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Paired metamorphic belts revisited

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ABSTRACT

The modern plate tectonics regime is characterized by a duality of thermal environments, one representing the subduction zone and the other representing the arc–backarc or orogenic hinterland. This duality is the hallmark of one-sided (asymmetric) subduction, and the characteristic imprint of one-sided subduction in the geological record is predicted to be the broadly contemporaneous occurrence of two contrasting types of metamorphic belt, one of high d*T*/d*P* type and the other low d*T*/d*P* type. The broadly contemporaneous occurrence of granulite and ultrahigh-temperature metamorphism with eclogite–high-pressure granulite metamorphism in the geological record since the Neoarchean Era is evidence of dual thermal environments and indicates that subduction has operated on Earth since that time. Classic 'paired' metamorphic belts in which an inboard high d*T*/d*P* metamorphic belt is juxtaposed against an outboard low d*T*/d*P* metamorphic belt along a tectonic contact—such as the Ryoke and Sanbagawa belts in Japan—are found in Phanerozoic accretionary orogens of the circum-Pacific. Generally, they appear to result from juxtaposition of terranes with different metamorphic facies series that may or may not be exactly contemporaneous and that may or may not be far-traveled. This is a consequence of the difference between globally-continuous subduction, generating a low-to-intermediate d*T*/d*P* environment in the subduction zone and a high d*T*/d*P* environment in the arc–backarc system, and metamorphic imprints in the geological record that represent discrete 'events' due to changes in plate kinematics or subduction boundary dynamics, or as a result of collision of ridges, arcs or continents with the upper plate at the trench. The concept of 'paired' metamorphic belts may be generalized and extended more widely than in the original proposition to subduction-to-collision orogenic systems in addition to accretionary orogenic systems. In this wider application, the term "paired metamorphic belts" may be used for "penecontemporaneous belts of contrasting type of metamorphism that record different apparent thermal gradients, one warmer and the other colder, juxtaposed by plate tectonics processes" (Brown, 2009). This extends the original concept of Miyashiro (1961) beyond the simple pairing of high d*T*/d*P* and low d*T*/d*P* metamorphic belts in circum-Pacific accretionary orogens, and makes it more useful in the context of our better understanding of the relationship between thermal regimes and tectonic settings. This is particularly useful in subduction-to-collision orogenic systems, where the suture and lower plate materials will register the imprint of low-to-intermediate d*T*/d*P* and the upper plate will register penecontemporaneous high d*T*/d*P* metamorphism commonly manifested at shallow crustal levels by the occurrence of granites in the rock record.

1. Introduction

The plate tectonics revolution of the late 1960s provided a model of global mantle dynamics and a kinematic schema within which to understand global tectonics during the Cenozoic and Mesozoic Eras, the maximum lifespan of the ocean floors before return to the mantle via subduction (e.g., Isacks et al., 1968; Le Pichon, 1968). This paradigm shift provoked a new look at the geological record and its interpretation. Orogenesis—the process by which mountain belts are constructed—became understandable once placed within a plate tectonics context; orogenesis has since become a collective term for convergent margin processes. Within a few years Atwater (1970) and Dewey et al. (1973) had demonstrated that the evolution of young orogenic systems along active continental margins and in continental collision zones could be unraveled by inverting geological data in combination with ocean floor magnetic anomaly maps and following the kinematic principles of plate tectonics. Today the paradigm that 'the present is the key to the past' is still a valid approach, at least for the Phanerozoic (e.g., Glen and Meffre, 2009).

By the early 1970s the relationship between plate tectonics and petrology was a 'hot' topic, leading to advances in understanding processes at island arcs and active continental margins, at mid-ocean ridges and hot spots, and in placing ophiolites in an appropriate context—all topics to which Akiho Miyashiro made significant contributions. The relationship between the geology of metamorphic belts and convergent plate margins was addressed by Matsuda and

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Uyeda (1971) and Miyashiro (1972, 1973), quantitative aspects of generating the thermal structure of metamorphic belts were addressed by Oxburgh and Turcotte (1971), and the formation of blueschists in the context of plate tectonics was discussed in detail by Ernst (1971, 1973, 1975) and Brothers and Blake (1973).

In the last two decades, the formation of metamorphic belts and the *P–T–t* evolution of orogens, and a consideration of secular trends in the thermal evolution of metamorphic belts have been reviewed in a series of papers by Brown (1993, 1998b, 2001, 2002, 2007, 2008, 2009). These complement papers by Sandiford (1989), Ernst and Liou (1995, 2008), Maruyama et al. (1996), Maruyama and Liou (1998, 2005), Liou et al. (2004, 2009), Ernst (2006) and Tsujimori et al. (2006), and many others. In this contribution, I summarize the tectonics of orogenic systems on Earth, since this provides a context for regional-scale metamorphic belts, before I review the concept of 'paired' metamorphic belts as developed in Japan by Miyashiro (1961), including a description of the classic Ryoke–Sanbagawa 'paired' metamorphic belts. This is followed by comments on the classification of types of metamorphism to evaluate the tectonic setting of metamorphic belts through time, before moving on to a consideration of the imprint of these different types of metamorphism in the geological record back to the Neoarchean Era.

I use a dataset for high-temperature and high-pressure metamorphism compiled in 2005 (Brown, 2007). Using this dataset, I define three types of metamorphism characterized by different ranges of apparent thermal gradient, which I relate to the changing tectonics of orogenic systems through Earth history. This view back to the Neoarchean leads to a broader interpretation of paired metamorphic belts than envisaged by Miyashiro in 1961, but his original concept remains sound in many respects.

2. Tectonics of orogenic systems on Earth

At a global scale on modern Earth, subduction at convergent plate boundaries is essentially continuous. Orogenic systems occur along convergent plate boundaries, where they act as buffer zones (Lister et al., 2001) to accommodate deformation (Kreemer et al., 2003) forming mountain chains. Currently, the circum-Pacific and Alpine–Himalayan–Indonesian orogenic systems define two orthogonal great circle distributions of the continents, each of which has a different type of orogenic system along the convergent plate boundary zone (Dickinson, 2004). These orogenic systems record the two main zones of active subduction into the mantle, the circum-Pacific and the Alpine–Himalayan–Indonesian subduction systems (Collins, 2003).

Young mountain chains on Earth are clearly associated with linear belts of distinctive sedimentation, deformation, magmatism and metamorphism, as well as the high relief. In contrast, ancient orogenic belts must be identified based on sedimentation and stratigraphy, particularly the occurrence of unconformities in the rock record, the type of associated volcanism and plutonism, commonly using chemical fingerprinting, and the style of tectonic deformation and regional metamorphism.

Accretionary orogenic systems form above a subduction boundary (also referred to as a hinge or trench) during ongoing plate convergence in the absence of continental collision, as exemplified by the evolution of the Pacific Ocean rim during the Phanerozoic Eon (Coney, 1992). The behavior of the subduction boundary in relation to the upper plate is important (Uyeda and Kanamori, 1979; Uyeda, 1982; Royden, 1993a,b; Lister et al., 2001; Schellart, 2007; Schellart et al., 2007; Schellart, 2008a; Lallemand et al., 2008; Lister and Forster, 2009; Schellart, 2009; Capitanio et al., 2009; but see Doglioni (2008) for an alternative perspective).

Accretionary orogenic systems vary according to whether the subduction boundary is retreating (is pulled back faster than the upper plate is able to adjust), neutral or advancing (is pushed back by the advance of the upper plate). Although migration of the subduction boundary correlates with the velocity of the subducting plate, which largely depends on its age at the trench (Lallemand et al., 2008), ever more sophisticated modeling of free subduction shows that migration is controlled by many factors including plate width, proximity to lateral slab edges and far-field boundary conditions (Schellart et al., 2007; Schellart, 2008b; Stegman et al., 2009), as well as the upper plate itself and feedback relations between the subducting slab and the upper mantle (Capitanio et al., 2009; Stegman et al., 2009). Lister and Forster (2009) have argued that accretionary orogenic systems may exhibit tectonic mode switches (shortening *versus* extension) and in some cases perhaps cyclic behavior as a consequence of changes in subduction boundary migration (cf. Collins and Richards, 2008), although alternating cycles of whole-orogen shortening and extension are not widely reported in the literature.

In addition to subduction boundary migration, orogenesis in accretionary orogenic systems may be driven by reorganization of plate motions (Dewey, 1975) or some other geodynamic change in convergence across the subduction boundary (Agard et al., 2009), ridge–trench interactions (Brown, 1998b; Wakabayashi, 2004), subduction of ocean floor debris (Cloos, 1993; Collins, 2002b), or terrane accretion (Jones et al., 1983; Howell et al., 1985; Coney, 1992), leading to episodic imprints in the geological record (Dewey, 1981; Monié and Agard, 2009), some of which may be globally significant (Lister et al., 2001). Shortening of the upper plate and formation of an orogenic plateau in the hinterland behind a mountain chain in the absence of terminal continent collision, such as occurs in the modern Andes, requires resistance to retreat of the subduction boundary, which condition is met far from lateral slab edges (Schellart et al., 2007; Schellart, 2008b), and upper plate motion towards the trench (van Hunen et al., 2002), which is most likely driven by ridge push forces. In addition, in these advancing systems, extensional collapse of the orogenic suprastructure may be a factor due to the gravitational potential energy of the orogen, as described for collisional orogenic systems by Dewey (1988).

Accretion of arcs and/or allochthonous terranes, some of which may be far-traveled, is a common feature of accretionary orogenic systems (Coney, 1992), making the distinction from collisional orogenic systems somewhat arbitrary with the exception of terminal continent–continent collisions. Previously these orogenic systems have been called *Pacific-type* (e.g. Matsuda and Uyeda, 1971) or *Cordilleran-type* (e.g. Coney et al., 1980), and more recently Maruyama (1997) has proposed that they should be called *Miyashiro-type*.

Collisional orogenic systems are those in which an ocean is closed as arcs and/or allochthonous terranes and/or continents collide (Dewey and Bird, 1970). Island arc collisions with passive continental margins are variable, although since the collision chokes the subduction zone as thinned continental crust is progressively subducted, break-off of the subducting slab commonly occurs. A reversal or flip in the subduction polarity may occur if subduction is initiated behind the accreted arc. These 'soft' collisions generate a period of short-lived orogenesis because the forces opposing shortening are relieved by initiation of subduction outboard of the accreted arc (e.g., Dewey, 2005). A similar process occurs where allochthonous blocks and terranes are sutured to an active continental margin, except that the subduction boundary steps back and continues to subduct towards the upper plate and the associated orogenic event is minimal (e.g., Glen and Meffre, 2009). However, such 'soft' collisions are not always the case and arc–continent collisions may be terminal, as exemplified by the Brasiliano belts in West Gondwana (e.g. Heilbron et al., 2008; Reno et al., 2009).

Orogenesis in which two continents become sutured involves significant thickening of the continental lithosphere over a wide zone, perhaps up to 1500 km across, and far-field shortening of the crust. This generates a mountain front and a wide orogenic plateau surrounded by internal basins which themselves are bordered by thrust belts (e.g., Dewey, 2005). Mountain building by continent–continent collision generally is the result of several successive stages.

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Assuming one passive margin and one active convergent margin, the first stage involves subduction of the ocean plate along the active convergent margin, which may generate an accretionary orogenic system as discussed above. Next, the introduction of the thinned passive continental margin into the trench induces detachment and stacking of upper crustal units and metamorphism at depth in the subduction zone—forming mineral assemblages that are characteristic of higher-pressure (low-to-intermediate d*T*/d*P*) metamorphism—accommodating convergence between the two plates mostly within the subduction zone (e.g. Reno et al., 2009). Finally, the ongoing convergence induces a more penetrative shortening and pronounced thickening on a lithosphere scale, which induces widening of the orogen as the orogenic front migrates and formation of an orogenic plateau with higher-temperature (high d*T*/d*P*) metamorphism at depth (Dewey, 2005; McKenzie and Priestley, 2008).

Features such as deformation, metamorphism and magmatism may vary in intensity along and across the length and breadth of these systems because the continental margin being subducted need not be rectilinear (Ernst et al., 1997). Furthermore, both continents may be bordered by active convergent margins. For example, in the Alpine–Himalayan–Cimmerian orogenic system, the Paleotethyan suture marks the former Paleotethys Ocean basin, both sides of which were active accretionary orogenic systems above subducting boundary zones prior to collision, although each had quite different character (Şengör, 1992). Previously these orogenic systems have been called 'Himalayan-type' (Liou et al., 2004) or 'Turkic-type' (Şengör and Natal'in, 1996).

3. Metamorphism and tectonics

A characteristic feature of subduction boundary zones is the development of dual thermal environments (Oxburgh and Turcotte, 1970, 1971), representing the subduction zone or collisional suture (cooler) and the arc–backarc system or orogenic hinterland (warmer). This feature is the hallmark of asymmetric or one-sided subduction on modern Earth (Gerya et al., 2008). Brown (2006) showed that different types of metamorphism would be registered in each of these thermal environments, and proposed that the record of metamorphism in ancient orogens may be inverted to determine when this style of subduction boundary zone first was registered in the geological record. We will return to this topic later in this paper.

3.1. Tectonic controls on the style of metamorphism

In the years since Miyashiro (1961) introduced the idea of 'paired' metamorphic belts in accretionary orogenic systems and Oxburgh and Turcotte (1971) offered an explanation in relation to the thermal structure of island arc regions we have developed a more sophisticated understanding of the tectonic controls on styles of metamorphism at convergent plate boundary zones. We now understand the wide variation in *P*–*T* conditions of ongoing regional metamorphism in an active subduction zone environment (Omori et al., 2009) and why backarcs are uniformly hot (Currie and Hyndman, 2006). Furthermore, we now realize that metamorphic imprints in orogens are likely to be the result of discrete events caused locally by a geodynamic change in convergence across the subduction boundary and/or migration of the subduction boundary, ridge–trench interactions or subduction of other ocean floor debris, and terrane accretion and/or terminal continent collision, or globally by changes in plate kinematics to regain the plate boundary torque balance (Brown, 2009, and references therein). However, within this framework there are contrasting views concerning intra-orogenic and extra-orogenic controls on the style of metamorphism.

Thompson et al. (1997) treat orogenic systems along subduction boundaries as complex zones of transpressive deformation in which the degree of obliquity controls the style of metamorphism, whereas Lister and Forster (2009) argue that switches in tectonic mode related to subduction boundary dynamics are primarily responsible for differences in style of metamorphism. Thompson et al. (1997) propose that a low ratio of pure shear to simple shear, typical for wrench-dominated plate boundaries, implies a larger component of horizontal transport from a position deep in a transpressive orogenic system, which allows for a longer time during which heating may occur. In contrast, a high ratio of pure shear to simple shear, typical for convergence dominated plate boundaries, implies a smaller component of horizontal transport from a position deep in a transpressive orogenic system, which drives more rapid exhumation and allows less time during which heating may occur. On this basis, Thompson et al. (1997) propose that high d*T*/d*P*, intermediate d*T*/d*P* and low d*T*/d*P* metamorphism are associated with an increasing angle of subduction obliquity, respectively. Lister and Forster (2009; cf. Collins and Richards, 2008) propose two end-member types of orogenic system based on cyclicity of tectonic mode switches. They suggest that systems that evolve through a cycle in which a retreating trench changes to an advancing trench ("pull–push orogenic cycle") will be associated with high thermal gradient type of metamorphism (>750 °C/GPa), whereas other systems that evolve through a cycle in which an advancing trench changes to a retreating trench ("push–pull orogenic cycle") will be associated with low (<350 °C/GPa) to intermediate (350–750 °C/GPa) thermal gradient types of metamorphism. However, neither of these postulates has been tested adequately against the geological record of metamorphism.

In the Alpides, the occurrence of low d*T*/d*P* metamorphic rocks in several belts related to a single subduction system suggests the possibility of recurrent transient events (Lister et al., 2001). Exhumation of these metamorphic rocks appears to have been associated in time and space with subduction–accretion of continental ribbon terranes that triggered slab rollback or slab step-back outboard of the accreted terrane to create the necessary space for exhumation (Brun and Faccenna, 2008). However, this is not the only mechanism by which low d*T*/d*P* metamorphic rocks are exhumed. Some belts of low d*T*/d*P* metamorphic rocks further east in the Tethysides appear to have been exhumed from a common depth equivalent to ~1 GPa pressure within <25 Ma over several thousands of kilometers of strike length, perhaps owing to a change in the long-term interplate mechanical coupling (Monié and Agard, 2009). A detailed discussion of exhumation mechanisms for low d*T*/d*P* metamorphic rocks is outside the remit of this paper and the interested reader is referred to papers by Platt (1993), Ernst et al. (1997), Gerya et al. (2002), Warren et al. (2008a, b, c), Agard et al. (2009) and Li and Gerya (2009) and references therein.

High d*T*/d*P* metamorphism may be related to thickening of backarcs (Hyndman et al., 2005a), which is a popular model for some accretionary orogenic systems (e.g., Collins, 2002a; Collins and Richards, 2008; Brown, 2009). However, it should be noted that the model of Collins (2002a) would produce counterclockwise *P*–*T*–*t* paths (Brown, 2003), consistent with observations from high d*T*/d*P* metamorphic belts of the Lachlan orogenic system (e.g., Johnson and Vernon, 1995) and the Acadian orogen in New England (e.g., Johnson et al., 2003), whereas the model of Collins and Richards (2008) would produce clockwise *P*–*T*–*t* paths, consistent with observations from the high d*T*/d*P* Ryoke metamorphic belt in Japan (e.g., Brown, 1998a) but not those of the Lachlan or Acadian metamorphic belts. Furthermore, the models of Collins (2002a) and Collins and Richards (2008) do not consider orogen-parallel translations, whereas Glen et al. (2009) have argued that the Lachlan orogenic system is composed of several terranes that have been translated along the eastern Gondwanan active plate margin during the Lower Paleozoic.

4. Paired metamorphic belts revisited

4.1. Historical perspective

Miyashiro (1961) classified metamorphic belts into one of three metamorphic facies series types, with two intermediate groups, in

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order of increasing pressure as follows: andalusite–sillimanite type, low-pressure intermediate group, kyanite–sillimanite type, high-pressure intermediate group, and jadeite–glaucophane type. Subsequently, Miyashiro (1973) related each of the three main types to an average geothermal gradient (>25 °C km^{-1}, ~20 °C km^{-1} and ~10 °C km^{-1}, respectively). It is noteworthy that Miyashiro (1961) perspicaciously observed (in relation to secular change), "… regional metamorphism under higher rock pressures appears to have taken place in later geological times."

In Japan and other parts of the circum-Pacific region, there is a spatial relationship between metamorphic belts of the andalusite–sillimanite type and/or low-pressure intermediate group (low-*P*/*T* type) and metamorphic belts of the jadeite–glaucophane type and/or high-pressure intermediate group (high-*P*/*T* type) as they are located side-by-side. This spatial arrangement of metamorphic belts of apparently similar age led Miyashiro to the idea that metamorphic belts develop as a pair (Miyashiro, 1961).

The introduction of the plate tectonics paradigm in the late 1960s led to the development of models for regional metamorphism and to an understanding of the temporal change of *P*–*T* conditions during the evolution of metamorphic belts. Formation of 'paired' metamorphic belts was thought to be a result of underthrusting of an oceanic plate beneath an island arc or continental margin (Oxburgh and Turcotte, 1970; Ernst, 1971; Miyashiro, 1972), and Oxburgh and Turcotte (1971) demonstrated that paired metamorphic belts were the manifestation of thermal perturbations due to elevation of the geotherm in arcs (high d*T*/d*P* metamorphism) and depression of the geotherm in trenches (low d*T*/d*P* metamorphism).

Metamorphic belts became viewed as part of a dynamic Earth, in which supracrustal rocks are taken to depth, metamorphosed and exhumed (e.g. Brown, 1993; Brown and O'Brien, 1997). A metamorphic belt no longer could be considered characterized by a single geothermal gradient, because the thermal history must record evolution across a range of geotherms with time. The trajectory in *P*–*T* space followed by a particular volume of the metamorphic belt during some interval of time is a *P*–*T* path. *P*–*T* paths within a nested set of common origin intersect Earth's surface to generate the metamorphic field gradient (MFG), along which successive mineral assemblages define the metamorphic facies series. The MFG is diachronous, being younger at higher grade, as was pointed out by England and Richardson (1977). In effect, the exemplar *P*–*T* trajectories shown by Miyashiro (1961, his fig. 4) represent MFGs.

During the 1970s and 1980s our understanding of processes that occur along convergent plate margins increased dramatically to include the realization that spreading ridge systems ultimately interact with trenches during the subduction process (DeLong and Fox, 1977), the concept of accretion of allochthonous terranes (Schermer et al., 1984), the recognition of orogen-parallel stretching (Toriumi, 1985; Ellis and Watkinson, 1987), and an awareness that plate convergence typically is oblique, leading to transpressive/transtensive deformation and slip partitioning in orogenic belts formed at convergent plate margins (McCaffrey, 1992). Modeling of the thermal effects of subduction of young oceanic lithosphere and an active ridge by DeLong et al. (1979) and Molnar and England (1995) led to questions about the validity of the classic idea that 'paired' metamorphic belts formed *in situ* (Brown 1998a,b). In particular, if a high d*T*/d*P* metamorphic belt records the thermal effects of ridge subduction and slab window formation, then it is likely that the adjacent low d*T*/d*P* metamorphic belt was accreted after the interaction between ridge and trench (Brown, 2002). Furthermore, it is implicit in the plate tectonics paradigm that bathymetric highs of sufficient size within ocean basins eventually must collide with an upper plate in the trench, where the ultimate fate of these features will be decided by their relative buoyancy (e.g. Nur and Ben-Avraham, 1983; Cloos, 1993; Collins, 2002b).

Because of the processes summarized above, allochthonous terranes and microplates may form along active continental margins (Nelson et al., 1994; Stock and Lee, 1994), and may be transported along active continental margins (Jarrard, 1986; Beck, 1991; Irving et al., 1996; Cowan et al., 1997; Johnston, 2001). Thus, tectonic units such as volcanic arcs, forearc basins and subduction complexes may be extensive along a continental margin, but these units may not have formed in their present position, and caution must be exercised in applying plate tectonics models that assume tectonic units presently juxtaposed were genetically related or were formed as presently configured (e.g., Jones et al., 1983; Glen et al., 2009).

It is perhaps surprising that an essentially static concept like the *in situ* formation of 'paired' metamorphic belts has survived the terrane revolution. These parallel metamorphic belts of different type are more likely to have been contemporaneous lateral equivalents that have been juxtaposed due to trench-parallel translations during oblique subduction.

Miyashiro did recognize the importance of the major mylonite zone separating the classic 'paired' metamorphic belts of southwest Japan, but he interpreted it to be a younger structure (Miyashiro, 1961), and although lateral translation of terranes had not been recognized when he considered the Mesozoic–Cenozoic plate tectonics evolution of the Japanese Islands (Uyeda and Miyashiro, 1974), the trench-parallel ridge subduction invoked is similar to that posited by Brown (1998a,b). Given the importance of the 'paired' metamorphic belts of southwest Japan in the history of metamorphic geology, in the next section I deal with this example in some detail.

4.2. Southwest Japan

In southwest Japan, the high d*T*/d*P* Ryoke metamorphic belt is juxtaposed against the low d*T*/d*P* Sanbagawa metamorphic belt along the Median Tectonic Line (MTL; Fig. 1). A recent multi-purpose seismic experiment along a more-than-240-km-long line from the Pacific coast to the Japan Sea coast provides the first crustal-scale cross section across southwest Japan (Ito et al., 2009). This experiment revealed that southwest Japan is composed of two completely different crustal units juxtaposed by the MTL, supporting the earlier interpretation of Kawamura et al. (2003) based on a less extensive seismic experiment.

The MTL started its activity associated with lower crustal thinning and formation of an upper crustal half-graben (Ito et al., 2009), which is evidenced by the Upper Cretaceous forearc basins of the Izumi belt that are unconformable on the Ryoke belt (Fig. 1; Ichikawa, 1980; Miyata, 1980; Taira et al., 1983; Kodama, 1989). The MTL has a complex history of syn-peak to retrograde metamorphic lateral displacements since its birth (Ichikawa, 1980; Miyata, 1980; Taira et al., 1983; Kodama, 1989; Ohtomo, 1993; Ito et al., 1996), but the net displacement probably reached several hundreds of kilometers in a left-lateral sense (Yamakita and Otoh, 2000; Sakashima et al., 2003; Takagi and Arai, 2003), which most likely reflects terrane displacement and juxtaposition of the Sanbagawa belt against the Ryoke belt.

North of the MTL is the granite province of southwest Japan, which is subdivided into the Ryoke, the San-yo and the San-in zones, respectively, from the MTL to the Japan Sea (Fig. 1). The ilmenite/magnetite series line (Ishihara, 1997) separates ilmenite-bearing plutons of Cretaceous age in the Ryoke and San-yo belts from magnetite-bearing plutons of Cretaceous to Paleogene age in the San-in belt. To the southeast, outboard of the Sanbagawa belt, are the Northern and Southern Chichibu belts, separated by the Kurosegawa tectonic zone (KTZ), which represents the disrupted remnants of a Paleozoic terrane (Aitchison et al., 1991; Kato and Saka, 2003), and further southeast across the Butsuzo tectonic line is the Northern Shimanto belt (Fig. 1).

4.2.1. The Ryoke belt

High d*T*/d*P* metamorphism of the Ryoke belt was superimposed on low-grade rocks of the Mino–Tanba belt, which is a Jurassic accretionary complex (Takami and Itaya, 1996; Takeuchi and Wang, 1999) with a

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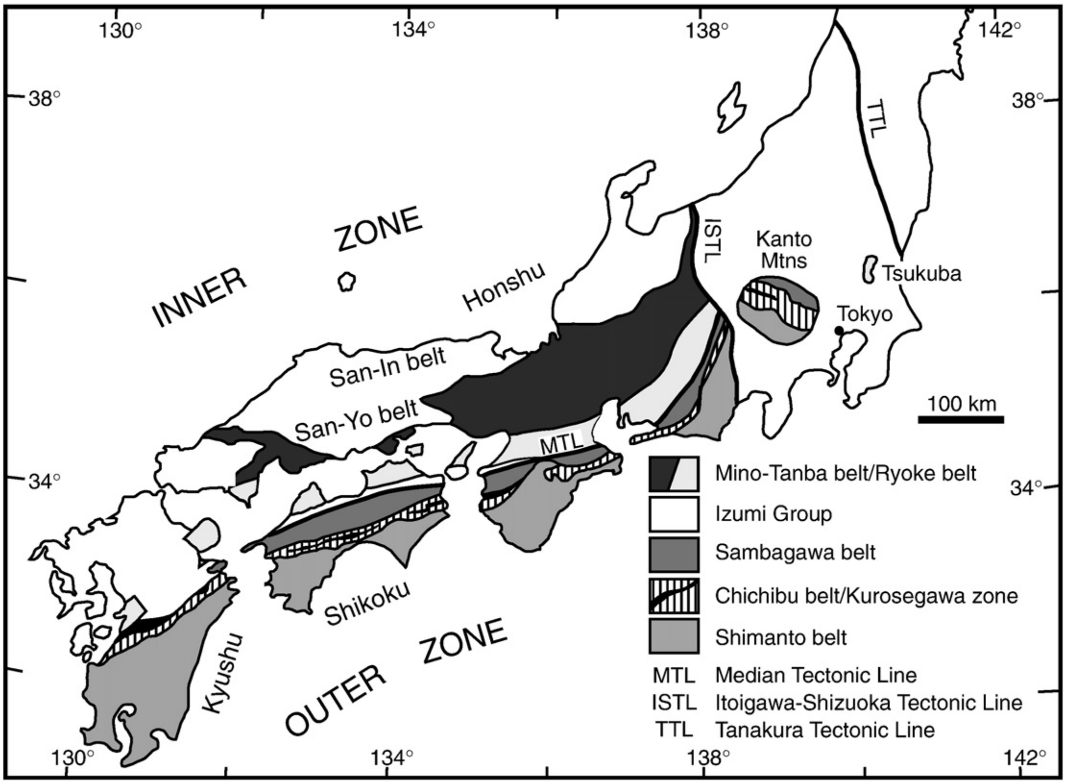

Fig. 1. Geological map of southwest Japan to show in particular the spatial arrangement of the Ryoke and Sanbagawa metamorphic belts, the Izumi Group and the Median Tectonic Line (MTL).

basement that is distinct from the adjacent Sanbagawa belt (Kagami et al., 2000; Okano et al., 2000; Ito et al., 2009). The Mino–Tanba belt has been divided into three units, separated by tectonic boundaries, which have different features of lithology, fossil age, metamorphic grade and K–Ar age. Microfossil evidence suggests that accretion occurred in Lower Jurassic, early-Middle Jurassic and Upper Jurassic, whereas K–Ar ages inferred to date mica growth indicate that deformation and metamorphism extended to *ca.* 23 Ma after accretion with ages of 134–122 Ma in the lower structural unit recording the last subduction-related event (Takami and Itaya, 1996).

In the Ryoke belt, the metamorphic foliation is generally subparallel to lithological layering, which is folded into tight-to-isoclinal folds with subhorizontal belt-parallel hinge lines (Okudaira and Beppu, 2008; Okudaira et al., 2009). Peak metamorphic conditions were about 850 °C at 0.5 GPa, and regional-scale migmatites were generated by mica-breakdown melting (Brown, 1998a). The metamorphism follows tight clockwise 'hairpin' P–T paths defining a low dT/dP metamorphic field gradient concave towards the temperature axis in P–T space (Brown, 1998a), and neither the P–T path nor the metamorphic field gradient correspond to transient geotherms at any point during the metamorphic evolution. The age of the thermal peak of the superimposed Ryoke belt metamorphism is suggested to have been *ca.* 100 Ma along the length of the belt, based on chemical ages of monazite from samples from the high-grade metamorphic zones (Suzuki et al., 1996; Suzuki and Adachi, 1998).

In western parts of the Ryoke belt, the age span of granite crystallization, based on chemical ages of monazite, is *ca.* 100–80 Ma, whereas towards the east in central Japan the granites were emplaced over a longer period of *ca.* 100–70 Ma (Nakai and Suzuki, 1996; Suzuki and Adachi, 1998). ID-TIMS U–Pb dating of zircon from Yashiro-jima, near Yanai in the west, yields ages of 96.2 ± 3 and 95.3 ± 1 Ma for the Kita-Oshima and Gamano granites, respectively, overlapping the chemical age of monazite of 95.2 ± 3.9 Ma for the Gamano granite (Suzuki et al., 1994). SHRIMP U–Pb dating of zircon from granites in the eastern Ryoke belt suggests crystallization ages for Ryoke granites of *ca.* 85 Ma, although there are also younger two-mica granites that yield ages in the range 85–70 Ma (Nakajima, 1996; Watanabe et al., 2000). The pattern of magmatism is clearly not a simple one and further geochronological studies are required to unravel the spatial and temporal evolution of granite genesis and emplacement (Watanabe et al., 2000; Yuhara et al., 2000).

Mineral ages (K–Ar hornblende, Rb–Sr/K–Ar biotite and K–Ar K-feldspar) from metamorphic rocks and granites young systematically eastward along the belt and northward across-belt. For example, the biotite K–Ar age data compiled and evaluated by Kinoshita (1995, 1999) indicate cooling through ~300 °C at *ca.* 90 Ma in the western part of the belt and *ca.* 70 Ma in the east, from which a rate of migration of cooling through the ~300 °C isotherm of ~30 km Myr^{-1} may be calculated (Kinoshita, 1999). Fission track ages determined from zircon and apatite in the western part of the belt yield *ca.* 90–70 and *ca.* 60 Ma, respectively (Kamp and Takemura, 1993; Okudaira et al., 2001), whereas towards the east in central Japan fission track ages on zircon and apatite are 65–55 Ma and *ca.* 50 Ma, respectively (Tagami et al., 1988). These data yield smooth T–t curves, which suggest initially fast rates of cooling of ~40 °C Ma^{-1}, declining to 10–5 °C Ma^{-1} with decreasing temperature, with faster cooling in the west than in the east (Suzuki and Adachi, 1998; Yuhara et al., 2000; Okudaira et al., 2001).

Overall, the chronological data imply that synchronous peak metamorphism along the length of the Ryoke belt was followed by diachronous cooling from southwest to northeast. This pattern has been interpreted to record diachronous exhumation from southwest to northeast at a decreasing rate with time (Brown, 1998a). Whatever the cause of exhumation, the event also was time transgressive, progressing from southwest to northeast.

Southwest Japan formed part of the Eurasian continental margin before the rigid-body rotation of the Japanese islands associated with the Miocene opening of the Japan Sea. Palaeomagnetic studies show

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that the rotation of Japan can be described by a clockwise rigid-body rotation of 45–50° and age data constrain this rotation to have taken place during the last twenty million years (Otofuji and Matsuda, 1987). Restoring the Japanese islands to their pre-Miocene configuration results in a roughly north-northeast–south-southwest orientation of the Ryoke and Sanbagawa metamorphic belts along the Eurasian continental margin.

Although the plate geometry and plate motion vectors in the Pacific Ocean basin close to the Eurasian continental margin during the Cretaceous may be derived with some certainty from the pattern of sea floor magnetic anomalies and bathymetry (e.g., Engebretson et al., 1985), the position of former plate boundaries that were lost by subduction is subject to large uncertainties. Therefore, which of the several plates in the Pacific Ocean basin was subducting beneath the Japanese sector of the Eurasian continental margin during most of the Cretaceous cannot be constrained with certainty; before *ca.* 85 Ma it was probably the Farallon or Izanagi plate and after *ca.* 85 Ma the Pacific plate (Cox et al., 1989; Wallis et al., 2009). During the Lower Cretaceous, the boundary between the Farallon and Izanagi plates is thought to have been a spreading ridge system (Engebretson et al., 1985), which probably interacted with the trench along the Eurasian continental margin during the late Lower Cretaceous.

Although the motion of the Farallon and Izanagi plates compared with Asia is known (Cox et al., 1989), the orientation of the system of ridges and transforms that formed a boundary between them is not well constrained and the ridge segment/transform segment lengths along the boundary are unconstrained. Based on the synchronous age of peak metamorphism along the length of the Ryoke belt (~1000 km), Brown (1998a,b) posited that the ridge was likely to have been subparallel to the trench and composed of one or several long segments. The vector for the Farallon plate from 115 to 100 Ma was close to orthogonal with respect to the Eurasian continental margin whereas that for the Izanagi plate indicates a strong component of left-lateral oblique convergence (Engebretson et al., 1985; Wallis et al., 2009) consistent with the evidence of sinistral transpressive deformation recorded by the rocks during exhumation (Toriumi, 1985).

4.2.2. The Izumi belt

In Shikoku and eastward along the MTL, the Izumi belt forearc basins existed from Campanian to Maastrichtian time (Taira et al., 1983). These basins were filled with sediment supplied mostly from the north, which comprised mainly clastic material derived from felsic to intermediate volcanic and granitic sources with a minor sedimentary and metamorphic component (Teraoka et al., 1998). No detritus from the Sanbagawa belt has been identified in Izumi belt rocks (Ichikawa, 1980; Teraoka et al., 1998), even though $^{40}Ar/^{39}Ar$ mineral age data and fission track ages on zircon from the Sanbagawa belt indicate cooling at about 10 °C Myr^{-1} during the Late Cretaceous–Paleocene, which data suggest exhumation was occurring contemporaneously with filling of the forearc basins (Isozaki and Itaya, 1990; Takasu and Dallmeyer, 1990; Dallmeyer and Takasu, 1991; Takasu and Dallmeyer, 1992Shinjoe and Tagami, 1994). The lack of any Sanbagawa detritus within the now proximal Izumi belt rocks suggests significant palinspastic separation of the Sanbagawa belt from the Ryoke belt at the time the unconformable Izumi belt rocks were deposited. The diachronous nature and decreasing rate of cooling of rocks within the Ryoke belt from southwest to northeast is consistent with the sequential younging from southwest to northeast of sedimentation within the Izumi belt forearc basin depocenters, which is inferred to reflect erosion of Ryoke belt rocks as they are progressively exhumed from southwest to northeast (Brown, 2002).

4.2.3. The Sanbagawa belt

The Sanbagawa and Northern Chichibu belts, which are dominated by low d*T*/d*P* metamorphism, are sandwiched between the adjacent (overlying) Ryoke belt, juxtaposed along the MTL, and the adjacent (underlying) Southern Chichibu (Sanbosan) belt, juxtaposed along the KTZ; outboard of these elements, juxtaposed along the Butsuzo Tectonic Line, is the Northern Shimanto belt (Taira et al., 1983; Yamakita and Otoh, 2000). Both the MTL (Miyata, 1980; Ichikawa, 1980; Taira et al., 1983; Ohtomo, 1993) and the KTZ (Taira et al., 1983; Yamakita and Otoh, 2000; Kato and Saka, 2003) are zones of left-lateral strike–slip displacement. Along the Butsuzo Tectonic Line (BTL) the Chichibu and Sambagawa belts are thrust over the Northern Shimanto belt.

The dominant structural features in the Sanbagawa belt metamorphic rocks are a northward-dipping foliation, generally parallel to lithological layering, and an east–west subhorizontal mineral elongation lineation. This main fabric was not formed during prograde metamorphism but rather was imposed by ductile orogen-parallel flow associated with viscous thinning during retrograde metamorphism and the early stage of exhumation (Faure, 1983; Wallis et al., 1992; Wallis, 1995; Osozawa and Pavlis, 2007). The orogen-parallel flow suggests that plate movement was oblique to the plate margin, consistent with a terrane model and the predicted plate motion vector of the Izanagi plate during the early Upper Cretaceous (Engebretson et al., 1985; Cox et al., 1989; Brown, 1998a,b, 2002; Wallis et al., 2009).

A metamorphic inversion is present in central Shikoku, which has been explained by south-closing (Banno et al., 1978) or north-closing recumbent folding (Wallis et al., 1992), juxtaposition of nappes by thrusting (Hara et al., 1980) and wedge extrusion by contemporaneous normal (structurally higher) and thrust (structurally lower) faulting (Maruyama et al., 1996; Yamamoto et al., 2004; Ota et al., 2004; Masago et al., 2005; Terabayashi et al., 2005; Fukunari and Wallis, 2007; Osozawa and Pavlis, 2007; Aoki et al., 2008). The first stage of exhumation may have been triggered by the approach of the Izanagi–Pacific ridge to the trench (Wallis et al., 2009), whereas the transition from extrusion by ductile orogen-parallel flow to brittle orthogonal extrusion has been related to subduction of the ridge (Osozawa and Pavlis, 2007).

Early petrological studies of Sanbagawa schists indicated that peak temperature occurred after peak pressure in the higher-grade metamorphic zones of the belt, resulting in clockwise *P*–*T* paths. This conclusion was based on results of numerical modeling of chemical zonation in garnet (Enami, 1998), change in amphibole composition in hematite-bearing mafic schists (Otsuki and Banno, 1990) and chemical zoning in pyroxene (Enami et al., 1994). In contrast, some more recent results of thermodynamic modeling of chemical zoning in amphibole and garnet indicate that the metamorphic evolution may have involved simultaneous heating and increase of pressure followed by cooling after the metamorphic peak, yielding counterclockwise *P*–*T* paths (e.g., Wintsch et al., 1999; Banno, 2000; Okamoto and Toriumi, 2001, 2005; Inui and Toriumi, 2002; Okamoto and Toriumi, 2005). Peak *P*–*T* conditions in all of these studies are similar (around 1 GPa at ~500 °C), but the samples are taken from different localities within central Shikoku.

This disparity in *P*–*T* paths may be due to variations in thickness of units during subduction, consistent with structural features of the Sanbagawa belt, particularly metamorphic discontinuities at outcrop to map scales identified on Shikoku and eastwards (Wallis, 1998; Osozawa and Pavlis, 2007). Modeling by Aoya et al. (2002) shows that when the accreted unit is several kilometers thick, post-accretion heating occurs due to the spatial shift of the subduction boundary and rocks follow clockwise *P*–*T* paths. In contrast, units less than one kilometer thick have a decreased potential for post-accretion heating and cannot maintain high temperature during exhumation leading to counterclockwise *P*–*T* paths.

Although eclogites associated with the schists preserve complex metamorphic histories (Takasu, 1989), both the eclogites and intercalated metapelites generally yield similar maximum *P*–*T* conditions much higher than the schists, around 1.8–2.0 GPa and 600–650 °C (Aoya

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et al., 2003; Matsumoto et al., 2003; Ota et al., 2004; Zaw et al., 2005; Endo et al., 2009), although both slightly lower (Aoki et al., 2008, 2009) and higher (Enami et al., 2004) *P–T* conditions also are reported. $^{40}Ar/^{39}Ar$ isotope correlation ages for amphibole in the range 96–87 Ma from the Western Iratsu and Seba eclogites were inferred to date the timing of peak metamorphism (Takasu and Dallmeyer, 1990; Dallmeyer and Takasu, 1991). However, recent garnet–omphacite Lu–Hf isochron dating of the Seba and Kotsu eclogites by Wallis et al. (2009) yielded ages of 89–88 Ma, consistent with an age for metamorphic rims on zircon of ca. 86 Ma from pelitic schists exposed along the Asemi-gawa (Aoki et al., 2009), which suggests that timing of peak metamorphism in the Sanbagawa belt may be *ca.* 10 Ma younger than that in the Ryoke belt.

In the Western Iratsu eclogite, an earlier episode of upper amphibolite facies metamorphism is registered at 120–110 Ma, based on SHRIMP U–Pb zircon ages (Okamoto et al., 2004) and garnet–omphacite Lu–Hf isochron ages of *ca.* 116 Ma (Endo et al., 2009). Also, older $^{40}Ar/^{39}Ar$ isotope correlation or plateau ages for amphibole (ca. 157 and ca. 131 Ma, Takasu and Dallmeyer, 1992; ca. 117 and ca. 103 Ma, Nuong et al., 2009) and white mica (ca. 116 and ca. 109 Ma, Takasu and Dallmeyer, 1992) have been reported from clasts with the Kuma Group, an Eocene unit that overlies unconformably the Sanbagawa belt in central Shikoku. These older ages may indicate local preservation of evidence for more than one tectonic event in the early evolution of the Sanbagawa subduction zone.

Based on a spatially-limited dataset of $^{40}Ar/^{39}Ar$ mineral ages from the Sanbagawa schists, exhumation of the belt may have been diachronous along the length of the orogen (Takasu et al., 1996). The diachronous nature and decreasing rate of cooling of rocks within the Ryoke belt from southwest to northeast is consistent with subduction docking of a Sanbagawa terrane against and under the Ryoke belt to drive progressive exhumation of that belt (Brown, 1998a,b). Docking of the Sanbagawa terrane was driven by the left-lateral oblique convergence of the Izanagi plate after subduction of the Farallon–Izanagi ridge under the Ryoke belt. This is consistent with structural evidence from the Sanbagawa belt—the obliquity of the stretching direction and the sinistral sense of shear with respect to the Eurasian continental margin—which implies movement of the subducting plate from the southwest to northeast (Wallis et al., 2009, and references therein).

The model of diachronous terrane emplacement implies that the main evolution of the Sanbagawa belt occurred at a different location along the proto-Pacific margin compared to that of the Ryoke belt. It is possible that variable ages, peak metamorphic conditions and *P–T* paths in the Sanbagawa belt relate to more than one tectonic event in the early evolution of the Sanbagawa subduction zone, and that a polyphase history is responsible for the ambiguity over the age of peak metamorphism in the Sanbagawa belt.

A second ridge subduction event—the Izanagi–Pacific ridge—may have been responsible for the final imprinted thermal structure and initial exhumation of the Sanbagawa belt (Aoya et al., 2003; Uehara and Aoya, 2005; Osozawa and Pavlis, 2007; Wallis et al., 2009), but after *ca.* 85 Ma the vector for the Pacific plate suggests subduction was close to orthogonal with respect to the Eurasian continental margin (Engebretson et al., 1985; Wallis et al., 2009). Wallis et al. (2009) posit that fast exhumation of Sanbagawa belt eclogites and schists allowed them to avoid strong thermal overprinting during ridge subduction. If correct, this model of Sanbagawa evolution precludes those models for the Ryoke metamorphism and Upper Cretaceous plutonism based on syn- or post-Sanbagawa metamorphism opening of a slab window (Iwamori, 2000, 2002; Iwamori et al., 2007; Aoya et al., 2009), since metamorphism in the Ryoke belt occurred prior to exhumation of the Sanbagawa belt.

4.2.4. 'Paired' metamorphic belts in southwest Japan

Based on a similar pattern of strain in Ryoke and Sanbagawa belt rocks, it has been proposed that the main peak-to-retrograde metamorphic deformation of both belts occurred during exhumation within a single tectonic framework (Toriumi, 1985). The predominantly constrictional strain is consistent with orogen-parallel stretching and the top-to-the-west sense of shear (Adachi and Wallis, 2008) indicates sinistral displacement on the MTL. These observations support amalgamation of the Ryoke and Sanbagawa belts by left-lateral displacement along the MTL during the Upper Cretaceous, driven by oblique subduction of the Izanagi plate under the Eurasian continental margin (Cox et al., 1989; Brown, 1998b; Wallis et al., 2009). Such a model is consistent with the different crustal structure across the MTL, the close but different ages of peak metamorphism in the Ryoke and Sanbagawa belts and diachronous exhumation as discussed above, features that are not explained by *ad hoc* models that ignore lateral displacements of terranes (e.g., Iwamori, 2000, 2002; Iwamori et al., 2007; Aoya et al., 2009).

Whether exhumation of the Sanbagawa metamorphic rocks was due to increased coupling of plates and orogen-normal stress associated with collision of an actively-spreading ridge, followed by oblique subduction, as was proposed by Osozawa and Pavlis (2007) is an open question. However, if the plates involved were the Izanagi and Pacific plates, respectively, as suggested by Wallis et al. (2009), then the motion of the Pacific plate with respect to a restored Japan along the Eurasian continental margin was close to orthogonal (Engebretson et al., 1985), which implies that oblique subduction is not a requirement of wedge extrusion, consistent with the modeling of Iwamori (2000, 2002; Iwamori et al., 2007).

Exhumation of the Sanbagawa belt appears to have been contemporaneous with rapid late Upper Cretaceous growth of the Shimanto accretionary complex. The eroded remnants of an inferred Kuma nappe are found in the Eocene Kuma Group conglomerates that overlie unconformably the Sanbagawa belt in western Shikoku (Yokoyama and Itaya, 1990; Takasu and Dallmeyer, 1992), and the KTZ is overlain unconformably by unmetamorphosed fluvial and shallow marine sedimentary rocks of Lower Cretaceous age (Maruyama, 1981). These features suggest the main displacement along the KTZ predated that along the MTL, and that accretion and exhumation of the Sanbagawa and Chichibu belts occurred as a single tectonic unit. Final exhumation must have post-dated ridge subduction under both the Ryoke (Farallon–Izanagi ridge) and Sanbagawa (Izanagi–Pacific ridge) belts, and most likely was a consequence of the rapid growth of the Shimanto accretionary complex.

As discussed above, before the Miocene the Japanese Islands were part of the Eurasian continent, and the plate tectonics evolution of southeast Japan cannot be discussed in isolation from that of the whole Eurasian continental margin. The terrane model of Brown (1998a,b) was developed in the wider context of explaining the slightly older metamorphism and magmatism of the Abukuma belt and the evolution of the Kitakami batholith in northeast Japan, as well as the Upper Cretaceous evolution of southwest Japan.

On Hokkaido (Japan) and in Sakhalin to the north, the Kamuikotan and Susunai low d*T*/d*P* metamorphic belts lie outboard of the Lower Cretaceous Kitakami Batholith (northeast Japan) and the Cretaceous plutonic province of Sikhote Alin on the Eurasian mainland (Kimura, 1994). It is likely that these metamorphic belts also have been translated by left-lateral displacement along the Eurasian continental margin. Orogen-parallel strain in forearcs is sufficient to produce geologically significant effects, such as exhumation of high d*T*/d*P* metamorphic rocks during arc-parallel extension and disruption of transported forearc terranes (McCaffrey, 1996). The time between peak metamorphism in the Ryoke belt (*ca.* 100 Ma), which presumably post-dates subduction of the Farallon–Izanagi ridge at a trench outboard of the Mino–Tanba belt, and subduction of the Izanagi–Pacific ridge at a trench outboard of the Sanbagawa belt (*ca.* 85 Ma), which Wallis et al. (2009) argue post-dates peak *P–T* in the Sanbagawa eclogites, represents the minimum period of highly oblique left-lateral transpression related to subduction of the Izanagi

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plate. Hundreds to possibly several thousand kilometers of left-lateral displacement likely occurred along the Eurasian continental margin during this interval of time (Yamakita and Otoh, 2000; Sakashima et al., 2003). Thus, the Susunai, Kamuikotan and Sanbagawa belts are likely to have been displaced along the MTL from a position south-southwest of the Japanese sector of the Eurasian continental margin to their present locations by the late Upper Cretaceous.

5. The wider view

The signature of subduction is recognized with some confidence in the Phanerozoic continental geological record, and, at a minimum, we may extend the plate tectonics paradigm back to the beginning of the Cambrian. Evidence for plate tectonics in the Precambrian continental geological record is less complete and sometimes may be ambiguous. However, the different types of metamorphic facies series recognized by Miyashiro (1961) and the occurrence of 'paired' metamorphic belts are generally regarded as evidence of subduction (Matsuda and Uyeda, 1971; Oxburgh and Turcotte, 1971; Miyashiro, 1972, 1973). In this wider view, we will examine the continental geological record of metamorphism to evaluate the duality of thermal regimes implied by the concept of 'paired' metamorphic belts and the role of plate tectonics during Earth history.

5.1. The classification of metamorphic belts

Miyashiro used the metamorphic field gradients determined for a limited number of metamorphic belts to place each of them into one of his five types of metamorphism based on increasing pressure (Miyashiro, 1961, his fig. 4). The concept of grouping metamorphic belts by pressure is a useful one. However, the lower grade and/or prograde history of many higher-temperature belts commonly is not recorded. For this reason, in this review I use apparent thermal gradient defined by close-to-peak P–T conditions for classification rather than metamorphic field gradients.

As with Miyashiro's approach, the resulting classification into high dT/dP (synonymous with low-P–high-T or LP–HT), intermediate dT/dP (similar to 'Barrovian') and low dT/dP (synonymous with high-P–low-T or HP–LT) metamorphism coincides with major changes in facies series. These three types of metamorphism culminate in (Fig. 2): granulite and ultrahigh temperature metamorphism (G-UHTM; Harley, 1998; Brown, 2007; Harley, 2008; Kelsey, 2008); eclogite–high-pressure granulite metamorphism (E-HPGM; O'Brien and Rötzler, 2003; Brown, 2007); or, high pressure and ultrahigh pressure metamorphism (HPM–UHPM; Chopin, 2003; Liu et al., 2007; Brown, 2007). In this review, the diagnostic minerals or assemblages or robustly-determined P–T conditions definitive of each of type of metamorphism (G-UHTM, E-HPGM and HPM–UHPM) are the same as those specified by Brown (2007) and they are not repeated here. Metamorphic rocks of each type register the imprint of different thermal environments in the geological record (Fig. 3), each with a characteristic range of dT/dP or apparent thermal gradient (Brown, 2006, 2007, 2008).

This simple approach to the geological record of metamorphism may appear incompatible with the dynamic nature of the processes involved and the complexity of evolution implied by the discussion of orogenic systems. However, prograde metamorphism involves dehydration and melting of (mostly fertile) supracrustal and upper crustal protoliths leading ultimately at high to ultrahigh pressures and temperatures to nominally anhydrous mineral assemblages that are generally robust recorders of pressure and temperature and that are difficult to retrogress or overprint without fluid influx. Furthermore, some (ultra-) high pressure metamorphic rocks overprinted during exhumation may preserve close-to-peak phase assemblages as inclusions in rock-forming or accessory minerals, particularly zircon. For these reasons, the analysis below is limited to crustal metamorphism under conditions of extreme pressure, pressure–temperature or temperature, and the complexities of orogenic evolution are reduced effectively to background 'noise'.

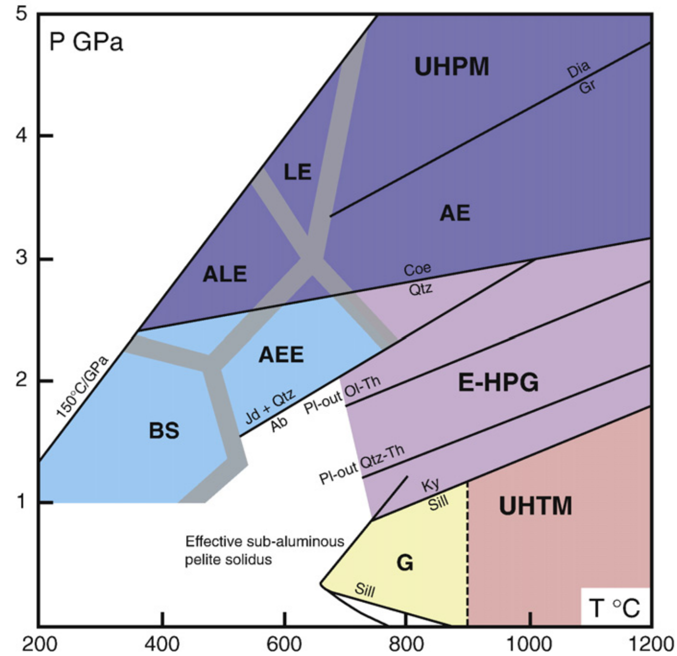

Fig. 2. P–T diagram to show the P–T location of selected metamorphic facies and P–T ranges of different types of metamorphism. HPM–UHPM includes the following: BS = blueschist facies, AEE = amphibole-epidote eclogite facies, ALE = amphibole-lawsonite eclogite facies, LE = lawsonite eclogite facies, AE = amphibole eclogite facies, UHPM = ultrahigh-pressure metamorphism. E-HPG = medium temperature eclogite–high pressure granulite metamorphism. G = granulite facies metamorphism, whereas UHTM = the ultrahigh-temperature metamorphic part of the granulite facies.

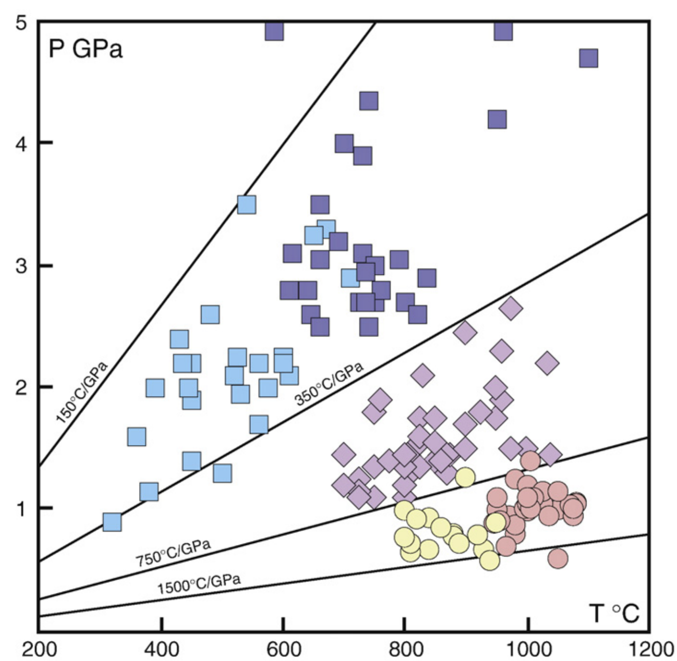

Fig. 3. Metamorphic patterns based on representative 'peak' metamorphic P–T conditions of about 140 metamorphic belts in relation to thermal gradients. Granulite and ultrahigh temperature metamorphism — G-UHTM belts (P at maximum T; circles — data from tables 1 and 2 of Brown, 2007); medium temperature eclogite–high-pressure granulite metamorphism — E-HPGM belts (peak P–T; diamonds — data from table 3 of Brown, 2007); lawsonite blueschists–lawsonite eclogites and ultrahigh pressure metamorphic rocks — HPM–UHPM belts (T at maximum P; squares — data from tables 4 and 5 of Brown, 2007).

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5.2. Metamorphism and secular change

In this section, we will examine the continental geological record of metamorphism. However, before we proceed there are a number of caveats to consider (cf. Brown, 2007). Metamorphic imprints record discrete 'events' (subduction boundary migration, kinematic, ridge–trench interactions or subduction-to-collision) whereas subduction is globally 'continuous' (at least on a timescale shorter than the supercontinent cycle). We must also be aware of possible bias in the continental geological record. It is commonly argued that going back through time increases loss of information by erosion of the older record. However, the data in Brown (2007) plot in particular periods (discussed below) and there is a clear distinction, for example, between the period before the Neoproterozoic Era, where UHPM does not occur, and the period from the Neoproterozoic Era through the Phanerozoic Eon, where UHPM is common. This observation is inconsistent with a progressively degraded record with increasing age. However, it is true that the record of crustal metamorphism is a function of what is preserved or exhumed. If the preservation potential of some types of metamorphic rock was poor or if exhumation of some types of metamorphic rock was not possible earlier in Earth history, then the record may be biased.

In some cases the record of crustal metamorphism may be the result of overprinting of one or more younger orogenic events on an older orogenic evolution, leading to polymetamorphism that must be avoided where ever possible or where present or suspected must be distinguished (e.g. Hensen and Zhou, 1995; Hensen et al., 1995). Overprinting has been avoided in compiling the dataset used for this analysis (Brown, 2007). Lastly, in evaluating secular change in the patterns of metamorphism it is essential to use precise *P*–*T* and age (*t*) relations. The *P*–*T* conditions should be assessed based on robust thermobarometry or at a minimum by the presence of a diagnostic mineral assemblage in an appropriate bulk composition and oxidation state, and the age should be determined using a robust chronometer and should be related to a specific *P*–*T* point along the *P*–*T*–*t* evolution, if possible, close to peak *P*–*T*.

5.2.1. Metamorphism since the Neoarchean Era

I review the geological record of metamorphism since the Neoarchean Era in relation to the following typology using the dataset from Brown (2007). Metamorphic belts are classified into three types. G-UHTM is characterized by granulite facies series rocks that may reach ultrahigh-temperature metamorphic conditions (Fig. 2), where the pressure plotted in Fig. 3 is that registered at maximum temperature. E-HPGM is characterized by facies series that reach peak *P*–*T* in the eclogite–high-pressure granulite facies (Fig. 2; O'Brien and Rötzler, 2003), where maximum pressure and temperature generally are achieved sequentially, but close enough to be considered as contemporaneously for this analysis. HPM–UHPM is characterized by lawsonite blueschist to lawsonite eclogite facies series rocks and blueschist to eclogite to ultrahigh-pressure facies series rocks (Fig. 2), where the temperature plotted in Fig. 3 is that registered at maximum pressure.

The *P*–*T* value for each of about 140 metamorphic belts shown in Fig. 3 records a point on a metamorphic (transient) geotherm, and different apparent thermal gradients are implied by each type of metamorphism. These apparent thermal gradients are inferred to reflect different tectonic settings. G-UHTM is characterized by apparent thermal gradients ≫750 °C/GPa (≫20 °C/km); many of these terranes probably require an advective component of heating (Brown, 2008). E-HPGM is characterized by apparent thermal gradients of 350–750 °C/GPa (approximately equivalent to 10–20 °C/km). For these terranes heating may be a conductive response to thickening; they appear to record the process of subduction-to-collision orogenesis (Brown, 2008). HPM–UHPM is characterized by apparent thermal gradients of 150–350 °C/GPa (approximately equivalent to 4–10 °C/km). We know from the global context that these HPM-UHPM terranes were associated with subduction (Brown, 2008).

Fig. 4 illustrates apparent thermal gradient, which is inferred to relate to tectonic setting, plotted against age of peak metamorphism. Each type of metamorphism has a distinct range of apparent thermal gradient, as anticipated from Fig. 3, and HPM–UHPM is restricted to the later part of the Neoproterozoic Era and the Phanerozoic Eon. However, what is now clear is the dual nature of the thermal regimes represented in the metamorphic record since the Neoarchean Era.

The period from the Neoarchean Era to the Neoproterozoic Era is characterized by G-UHTM and E-HPGM, whereas the period from late in the Neoproterozoic Era through the Phanerozoic Eon is characterized by HPM–UHPM and E-HPGM together with some examples of G-UHTM, although the latter occur only sporadically after the Cambrian Period. We might expect that the high d*T*/d*P* metamorphism would be of similar age or younger than the low to intermediate d*T*/d*P* metamorphism, since the later records the transition from subduction to collision whereas the former records inversion of a backarc basin (Hyndman et al., 2005b) or heating by radioactive decay in a thickened orogenic hinterland (Le Pichon et al., 1997; McKenzie and Priestley, 2008). At present we do not have data to test this prediction.

Analysis of the data in Fig. 4 provides a set of compelling first-order observations from which to argue that the modern era of ultra-low temperature subduction began in the Neoproterozoic Era, as registered by the occurrence of HPM–UHPM, but that ultra-low temperature subduction alone is not the hallmark of plate tectonics. In contrast, G-UHTM and E-HPGM are present in the exposed rock record back to at least the Neoarchean Era, registering a duality of thermal regimes, which has been argued to represent the hallmark of plate tectonics (Brown, 2006). Based on this observation, plate tectonics processes likely were operating in the Neoarchean Era as recorded by the imprints of dual types of metamorphism in the rock record, and this may manifest the first record of a global plate tectonics mode on Earth.

Changes in the metamorphic record broadly coincide with the transitions from the Archean to Proterozoic Eons and the Proterozoic to Phanerozoic Eons, and imply a different style of tectonics in the Archean Eon in comparison with the Proterozoic Eon and in the Proterozoic Eon in comparison with the Phanerozoic Eon. Overall, the restricted time span of different types of metamorphism through Earth history and the periods of metamorphic quiescence during the Proterozoic Eon suggest a link with the supercontinent cycle and major events in the mantle. These issues are discussed in more detail in Brown (2008, 2009).

5.2.2. Paired metamorphism since the Neoarchean

In accretionary orogens around the Pacific Ocean basin, Miyashiro (1961) recognized that rocks belonging to his andalusite–sillimanite type (or low-pressure intermediate group)—the high d*T*/d*P* type of metamorphism of this paper—and his jadeite–glaucophane type (or high-pressure intermediate group)—the low d*T*/d*P* type of metamorphism of this paper—had developed penecontemporaneously. The low d*T*/d*P* metamorphic belt is found outboard (the "outer metamorphic belt" of Miyashiro), closer to the trench, whereas the high d*T*/d*P* metamorphic belt lies inboard (the "inner metamorphic belt" of Miyashiro), well away from the trench, which led him to the conclusion that these belts had developed in common as a pair. He wrote "… I have always called such paired metamorphic belts metamorphic belts of Japan type, because they are most typically developed and most thoroughly investigated in Japan …"

Studies that are more recent have led to the general conclusion that such 'paired' metamorphic belts result from tectonic juxtaposition of terranes with different metamorphic facies series that may or may not be exactly contemporaneous and that may or may not be far-traveled (Brown, 1998a,b; Tagami and Hasebe, 1999; Brown, 2002). This is an inevitable consequence of the difference between

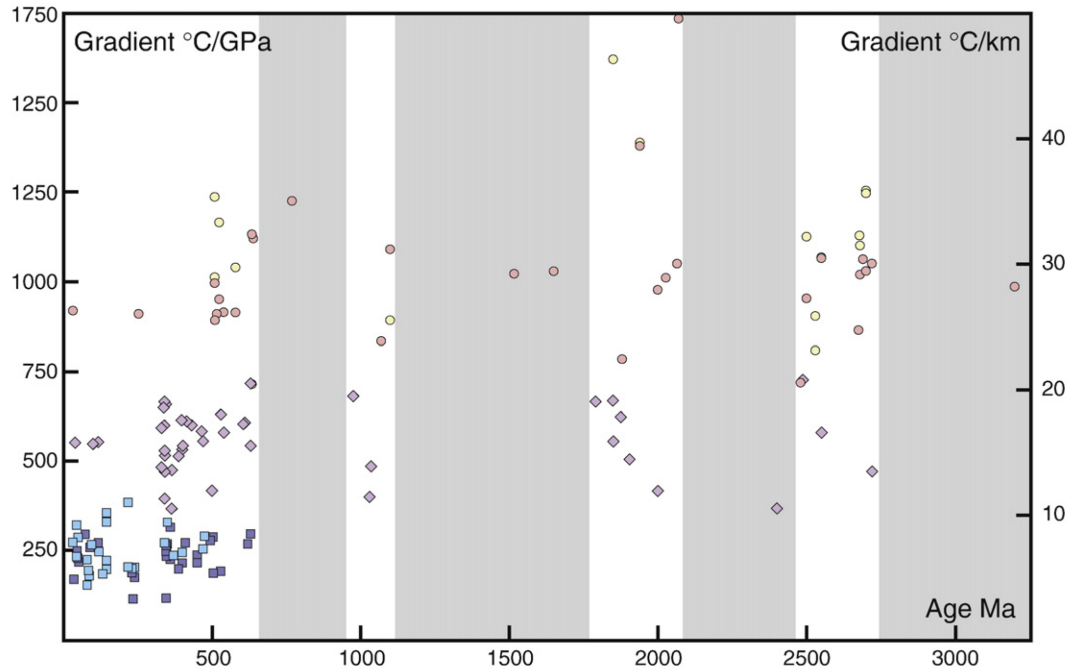

Fig. 4. Plot of thermal gradient in °C/GPa versus age in Ma for the three main types of extreme metamorphic belt — G-UHTM (circles), E-HPGM (diamonds) and HPM–UHPM (squares); an approximate conversion to °C/km is also shown (data from tables 1–5 of Brown, 2007).

continuous subduction, with formation of depositional basins in an arc–backarc system during slab rollback, and the timing of events such as ridge subduction (Thorkelson, 1996; Brown, 1998b; Groome and Thorkelson, 2009) and plate re-arrangements (Dewey, 1975, 1981) or tectonic mode switches (Collins, 2002b; Lister and Forster, 2009) that lead to accretion of low d*T*/d*P* blueschists and eclogites in the subduction zone and generate high d*T*/d*P* metamorphism in the arc–backarc (Brown, 2006). Thus, metamorphic belts of contrasting type may be formed during a single orogenic cycle along different sectors of a common convergent margin by multiple processes, but juxtaposition may have been due to the obliquity of convergence and lateral translation along the margin late in the orogenic event (Brown, 1998a,b).

The Ryoke–Sanbagawa metamorphic belts were used as the principal example of 'paired' metamorphism by Miyashiro (1961). However, it remains unclear whether these belts are typical or representative of the geological record, particularly with respect to multiple episodes of ridge subduction. Brown (1998b) suggested that ridge subduction was under-represented in models for the generation of high d*T*/d*P* metamorphism, and more recently Wakabayashi (2004) has proposed that processes such as subduction initiation, triple-junction interactions, initiation and termination of arc volcanism, subcontinental delamination, and hot spot migration should be considered as common rather than rare events in the metamorphic rock record, particularly of accretionary orogens. Although subduction-to-collision cycles have influenced metamorphic evolution in many orogenic belts, which is inevitable since this is the mechanism by which supercontinents are sutured (Brown, 2008, 2009), the potential impact of other types of process, particularly in accretionary orogens, should not be overlooked.

In his 1961 paper, Miyashiro included an intermediate d*T*/d*P* type of metamorphism (kyanite–sillimanite type) for the most commonly described type of metamorphic belt at that time, the Paleozoic belts of Europe and North America. Miyashiro (1973) subsequently suggested that "… paired and unpaired (single) metamorphic belts form by the same mechanism, and an unpaired belt represents paired belts in which the contrast between the two belts is obscure, or in which one of the two belts is undeveloped or lost." However, more recent studies have lead to the wider observation that such intermediate d*T*/d*P* metamorphic belts of Barrovian type commonly are juxtaposed against high d*T*/d*P* metamorphic belts of Buchan type (discussed below).

In fact, the distinction drawn by Miyashiro (1961) between 'paired' and 'unpaired' metamorphic belts effectively separates accretionary orogenic systems, with "metamorphic belts of Japan type," from subduction-to-collision orogenic systems, with metamorphism characterized by "the standard type of facies series" or "Barrovian" type. Also, it is now clear that many of the Phanerozoic sutures of Europe and Asia are decorated with high pressure and ultrahigh pressure metamorphic rocks (Maruyama et al., 1996; Liou et al., 2004; Tsujimori et al., 2006; Liou et al., 2009), which border mountain belts characterized by lower-pressure/higher-temperature metamorphism. Furthermore, these mountain belts commonly include metamorphic belts with contrasting types of *P*–*T* path, clockwise versus counter-clockwise in *P*–*T* space, representing metamorphism of intermediate d*T*/d*P* ("Barrovian") and high d*T*/d*P* ("Buchan") type, respectively (e.g., Goscombe and Hand, 2000; Spear et al., 2002). This raises the issue of whether to extend the concept of 'paired' metamorphic belts more widely than accretionary orogens, outside the original usage by Miyashiro (1961), to subduction-to-collision orogenic systems, as perhaps was implied by Miyashiro in the quote above from his later publication (Miyashiro, 1973).

The modern plate tectonics regime is characterized by a duality of thermal environments, the subduction zone and the suture zone of subduction-to-collision orogens, and the backarc or mountain belt/orogenic hinterland, in which contrasting types of regional-scale metamorphic belts are being formed contemporaneously. I consider this duality to be the hallmark of one-sided subduction (Brown, 2006). Thus, the characteristic imprint of one-sided subduction and perhaps of plate tectonics in the geological record will be the broadly contemporaneous occurrence of two contrasting types of metamorphism reflecting this duality of thermal environments (Brown, 2006). On this basis, I proposed the following (Brown, 2009): *Paired metamorphic belts are penecontemporaneous belts of contrasting type of metamorphism that record different apparent thermal gradient, one warmer and the other colder, juxtaposed by plate tectonics processes.*

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Using this definition, we may consider the combination of E-HPGM with G-UHTM in the continental geological record from the Neoarchean to the Neoproterozoic Eras and the combination of HPM–UHPM and/or E-HPGM with G-UHTM in the continental geological record of the Phanerozoic Eon as recording paired metamorphism. This extends the original concept of Miyashiro (1961) beyond the simple pairing of high d*T*/d*P* and low d*T*/d*P* metamorphic belts in circum-Pacific accretionary orogens, and makes it more useful in the context of our better understanding of the relationship between thermal regimes and tectonic setting. This is particularly useful in subduction-to-collision orogenic systems, where an accretionary phase is overprinted by a collision phase that will be registered by the imprint of penecontemporaneous low-to-intermediate d*T*/d*P* and high d*T*/d*P* metamorphism in the rock record (Brown, 2006).

6. Concluding remarks

In this contribution, I have summarized the tectonics of orogenic systems on Earth, looked back at the concept of 'paired' metamorphic belts, discussed the geology of the classic Ryoke–Sanbagawa 'paired' metamorphic belts in Japan, proposed a classification of types of metamorphism to evaluate secular change in the evolution of metamorphic belts, and considered of the imprint of these different types of metamorphism in the geological record back to the Neoarchean Era. This review has led to a broader interpretation of paired metamorphic belts than envisaged by Miyashiro in 1961, and to a conclusion that subduction and plate tectonics processes have operated on Earth since at least the Neoarchean.

Akiho Miyashiro's career began as a researcher of mineralogy, transformed into a researcher of metamorphic and igneous rocks, including ophiolites, from the late 1950s, through the 1960s and into the 1970s, and included contributions on the relationship between petrology and tectonics after the plate tectonics revolution. As we approach the 50th anniversary of the publication of his classic paper "Evolution of Metamorphic Belts" it is clear that his work has been extraordinarily influential not just in our understanding of metamorphism but also of petrology in general. This influence is clear from data in the ISW *Web of Knowledge*, which lists those publications by Miyashiro that are in English and published in the international literature (i.e. not including his early career contributions published in the Japanese literature). At the time of writing, the 1961 paper has been cited approximately 500 times. However, more extraordinary is the fact that his publications listed in the ISW Web of Knowledge average more than 100 cites per item! It is my hope that this retrospective essay about 'paired' metamorphic belts provides a fitting tribute to Miyashiro's contributions and his vision and influence in our community.

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