than offered in the original papers. Insufficient geochronologic information exists for many of the P – T paths listed in this table to ascertain whether they are products of a single tectonometamorphic event or whether they are a product of multiple events, or apparent P – T paths.

in recognizable mineralogic changes. This may be because rocks were exhumed to shallower and cooler levels and because the geothermal gradient is lower on the retrograde path. Thus, shallower or intermediate crustal levels would record the increasing geothermal gradient or an overprint, a clockwise $P-T$ path. At deeper crustal levels, the thermal peak may erase the prograde path, and the retrograde path would occur at

sufficiently high grade to leave a mineralogic record. Such a retrograde $P-T$ path would reflect decreasing geothermal gradients and would be an anticlockwise path.

Different tectonic settings have different time scales of $P-T$ path preservation and exposure. In this paper, the terms ‘young’ and ‘old’ will be used loosely to refer to rocks younger than and older

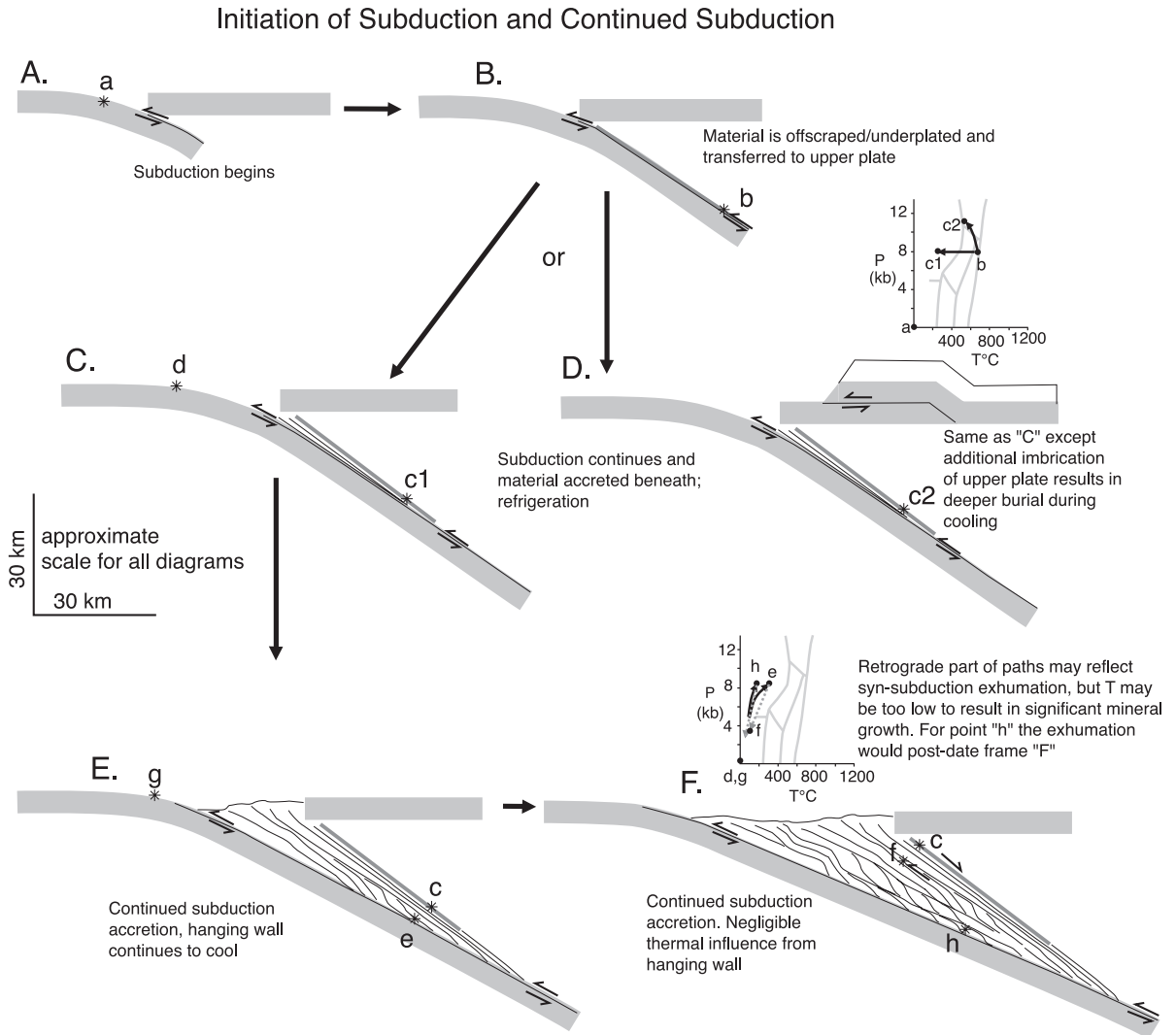


Fig. 2. Cross-sectional diagrams showing relationships between tectonic processes and generation of $P-T$ paths. Lower case letters and asterisks correspond to the position of a packet of rock that is represented with the same lower case letters on the $P-T$ path inset for each set of diagrams. Diagrams C and D show alternative positions *c* (*c1* and *c2*) for different tectonic scenarios that are also shown on the corresponding $P-T$ diagram. $P-T$ paths that correspond to each tectonic scenario are schematic and approximate.

Collisional Orogenesis

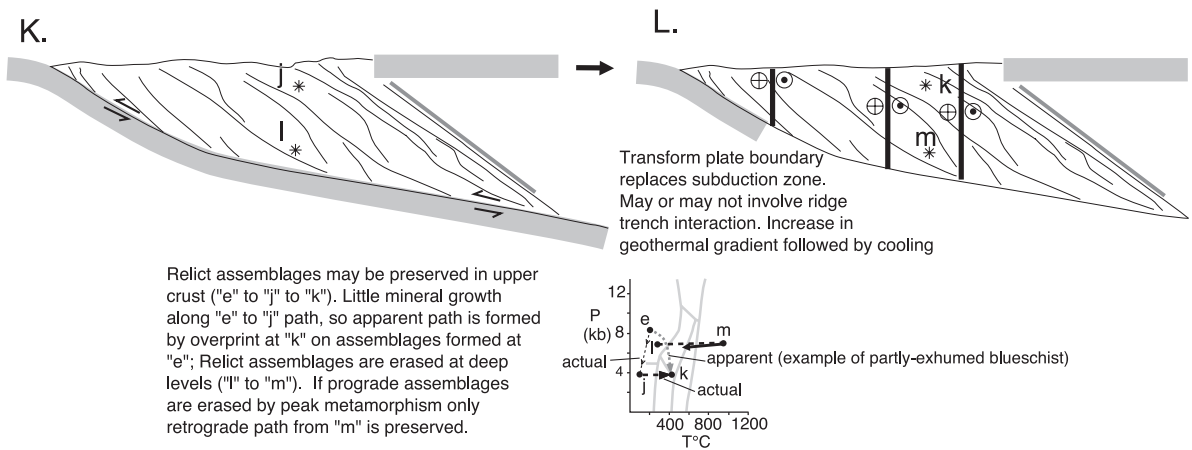
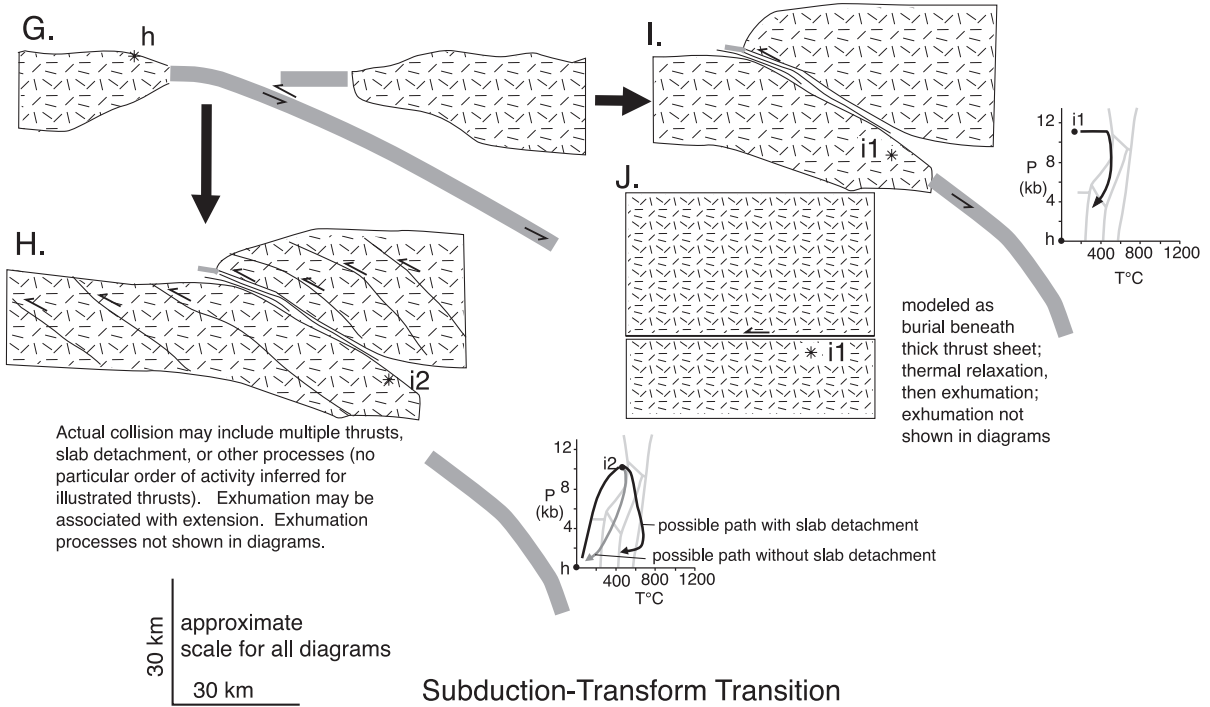
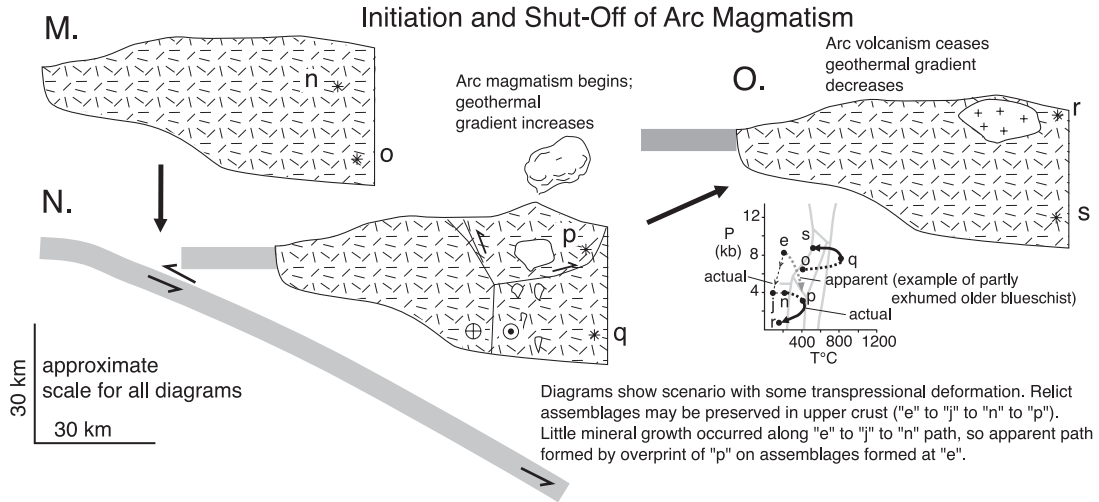


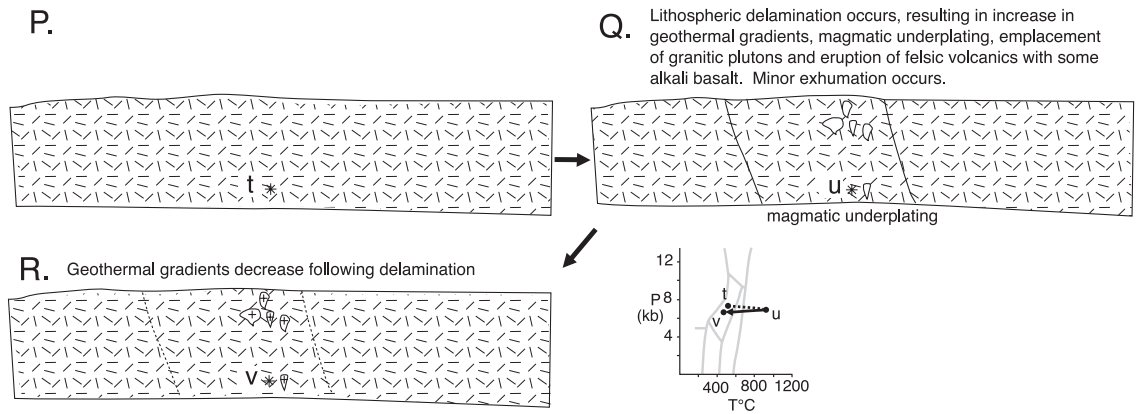
Fig. 2 (continued).

than about 400 Ma, respectively. Subduction and collisional settings are associated with the highest exhumation rates, and rates of several mm/year or more are common (e.g., Ring et al., 1999). Such settings are most likely to preserve young $P-T$ paths from deeply buried rocks. $P-T$ paths resulting from tectonic processes associated with high exhu-

mation rates, or those occurring at shallow crustal levels, would be preferentially preserved in young rocks. In contrast, high P metamorphism in tectonic settings with low exhumation rates may be preferentially exposed in old rocks. Metamorphism associated with processes with high exhumation rates, and general metamorphism occurring at shallow



Subcontinental Delamination (Not Associated With Subduction-Collision)



Migration of Hot Spot Toward and Away

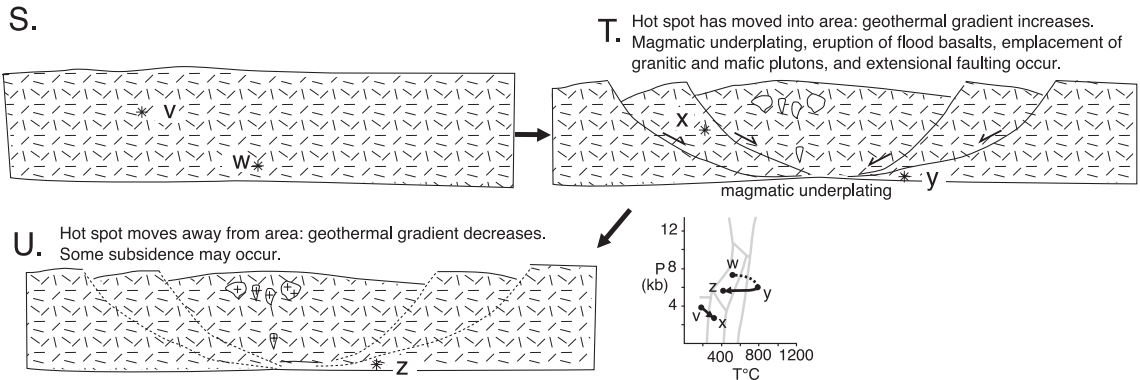


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crustal levels would be preferentially eroded away in older rocks.

The geothermal gradient represented by the type of metamorphism is also an important factor in the probability of preservation of a P – T path. Metamorphism at lower P/T ratios (higher than normal geothermal gradients) has a higher probability of preservation because they record higher grade metamorphism than the average at a given crustal depth. Conversely, high P /low T , subduction-related (such as blueschist facies) metamorphism created by subnormal geothermal gradients has a lower probability of long-term preservation because many tectonic processes can result in overprinting or erasure of such assemblages.

Another variable that affects the type of P – T path created and preserved from a given environment is the location of a packet of rock with respect to dip slip or oblique faults. For example, in a contractional setting, a shallowly buried rock may be on the upper plate of a thrust system, whereas a deeply buried rock may be on the lower plate. Rocks within the lower plate may experience greater burial during thrusting, whereas the rocks within the upper plate of thrust system may experience exhumation during the same thrusting event.

4. Some tectonic mechanisms that may result in P – T paths in the rock record

The mechanisms discussed in the following sections produce perturbations in geothermal gradients that relax after the event. Thrusting and continuous, or steady state, subduction depress geothermal gradients, and those gradients increase back to ambient levels following the cessation of these tectonic processes, resulting in clockwise P – T paths (e.g., Oxburgh and Turcotte, 1974; England and Thompson, 1984). In contrast, the other mechanisms discussed raise geothermal gradients, and the gradients decrease back to ambient levels after the tectonic event concludes. Extension as a separate tectonic mechanism is not discussed. Extension commonly occurs as a part of another tectonic process, such as extensional collapse of a collisional orogen, syn-subduction extensional exhumation (e.g., Platt, 1986; Dewey, 1988), or hot spot-triggered extension (e.g., Morgan, 1983).

4.1. Collisional orogens and thrust faulting

Although the emphasis of this paper is tectonic mechanisms other than thrusting–heating cycles, I will briefly review some aspects of thrusting and collisional tectonics, as they serve as a point of comparison for the other mechanisms discussed. A collisional tectonothermal event begins with subduction, then evolves to collision as a continental margin or other buoyant entity, such as an island arc or microcontinent, is partly subducted (e.g., Thompson and England, 1984; Ernst, 1988). The collision arrests subduction and geothermal gradients, which had been lowered by the subduction process, increase, resulting in a clockwise P – T path. In the latter stages of collisional orogenesis, slab detachment or delamination, (e.g., von Blanckenburg and Davies, 1995; van de Zedde and Wortel, 2001), convective removal of lithosphere (Platt and England, 1994), and gneiss dome emplacement (e.g., Teyssier and Whitney, 2002), can enhance the heating part of the clockwise P – T paths (Fig. 2H). Exhumation during collisional orogenesis is up to tens of kilometers and more, and exhumation occurs by some combination of extensional, erosional, or extrusional processes (e.g., Platt, 1986; Maruyama et al., 1996; Ring et al., 1999) (Fig. 2G–J).

Thrust faulting that causes metamorphism is not restricted to collisional orogens. For example, large-scale thrusting and crustal thickening may have taken place in the Sevier and Laramide belts of North America. These thrust belts occur in the back arc region of a continental margin arc-trench system, and may not have been associated with a collision (e.g., Dickinson and Snyder, 1978, but see Maxson and Tikoff, 1996 for a contrary view). Metamorphic evolution associated with non-collisional thrusting may be similar to collisional metamorphism except that the peak pressures of metamorphism and exhumation rates are lower.

The process of thrust faulting can produce anti-clockwise P – T paths in the lower portion of a thick thrust sheet where initially warmer material is thrust over cooler material (e.g., Chamberlain and Karabinos, 1987; Spear et al., 1990). Such P – T path development has been attributed to thrusting from an area of high geothermal to low geothermal gradients (e.g., Chamberlain and Karabinos, 1987;

Spear et al., 1990). However, even in areas with the same geothermal gradient, rocks at the base of a thick thrust sheet should experience cooling when thrust over other rocks, because such thrusting should place formerly deeper and warmer material over cooler, shallower, material. In order for an anticlockwise path to be generated, the temperature difference across the thrust fault must be significant.

Although the thrusting process may produce anticlockwise P – T paths, their preservation requires special circumstances. Anticlockwise P – T paths formed from such events may be preserved as a consequence of tectonic transport from a region of higher to lower geothermal gradient or decreasing geothermal gradient in the area during the thrusting event. However, it is difficult to move rocks away from a heat source with crustal shortening/thrusting. The decrease in geothermal gradient observed in many anticlockwise P – T paths may be a consequence of the cooling of the heat source rather than tectonic transport away from it. Exhumation of the rocks to relatively shallow levels must take place while active thrusting occurs beneath them so that thermal relaxation does not erase the anticlockwise P – T trajectory.

Examination of most anticlockwise P – T paths attributed to thrust or collisional settings shows that their peak metamorphism occurred under high geothermal gradients (e.g., Chamberlain and Karabinos, 1987; Spear et al., 1990). In most collisional settings, such hot conditions can probably only be achieved after slab detachment and resulting warming or after cessation of thrusting and emplacement of melts related to cessation of thrusting (e.g., von Blanckenburg and Davies, 1995). For anticlockwise P – T path development, crustal thickening must occur during cooling after the thermal peak from a delamination event. Following delamination or convective removal of lithosphere, crustal thinning is expected instead (e.g., Platt and England, 1994; von Blanckenburg and Davies, 1995). Accordingly, it appears that anticlockwise P – T paths should be created during collisional orogenesis, but such P – T paths are unlikely to be preserved. An exception may be some types of arc-continent collision discussed in the section on arc-related metamorphism.

Clockwise P – T paths from collisional orogenesis have a high likelihood of preservation and exposure

in young rocks, in part because of the high exhumation rates associated with such settings. Exhumation rates exceeding 1 cm/year and total exhumation exceeding 100 km have been recorded in rocks less than 100 My old (e.g., Ring et al., 1999).

4.2. Inception of subduction

The most extreme anticlockwise P – T paths have been interpreted from high-temperature metamorphic rocks progressively overprinted with high- P /low- T subduction assemblages. Anticlockwise P – T paths in the high-grade blocks of the Franciscan Complex of California have been suggested to have resulted from structural underplating at the inception of subduction (Wakabayashi, 1990). In this scenario (Fig. 2A–C), subduction initiated beneath young, hot oceanic lithosphere, resulting in high-temperature metamorphism on the top of the oceanic crust of the downgoing plate. Some of this high-grade metamorphic rock was transferred to the upper plate (Fig. 2B), either by offscraping/underplating or by thrust attenuation of a limb of a developing fold in the oceanic crust at the inception of subduction (Wakabayashi and Dilek, in press). As subduction continued, the hanging wall was rapidly refrigerated and assemblages indicative of a lower geothermal gradient overprinted the high- T metamorphic slice (Fig. 2C) (Wakabayashi, 1990). If the upper plate was imbricated during this process (Fig. 2D), or if blocks of the metamorphic slice are torn from their source and dragged to greater depth, additional burial of the rocks could occur during cooling (Wakabayashi, 1990). Anticlockwise P – T paths generated by thermomechanical processes at the inception of subduction have been simulated by modeling (Hacker, 1991; Aoya et al., 2002; Gerya et al., 2002) (Fig. 1A). Structurally, high material in Cloos' (1985) subduction model traverses an anticlockwise or isobaric cooling P – T path, although P – T paths are not discussed in that paper. Subduction initiation results in the creation of metamorphic soles found beneath ophiolites (e.g., Williams and Smyth, 1973; Spray, 1984; Jamieson, 1986). Counterclockwise P – T paths have been suggested in metamorphic soles based on thermal modeling (Hacker, 1991) and interpreted from metamorphic

assemblages in field-based studies (Hacker and Gnos, 1997; Dilek and Whitney, 1997; Önen and Hall, 2000) (Figs. 1A and 2A–D).

Anticlockwise P – T paths from the inception of subduction have a moderate probability of preservation in young rocks. Their probability of preservation is not as high as for clockwise P – T paths from subduction or collisional settings because of the extremely small area affected by this type of metamorphism. Anticlockwise P – T paths in subduction zones generally affect areas of tens of square kilometers or less, and structural thicknesses of a few hundred meters or less (e.g., Hacker and Gnos, 1997; Dilek and Whitney, 1997; Önen and Hall, 2000). These rocks commonly constitute much less than 1% of the rocks of a subduction complex (e.g., Coleman and Lanphere, 1971; Parkinson, 1996). Because of the small volume affected by such anticlockwise paths, preservation of such a record is unlikely for old rocks, as the rocks recording this P – T path would probably be completely eroded or overprinted by a subsequent thermal event. Nonetheless there are examples of this type of metamorphism from numerous orogenic belts (Table 1). Although they constitute a minute fraction of subduction complex or subophiolitic rocks, these rocks are important markers of tectonic history because they record the key signatures of the inception of subduction.

4.3. Continuous subduction

Continuous subduction, without collision, may generate clockwise P – T paths in high- P /low- T rocks, as a result of heat conduction from the cooling hanging wall of a subduction zone (e.g., Cloos, 1985; Aoya et al., 2002) (Fig. 2C–E–F). Later in an extended history of subduction the ‘steady state’ P – T may be more of a “hairpin” in which the exhumation path nearly reverses burial path (e.g., Ernst, 1988, 1993; Aoya et al., 2002) (Fig. 1E; 2E–F). P – T paths resulting from continuous subduction have a reasonable likelihood of being preserved in young rocks as long as exhumation occurs while subduction is active. The cessation of subduction results in thermal overprinting or erasure of subduction metamorphic assemblages (e.g., Ernst, 1988). The area affected by each such continuous subduc-

tion event can be tens to hundreds of thousand square km (e.g., Maruyama et al., 1996). Based on their common occurrence in the world’s orogenic belts (Aoya et al., 2002; Maruyama et al., 1996; Ernst, 1988), clockwise P – T paths from continuous subduction have a high likelihood of preservation and exposure in young rocks. Because subduction zone metamorphism occurs at high P/T ratios (low geothermal gradients), and is associated with high exhumation rates, the likelihood of preservation of subduction P – T paths is low in old rocks. The rate of exhumation (and erosion) as well as the probability of overprinting may be as important (Wakabayashi, 1996) as (possibly) higher Precambrian geothermal gradients (e.g., Ernst, 1972; Maruyama et al., 1996) in explaining the scarcity of Precambrian blueschist terranes (Fig. 2C–F).

4.4. Subduction–transform transition and ridge–trench interactions: slab window effects

Subduction refrigerates a subduction complex, creating the lowest geothermal gradients on Earth (e.g., Ernst, 1988). The cessation of subduction will result in warming, and development of clockwise P – T paths (e.g., Ernst, 1988). Collisions of buoyant terranes, such as volcanic arcs, continental margins or micro-continental fragments, are the most commonly proposed mechanisms by which subduction is arrested (e.g., Ernst, 1988) (Figs. 2K–L, 3 and 4).

Collisions are not the only mechanism that can result in the heating of a subduction complex, nor are they the only mechanism that halts subduction. Heating of a subduction complex can take place by subduction of an oceanic spreading ridge, called a ridge–trench interaction, with or without cessation of subduction (Sisson and Pavlis, 1993; Underwood et al., 1993; Brown, 1998a). Such heating can also occur as a result of conversion of subduction zone to a transform plate boundary by migration of a fault–fault–trench triple junction (Furlong, 1984), called a transform–trench interaction. I will refer to ridge–trench and transform–trench interactions collectively as triple-junction interactions and the corresponding metamorphism as triple-junction metamorphism. Triple-junction interactions involve the creation of slab-free windows through which asthenospheric upwelling occurs, resulting in heating and magmatic under-

plating (e.g., Dickinson and Snyder, 1979; Furlong, 1984; Thorkelson, 1996). Igneous activity is common with triple-junction interactions, resulting in eruption of volcanic rocks and emplacement of calc-alkaline plutons (e.g., Liu and Furlong, 1992; Dalrymple et al., 1999). If such a terrane is deeply exhumed, the field relations may appear arc-like (Wakabayashi, 1996; Brown, 1998a).

The distribution of subduction complex rocks affected by ridge–trench and transform–trench interactions is determined by the angle between the ridge crest and the trench and the obliquity of subduction. For ridge strikes less than 90° clockwise of the subduction zone strike in Fig. 3 (inset and A to D), both ridge–trench and fault–trench interactions occur. The slab windows associated with the resulting ridge–trench and transform–trench interaction pairs have been termed “fraternal” slab windows (Thorkelson, 1996). An example is coastal California, where the Rivera triple junction, a ridge–fault–trench triple junction, has migrated southward and the Mendocino triple junction, a fault–fault–trench triple junction has migrated northward, as a lengthening transform boundary (the San Andreas fault system) replaces the former subduction boundary between the two triple junctions (e.g., Atwater and Stock, 1998). Subduction of the ridge–transform system will result in the subduction complex being affected by either a ridge–trench or a transform–trench metamorphic event (Fig. 3C). For ridge strikes of 90° or more clockwise of the trench strike in Fig. 3 (inset and E to G), only ridge–trench interactions occur. In this case, a subduction zone may experience a succession of ridge–trench events separated by episodes of normal subduction. An example of this geometry is the Chile triple-junction area and affected reaches of the subduction zone (e.g., Forsythe and Nelson, 1985; Lagabriele et al., 2000). The azimuth of subduction will also influence the relative lengths of trench affected by different types of triple-junction interactions. Regardless of the obliquity of subduction, transform–trench type interactions can only occur for half of the range of possible angles between the ridge and trench (Fig. 3 inset). There are also subduction azimuths for which ridge–trench interactions will effect the entire length of a trench, even for ridge strikes favorable to “fraternal slab window” development. For example, for Fig. 3A–D, imagine a case

in which the subduction azimuth is either parallel to the oceanic transform or subduction that has a large dextral component. In the former case, there will be negligible length of trench affected by transform–trench interaction. In the latter case, trench segments affected by ridge–trench interactions overlap and segments with transform–trench interaction will be overprinted. The geometries of triple-junction interactions and effects indicate that ridge–trench interactions should affect greater lengths of former trenches than transform–trench interactions.

Triple-junction interactions result in rapid heating, commonly occurring in 5 Ma or less, to a thermal peak, followed by slower cooling (e.g., Furlong, 1984). In the case of coastal California, there has been less than 3 km of exhumation in most areas in the 25 My since triple-junction interactions began Dumitru (1989). This suggests that there has been little vertical crustal movement associated with the heating and cooling following that particular triple-junction interaction (Wakabayashi, 1996). The resulting P – T path may involve nearly isobaric heating and cooling, essentially an isobaric hairpin P – T path (Wakabayashi, 1996) (Fig. 2K–L). The Chugach terrane in Alaska and the Ryoke Belt of Japan record isobaric hairpin P – T paths, and their metamorphism has been attributed to ridge–trench interaction (Sisson et al., 1989; Sisson and Pavlis, 1993; Brown, 1998a,b). If peak and subsequent metamorphism erases prograde assemblages, the resultant P – T path for triple-junction metamorphism should feature isobaric cooling. Higher P/T ratios may be associated with transform–trench metamorphism than ridge–trench metamorphism, because the heat source is deeper in the former case (compare Fig. 1D to paths S89 and Br98 of Fig. 1B).

Where sufficient metamorphic temperatures are reached and sustained during cooling during a triple-junction metamorphism event, earlier, subduction-related, metamorphism may be completely erased. However, at shallower crustal levels, where triple-junction metamorphic temperatures are lower, subduction-related metamorphism may be preserved. high- P /low- T subduction-related rocks exhumed to relatively shallow levels during subduction may not leave a mineralogic record of the exhumation path because the exhumation took place under low geo-

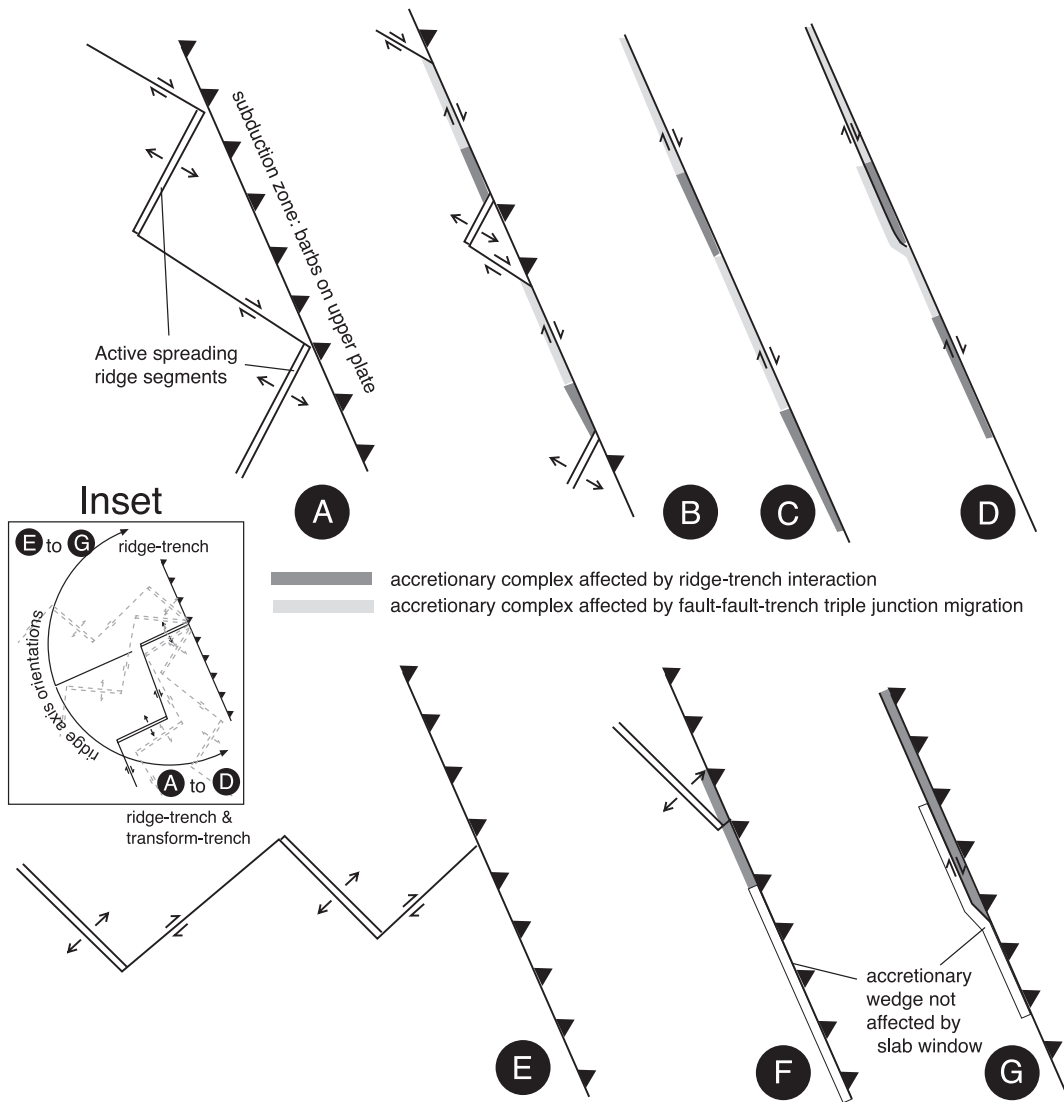


Fig. 3. Diagrams illustrating triple-junction interactions along trenches. No absolute scale is implied; ridge segments may range from 10 to 100 s of km in length. The interaction of a ridge–transform system with a trench can result in either a series of ridge interaction events, or a ridge–trench interaction paired with a fault–fault–trench interaction (see inset). Diagrams A to D show a sequence of subduction of spreading/oceanic transform system based on the interaction of fraternal slab windows (terminology of Thorkelson, 1996). With complete subduction of the spreading system, the margin may be converted to a transform margin, and shifting of the location of strike-slip faults may move higher P/T fault–fault–trench-influenced rocks outboard of ridge–trench-influenced rocks (D). This produces a paired metamorphic belt configuration (similar to concept proposed by Brown (1998a)). Diagrams E to G illustrate the formation of paired belts with ridge–trench interactions only, the other half of the angular possibilities. Such interactions can result in a subduction complex unaffected by slab window metamorphism being juxtaposed with an inboard low P , high T metamorphic belt that was affected by ridge–trench interaction.

thermal gradients and low temperatures (Ernst, 1988). At shallow crustal levels, partially exhumed subduction complex rocks affected by triple-junction metamorphism may develop an apparent $P-T$ path in

which greenschist facies metamorphism overprints blueschist facies metamorphism (Figs. 1H and 2E–F, K–L) (Wakabayashi, 1996). The apparent $P-T$ path developed in the sequence of diagrams Fig.

2E–F, and Fig. 2K–L illustrates a hypothetical P – T path developed in Franciscan Complex blueschist facies rocks that are still several kilometers beneath the surface of the present California Coast Ranges (Wakabayashi, 1996). These rocks were originally metamorphosed under blueschist facies conditions in the Cretaceous, then exhumed to mid-crustal levels while subduction was still active. No significant metamorphic mineral growth developed during the cold exhumation of the rocks. Following the partial exhumation, the triple-junction metamorphism occurred and the partly exhumed blueschist facies rocks were overprinted with greenschist facies assemblages creating an apparent clockwise P – T path. With many geochronologic methods, it may be difficult to determine whether such overprinting mineral relationships are a consequence of a single event, or an apparent P – T path. In many blueschist terranes, the only datable metamorphic mineral is white mica (e.g., Maruyama et al., 1996) and the closure temperature for Ar in white mica may be lower than the temperature of the greenschist facies overprint (e.g., Grove and Bebout, 1995). Greenschist facies triple-junction-related metamorphic overprints may completely reset white mica ages, leaving no geochronologic record of the earlier blueschist metamorphism.

Triple-junction metamorphism may be associated with fabrics that reflect orogen-parallel extension and shear related to the development of a transform plate boundary (Wakabayashi, 1996; Brown, 1998a). Overprints on blueschist facies rocks are commonly associated with orogen-parallel stretching lineations, suggesting that many such overprints may be caused by triple-junction interaction, rather than subduction–collision, as previously believed (Wakabayashi, 1996). The deepest levels of triple-junction metamorphism may reach granulite facies (Furlong, 1984; Sisson and Pavlis, 1993; Wakabayashi, 1996; Maeda and Kagami, 1996; Brown, 1998a). Transform–trench interactions has been proposed as a mechanism of formation for some medium to high- P (6–10 kbar) granulites (Wakabayashi, 1996), and ridge–trench interactions has been proposed for the development of low- P (~4 kbar) granulite belts, and low- P /high- T metamorphism in general (Brown, 1998a). Newton (1990) noted that a transition from thrusting to strike-slip deformation characterizes many medium to high- P granulite belts. Such a sequence of defor-

mation is consistent with the hypothetical structural evolution during subduction–transform transition. The relationship between CO_2 -rich fluids and granulite formation has been suggested (Newton, 1989). These fluids are thought to be mantle derived based on mass balance considerations (Newton, 1989) and carbon isotopic studies (Jackson et al., 1988). Triple-junction metamorphism and associated slab window development involves direct contact between mantle (upwelling asthenosphere) and lower crust. Along the San Andreas fault system, strike-slip faults associated with the transform fault plate boundary cut through the entire crust, based on recent seismic studies (Parsons et al., 2002). These faults provide potential pathways for mantle-derived fluids to reach the lower crust after magmatic underplating associated with slab window development occurs. Thus, triple-junction metamorphism and subsequent transform tectonics can provide an environment for an extended history of interaction between mantle-derived fluids and the lower crust.

Depending on the timing of transpressive or transtensional deformation, resulting from minor changes in relative plate motion or irregularities in strike-slip fault geometries (step-overs and bends), small pressure increases or decreases during heating and cooling may occur. Fluctuations in burial depth related to transpression or transtension may be as large as 10 km along the San Andreas fault system, based on the stratal thickness of strike-slip basins, and the structural relief generated by fold and thrust belts inverting such basins, (e.g., Yeats, 1987). Superposition of such fluctuations in burial depth will influence of the P – T path generated by triple-junction metamorphism. For example, the triple-junction interaction event may be associated with transpression and crustal thickening, followed by an extended period of nearly pure strike-slip. Such a history may result in crustal thickening during heating, with increasing burial for deeper rocks, followed by near isobaric cooling (e.g., Williams and Karlstrom, 1996). Conversely, initial ridge–trench interaction may be associated with nearly pure strike-slip followed by transpression. Such a P – T path may feature near isobaric heating, followed by an anticlockwise segment of a path, perhaps resulting in an anticlockwise P – T path similar to the JV95, Rb92 paths in Fig. 1B. During the history of a transform margin, the relative

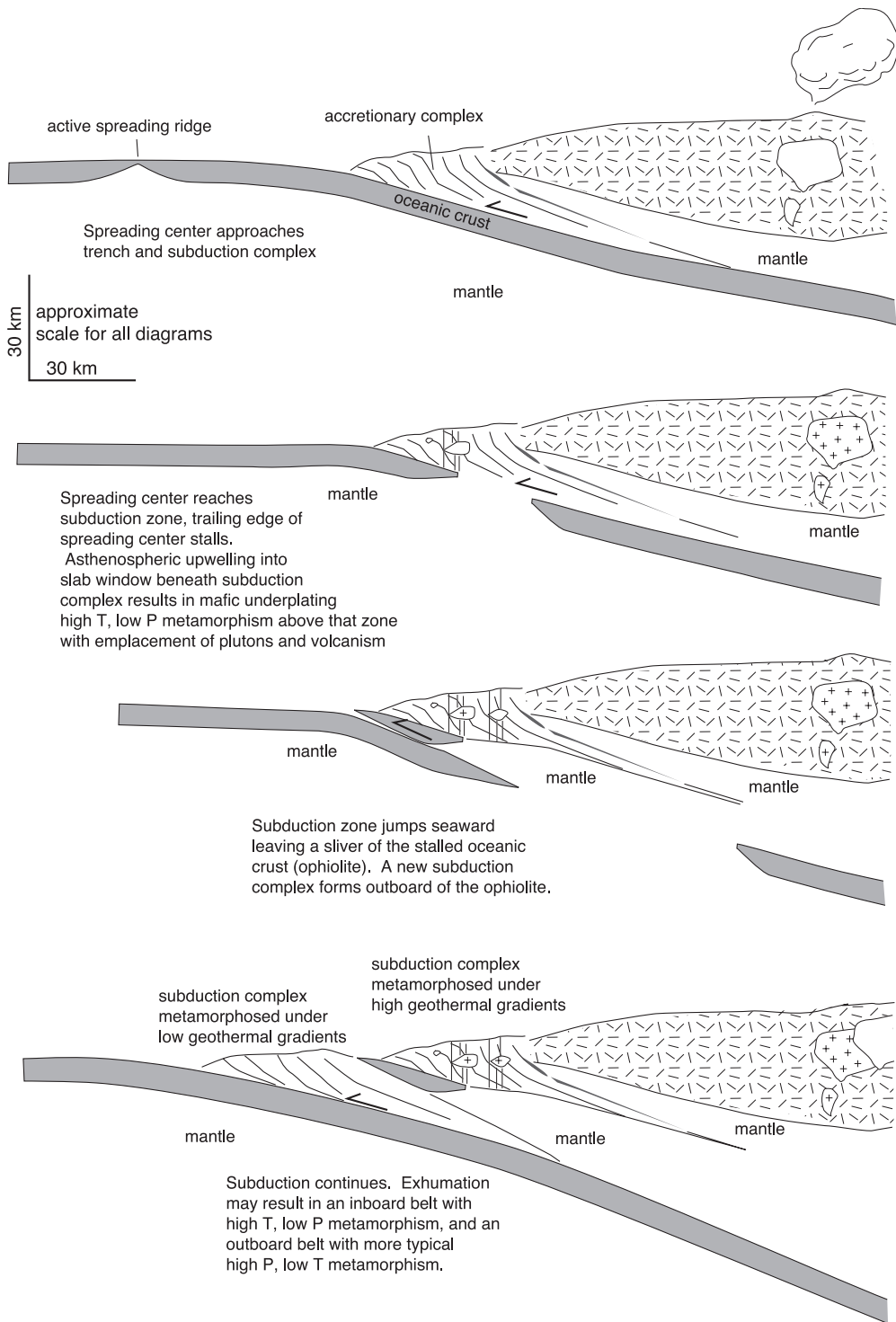
plate motion may shift between transtensional and transpressional and visa versa. For example, in the San Andreas transform system, plate motion across the system may have been transtensional from the inception of the transform fault system at 18 to about 8 Ma, after which relative plate motion became transpressional (Argus and Gordon, 2001). Oscillations between transpression and transtension along a transform plate boundary may cause alternating burial and exhumation, that may result in complex P – T paths for triple-junction interactions. The “yo yo tectonics” recorded by geothermobarometry in metamorphic rocks along a basement wrench zone in Anatolia (Casale et al., 2002) may be an example of the metamorphic signature of this type of tectonic mechanism.

An interesting consequence of triple-junction interactions is the potential to juxtapose belts of contrasting metamorphic styles and P – T evolution across strike-slip faults (Brown, 1998a). Brown (1998a,b) concluded that many paired metamorphic belts, particularly the Sanbagawa and Ryoke belts of Japan, became juxtaposed as a result of triple-junction interaction and subsequent strike-slip faulting, rather than being a product of paired subduction and arc-related metamorphism (e.g., Miyashiro, 1967, 1973). Possible mechanisms for such pairing of metamorphic belts are shown in Fig. 3, which differs from the diagrams of Brown (1998a) in showing both ridge–trench interactions and transform–trench interactions. In the mechanisms shown in Fig. 3, strike-slip faulting moves parts of the subduction complex outboard of those that have experienced higher temperature triple-junction metamorphism. Paired metamorphic belts can also be formed by ridge–trench interaction without strike-slip faulting (Fig. 4). Ridge–trench collision may result in the stalling of the oceanward side of the spreading center at the trench. The stalling of the oceanic crust may occur because there is no downgoing slab to pull on the ocean crust on the oceanward side of the spreading center and the leading edge of that section of ocean crust is very young and buoyant. If subduction resumes, a new subduction zone may form seaward, leaving a trapped piece of oceanic crust (ophiolite). Examples of such ophiolites are found on the Taitao Peninsula of Chile and in southern Alaska (Forsythe and Nelson, 1985; Lyt-

wyn et al., 1997). As subduction continues geothermal gradients will decrease again, and a subduction complex will form with typical subduction zone metamorphism, outboard of the older subduction complex that was affected by high- T /low- P ridge–trench metamorphism. This tectonic mechanism may produce paired metamorphic belts, but the high-grade metamorphism in the inboard belt should be slightly older than the oldest high- P /low- T metamorphism in the outboard belt.

For ridge–trench metamorphism, the probability of exposure in young rocks is probably high because the site of metamorphism is along an active plate margin, the depth of the highest grade levels of metamorphism is not excessive, and the metamorphism occurs at high geothermal gradients. Brown (1998a) suggested that ridge subduction may be the general process by which low- T , high- P terranes are formed. Such terranes occupy areas of up to tens of thousands of square kilometers in both Phanerozoic and Precambrian orogenic belts, although they are more common in the latter (Brown, 1998a). Nelson and Forsythe (1989) suggested that ridge–trench interactions were a major process in Archean crustal growth. Implicit in their suggestion is the premise that such interactions strongly influenced metamorphism in Archean orogenic belts.

For transform–trench interactions, the probability of exposure of amphibolite and granulite grade rocks in younger orogenic belts is lower than that of ridge–trench interactions because the metamorphism occurs deeper. The rates of exhumation along transform margins are probably insufficient to exhume the deeper (20 km or more) levels within a short period of time. For example, exhumation rates along most of the San Andreas transform plate boundary are less than 0.2 mm/year, averaged over 20 million years or more of transform plate boundary history (Dumitru, 1989). Medium- P granulites generated by this process would likely be found predominantly in older rocks (Wakabayashi, 1996). This premise that medium to high- P granulite terranes are associated with environments of low long-term exhumation rates is consistent with the observations of Newton (1987), who showed the increasing area of granulite terranes with increasing age. The shallower levels of transform–trench metamorphism are more likely to be exposed within younger rocks, and this process may account for the



thermal overprint on some high- P /low- T terranes (Wakabayashi, 1996).

The terminal event in the closure of an ocean basin is continent–continent collision, and such events form the most conspicuous orogenic belts on Earth (e.g., Dewey and Bird, 1970). Unless spreading ceased long before the terminal collisions, triple-junction interactions should have affected significant lengths of the active plate margins that eventually became parts of the collisional orogenic belt. I suggest that many collisional orogens may have earlier metamorphic records of pre-collisional triple-junction metamorphism. Triple-junction interactions are common on the present-day Earth, so such processes were probably equally common in the geologic past and have left a significant record in orogenic belts (Sisson et al., 1994).

4.5. Initiation and cessation of arc magmatism

Magmatic arcs have long been suggested as an environment of elevated geothermal gradients and associated metamorphism (e.g., Miyashiro, 1967, 1973). Geothermal gradients should increase in an area when arc magmatism begins and decreases after the shut off of magmatism. Initiation and cessation of arc magmatism in a region may result from starting and stopping subduction, but can also result from across-strike migration of arc volcanism associated with trench rollback or shallowing of subduction. Arc environments may have significant vertical tectonism associated with them, although this amount is smaller than that associated with subduction or collisional settings (e.g., Renne et al., 1993). Both transpressional and transtensional deformation may occur within an active arc (Tobisch et al., 1995). In the late Jurassic to late Cretaceous Sierra Nevada arc of California, exhumation during the late stages of arc development of 5 to 10 km was common, and greater amounts may have occurred locally (Ague and Brimhall, 1988; Renne et al., 1993; Tobisch et al., 1995; Pickett and Saleeby, 1993). In the southernmost Sierra Nevada, 100–115 Ma plutons emplaced at depths of about 30

km were fully exhumed before 52 Ma, some 30 Ma after shut off of the magmatic arc (Pickett and Saleeby, 1993) (Fig. 2M–O).

Associated with the lower levels of magmatic arcs is another possible cause of burial depth (P) increase, magmatic loading (e.g., Brown and Walker, 1993; Brown, 1996). In such a mechanism, the intrusion of sheets of magma will result in an increase of loading of material below. Magmatic loading should result in an increase in P and T for the deeper parts of the arc, even without thrust faulting (Brown and Walker, 1993; Brown, 1996).

In the Sierra Nevada, exhumation of arc rocks occurred during arc activity and was complete within the first 20 Ma or so after magmatism ceased, based on the presence of Eocene overlap assemblages and a dramatic decrease in forearc basin sedimentation rates after the Paleocene (Wakabayashi and Sawyer, 2001). Exhumation coinciding with the last stages of magmatism and the first 20 Ma after cessation of magmatism was generally 10 km or less (Ague and Brimhall, 1988). From the Eocene until about 5 million years ago, exhumation of the Sierra Nevada was no more than about 200 m (Wakabayashi and Sawyer, 2001).

If the Sierra Nevada is representative of magmatic arcs, then the tectonic history can be used to infer metamorphic P – T paths for such environments. The type of P – T path preserved from arc initiation and shut off may be a function of the crustal level exposed as well as the amount of vertical tectonism associated with arc development and shut off. At shallower levels, pre-arc metamorphism may be preserved, with a low-grade arc-related overprint forming an apparent P – T path. Retrograde metamorphism after arc shut-off would occur under conditions of lower geothermal gradient and shallower crustal levels as exhumation proceeds, favoring recording of an apparent prograde path over the retrograde path. Such an apparent P – T path would be noticeable only on partly exhumed high- P /low- T (blueschist facies) assemblages, otherwise the arc-related overprint would be difficult to distinguish from older retrograde metamorphism of higher grade rocks. Such an apparent P – T path should

Fig. 4. Cross-sectional diagrams showing how the interaction of a spreading ridge with a subduction zone and renewed subduction can form parallel belts of high- P /low- T and low- P /high- T rocks. If significant exhumation occurs, low- P /high- T rocks will be exposed in the inboard belt, whereas high- P /low- T rocks will be exposed in the outboard belt. The high-grade metamorphism in the inboard belt should be slightly older than the oldest high- P /low- T metamorphism in the outboard belt.

be a clockwise path, reflecting the increase in geothermal gradient represented by the arc over the pre-arc environment (Fig. 2E–F, M–O). An arc-related metamorphic overprint and resulting apparent P – T path may occur in the northern Sierra Nevada. In this region, metamorphism which may have resulted from increased geothermal gradients associated late Jurassic arc magmatism, overprinted blueschist facies rocks from an earlier, unrelated episode of subduction (Hacker, 1993). Another arc-related overprint occurs in blueschist facies rocks in Queensland, Australia, where overprinting may have occurred as arc magmatism migrated into the former subduction complex as a result of trench rollback (Little et al., 1992).

At deep enough crustal levels, pre-arc assemblages may be completely replaced, so only metamorphism related to arc development will be preserved. Crustal thickening associated with syn-magmatic transpressional deformation may have been associated with increases in P and T for deeper rocks and exhumation for shallower rocks (Fig. 2N–O). The 50 Ma period with negligible exhumation that followed arc shut off in the Sierra Nevada may be associated with isobaric cooling. The combined history of heating and cooling for the deeper levels of Sierra Nevada arc-related metamorphism may have resulted in an anticlockwise P – T path followed by isobaric cooling, if the rocks were on the footwall of transpressional fault systems (Fig. 2N–O). For the deepest and highest grade rocks beneath the Sierra Nevada, the prograde path may be erased leaving only the isobaric or anticlockwise cooling path. The peak P and T conditions of 8 kbar arc-metamorphic rocks in the southern Sierra have been estimated, but P – T paths have not been calculated (Pickett and Saleeby, 1993). Peridotite xenoliths erupted from late Cenozoic volcanoes and derived from the mantle from beneath the Sierra Nevada batholith record isobaric or nearly isobaric cooling, interpreted to be of Cretaceous age (Lee et al., 2000). The isobaric cooling recorded in the xenoliths may reflect cooling after shut off of the arc. Deeply buried rocks from arcs associated with less syn-magmatic vertical tectonism than occurred during Sierra Nevada history may feature near isobaric hairpin P – T paths.

The base of volcanic arcs has been suggested as a likely environment for granulite formation (Bohlen, 1987), and isobaric or near isobaric cooling after cessation of arc magmatism is consistent with P – T

paths associated with many granulite belts (Bohlen, 1987). However, high-grade, ~8 kbar metamorphic rocks exposed in the southern Sierra Nevada were associated with metamorphic fluids that had a higher water activity than fluids associated with typical granulite formation (Pickett and Saleeby, 1993). In contrast, arc-metamorphic rocks from the Coastal Cordillera or northern Chile are 5 kbar granulites that are overprinted by amphibolite facies assemblages (Lucassen and Franz, 1996). These rocks show near isobaric cooling from granulite to greenschist facies. The 8-kbar plutons in the southern Sierra are granitic (Pickett and Saleeby, 1993), whereas the 5-kbar metamorphic rocks from northern Chile are metabasaltic and interpreted to be the remnants of basaltic magmas underplated at the base of an arc (Lucassen and Franz, 1996). The contrast between the two regions suggests a significant difference in the thickness of the batholithic rocks, differences in geothermal gradients, and possibly differences in the metamorphic mechanisms. Some of these differences may be because the Chilean rocks were associated with an oceanic arc (Buchelt and Cancino, 1988; Vergara et al., 1995), whereas the Sierra Nevada arc was a continental margin arc (e.g., Ague and Brimhall, 1988). The Kohistan arc of Pakistan, however, with much higher P metamorphism (>10 kbar), is interpreted as an oceanic arc (e.g., Bard, 1983). An alternative hypothesis for the origin of the Chilean high-grade rocks is that they are the product of triple-junction metamorphism or delamination-related metamorphism instead of arc-related metamorphism.

Based on the above discussion, it appears that some variety of metamorphic P – T paths can be expected from the deeper rocks associated with magmatic arc metamorphism. In addition to the P – T paths discussed above, anticlockwise P – T paths associated with large changes in P have been interpreted from the base of the Kohistan Arc in Pakistan (Yamamoto, 1993). Such P – T paths may result if the arc is on the lower plate of a collision zone. For such anticlockwise P – T paths to form, arc magmatism should be extinguished prior to or during this partial subduction. The arc shut off itself may be associated with another collision, or a subduction–transform transition, that stopped the subduction associated with the development of that arc. Similar, collisionally related contraction during cooling of an arc may also explain the

pronounced anticlockwise P – T evolution of some high P /high- T terranes such as those shown in the oldest part of path HD92 and in path B98 in Fig. 1B. This type of tectonic evolution represents a special case of arc-related metamorphism, but such collisions may be relatively common in the geologic record, because several events of this nature have occurred during the Cenozoic in the southwest Pacific (Hall, 1996). Similar collisional events of this type have been proposed for the Phanerozoic development of the North American Cordillera (e.g., Moores, 1970).

Exhumation rates after shut off of magmatic arcs may be low, whereas syn-magmatic exhumation rates may be much higher, if the Sierra Nevada example is representative. Accordingly, exposures of arc-metamorphic rocks that record arc shut off may be relatively rare in young rocks, whereas arc-metamorphic rocks lacking the arc shut off signature may be relatively common. Examples of moderately deep arc rocks and their metamorphic products are common in young rocks from the North and South American Cordillera (Zen, 1988; Pickett and Saleeby, 1993; Lucassen and Franz, 1996). Exposure of the deep roots of Mesozoic magmatic arcs also occur, including the Kohistan Arc in Pakistan (e.g., Bard, 1983), and the Fjordland region in New Zealand (e.g., Bradshaw, 1989; Brown, 1996; Clarke et al., 2000).

Active magmatic arcs cover large areas of the Earth. Given the common occurrence of magmatic arcs throughout Earth history, it is likely that P – T paths resulting from arc magmatism have left a record in many orogenic belts.

4.6. Subcontinental delamination (distinct from slab delamination during subduction–collision)

In some areas, the mafic lower continental crust and subcontinental lithosphere may founder (e.g., Furlong and Fountain, 1986). The delamination considered in this section is distinct from the slab detachment that may occur in subduction–collision orogens. Delamination may result in asthenospheric upwelling that will raise the geothermal gradient above a normal continental geotherm, followed by possible magmatic underplating, and thermal relaxation (cooling) back to a normal geotherm (Furlong and Fountain, 1986). Asthenospheric upwelling and magmatic underplating are associated with eruption

of potassic felsic volcanic rocks, some alkali basalts, and emplacement of granite plutons (e.g., Moore and Dodge, 1980; Ducea and Saleeby, 1998a,b; Manley et al., 2000). Surface and rock uplift may accompany the delamination event, as a result of the lithospheric buoyancy created by the delamination of dense material (Ducea and Saleeby, 1998b). The amount of exhumation directly associated with such an event may be relatively small. For example, the eastern Sierra Nevada region, under which delamination may have occurred within the last 8 Ma (Ducea and Saleeby, 1998b), has experienced a maximum of about 1 km of exhumation within the past 4 to 5 Ma (Wakabayashi and Sawyer, 2001). As underplated magmas crystallize and the heated area cools, exhumation may slow down or cease (e.g., Crough, 1983) (Fig. 2P–R).

The metamorphic signature of a delamination event likely depends on the level of exposure. At upper crustal levels, pre-delamination assemblages may be preserved, and if those assemblages are of sufficiently low grade, an apparent P – T path may be formed by the superposition of peak delamination-related metamorphism on earlier metamorphic assemblages. At deeper crustal levels, pre-existing assemblages may be erased and a near isobaric hairpin P – T path is expected, because of the comparative lack of delamination-related exhumation. A near isobaric cooling path is expected if prograde assemblages are not preserved. The tectonic setting of subcontinental delamination and associated magmatic underplating has been proposed as an environment of granulite formation, and near isobaric cooling paths found in some granulites are consistent with this type of environment (Bohlen, 1987). Delamination also provides a means of delivering mantle-derived fluids into contact with the lower crust. Along the eastern margin of the Sierra Nevada, dextral and normal faulting was associated with or coincident with delamination, and has continued to the present day (e.g., Wakabayashi and Sawyer, 2001). This faulting may cut the entire crust, because alkali basaltic rocks erupted along these faults are thought to be mantle derived (e.g., Moore and Dodge, 1980; Ormerod et al., 1991). This faulting provides pathways for mantle-derived fluids to continue to drive metamorphism in the deep crust after the initial delamination and underplating event. The relationship between strike-slip faulting, mantle-derived fluids,

and high-grade metamorphism has been noted in a number of granulite terranes (e.g., Newton, 1989, 1990). In the case of the Sierra Nevada, deep metamorphism related to delamination has occurred or will occur in rock affected by earlier arc-related metamorphism. Differentiating between delamination and arc metamorphism may be difficult in the rock record. If the tectonic history of a plate margin is well enough known, the two environments may be distinguished on the basis of age of metamorphism compared to the timing of subduction and arc magmatism. In the Sierra Nevada case, delamination-related metamorphism should be 80 Ma younger than arc-related metamorphism (e.g., Ducea and Saleeby, 1998a) and it occurred at a time when the plate boundary is a transform one. Distinction between this type of delamination and a triple-junction-related metamorphism can be made on paleogeographic relationships. In late Cenozoic California, triple-junction interaction has overlapped in time with delamination, but the triple-junction interaction affects former subduction complex rocks at the continental margin, whereas the delamination occurs over 100 km inboard of the old subduction complex.

The area affected by subcontinental delamination events appears to be on a scale comparable to the size of volcanic arcs, if the Sierra Nevada example is representative (Ducea and Saleeby, 1998a,b). If we consider only delamination events that are distinct from other types of tectonic events, the amount of exhumation associated with such events appears to be relatively small. Consequently, the probability of exposure of the deep levels of such thermal events in young rocks is low. Relict assemblages overprinted by shallow levels of subcontinental delamination metamorphism are less likely than arc-related metamorphism to include high- P /low- T rocks, the only rocks in which the delamination overprint would be noticeable. Such rocks would be less likely to be associated with subcontinental delamination than magmatic arc initiation, because the former process is not restricted to occur near a continental margin as the latter is. Thus, subcontinental delamination events (as defined herein) may have had little noticeable impact on metamorphic P – T paths in shallowly buried young rocks. In contrast, the deeper, higher-grade rocks produced by delamination events may be an important component of old orogenic belts.

4.7. Approach and departure of a hot spot

Hot spots are known for their association with major igneous activity, particularly the eruption of flood basalts (e.g., Morgan, 1983), so they must have a significant metamorphic impact as well. Many hot spot tracks cross continents, so it is likely that they have had a major influence on the tectonic and thermal history of some orogenic belts (e.g., Morgan, 1983; Murphy et al., 1998). Geothermal gradients increase as the hotspot approaches (e.g., Nathenson and Guffanti, 1988), and significant exhumation and uplift may occur (e.g., Crough, 1983; Parsons et al., 1994; Murphy et al., 1998). Cooling and a return to pre-hot spot tectonics and thermal regimes are expected as the hot spot moves away from an affected area (e.g., Anders and Sleep, 1992). The Yellowstone hotspot, that has crossed part of western North America in the Cenozoic, is a good example of the impact of a hot spot on a continental margin (Anders and Sleep, 1992; Parsons et al., 1994; Murphy et al., 1998; Humphreys et al., 2000). The hotspot has either triggered or influenced extensional tectonics in the Basin and Range province (Morgan, 1983; Parsons et al., 1994; Murphy et al., 1998). Although the peak metamorphism associated with hot spot migration are superficially similar to that produced in other environments of high-grade metamorphism, there appear to be some significant differences. Hot spots commonly migrate across the structural grain of a continental margin, whereas delamination, triple-junction interactions, and magmatic arcs produce metamorphic belts parallel to subparallel the structural grain (e.g., Morgan, 1983; Keppie et al., 2003) (Fig. 2S–U).

The effects of a hot spot interaction are superimposed on the existing tectonic regime (e.g., Anders and Sleep, 1992; Parsons et al., 1994; Murphy et al., 1998, 1999). Hot spots are involved with prolonged heating with a continued delivery of hot material from an ascending plume, whereas delamination is usually followed by a single upwelling event and cooling (e.g., Duncan and Richards, 1991). The prolonged heating results in the eruption of greater volumes of primitive mafic lavas, including eruption of flood basalts and emplacement of mafic intrusives, (e.g., Duncan and Richards, 1991; Anders and Sleep, 1992), and greater exhumation as a result of extensional tectonics (Parsons et al., 1994), compared to delamination events.

The type of P – T path preserved is in part a function of the level of crustal exposure. At shallow crustal levels, preservation of pre-existing metamorphic assemblages may lead to the development of apparent P – T paths, that may be noticed as such only if the pre-existing rocks are high- P /low- T rocks. Deeper levels of hot spot metamorphism will likely erase preexisting assemblages. Because extension and exhumation associated with hotspot metamorphism may be significant, pressure may decrease during heating leading to a clockwise P – T path. A clockwise P – T path has been determined for low- P /high- T Devonian metamorphism in the northern Appalachians (Keppie and Dallmeyer, 1995) that has been attributed to heating by a hot spot (Murphy et al., 1999; Keppie and Krogh, 1999). Keppie et al. (2003) suggested that hot spot interaction resulted in a clockwise P – T path for Jurassic low- P /high- T metamorphism and related deformation in the Acatlan Complex of Mexico. Extension and exhumation slow down after the passage of the hotspot (Anders and Sleep, 1992), so the last part of the retrograde metamorphic P – T path may approximate isobaric cooling.

Hot spot metamorphism has been suggested as one mechanism of forming granulites (Bohlen, 1987; Newton, 1987). Morgan (1983) suggested that hot spots traversing a continent may form zones of weakness and trigger continental rifting. The timing of the passage of some hot spot tracks over the continents suggests that their passage may coincide with high-temperature metamorphism in certain regions. For example, the Bermuda hotspot may have passed through the area of the Sevier thrust belt at or a bit before 120 Ma (Morgan, 1983). The passage of the hotspot may have influenced both the metamorphism and the deformation in that area. The Bermuda hot spot may have also contributed to exhumation in the central and southern United States (Crough, 1983). Crough (1983) also suggested that some Jurassic intrusions in New Hampshire occurred as a result of interaction with the Cape Verde hot spot.

The significant exhumation associated with hot spot interactions suggests a reasonably high probability of exposure in young rocks for the deeper levels of the crust affected by hot spot metamorphism. The heating from a hot spot can affect an area of tens of thousands to hundreds of thousands of square kilometers (e.g., Crough, 1983; Sleep, 1990; Humphreys et al., 2000). It

is likely that hot spot interactions have left a much larger impact on the metamorphic record than has been previously appreciated (Murphy et al., 1998).

5. Conclusions

This paper has speculated on several tectonic mechanisms that result in metamorphic P – T paths in regionally metamorphosed rocks. The tectonic mechanisms described herein certainly do not cover all possible causes of P – T path development. However, the tectonic processes discussed serve to illustrate that there are probably many more causes of metamorphic P – T paths than are commonly considered in analyses of orogenic belts. In this paper, I have treated each type of tectonic interaction singly. During the evolution of an orogenic belt, many of these mechanisms may operate, interact with, and overprint one another on relatively short time scales. Although I have attempted to add greater complexity and flexibility to tectonic interpretations of metamorphic P – T paths, this effort itself is probably a gross simplification of actual tectonothermal histories experienced by many orogenic belts.

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