A new perspective on metamorphism and metamorphic belts

Shigenori Maruyama a,⁎, H. Masago b, I. Katayama c, Y. Iwase d, M. Toriumi e, S. Omori f, K. Aoki a

a Department of Earth and Planetary Sciences, Tokyo Institute of Technology, Japan
b Center for Deep Earth Exploration, Japan Agency for Marine-Earth Science and Technology, Japan
c Department of Earth and Planetary Systems Science, Graduate School of Science, Hiroshima University, Japan
d Department of Earth and Ocean Sciences, National Defense Academy of Japan, Japan
e Department of Earth and Planetary Science, Graduate School of Frontier Sciences, The University of Tokyo, Japan

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ABSTRACT

The discovery of ultrahigh-pressure rocks from collision-type orogenic belts has revolutionized the classic interpretation of (1) progressive and retrogressive metamorphism recorded on surface exposures of regional metamorphic belts, (2) geochronology of the various stages of metamorphism, (3) origin of metamorphic textures, (4) P–T–t path, (5) metamorphic facies series, (6) exhumation model, and (7) role of fluids during regional metamorphism. Based mainly on our recent studies of the Kokchetav, Dabie Shan, Indonesia, Franciscan and Sanbagawa belts, we suggest the following revolutionary paradigm shifts.

The so-called mineral isograds defined on the maps of regional metamorphic belts were a misunderstanding of the progressive dehydration reaction during subduction because extensive late-stage hydration has mostly obliterated the progressive minerals in pelitic–psammitic and metabasic rocks. Progressive zoned garnet has survived as the sole progressive mineral that was unstable with the majority of matrix-forming minerals. The classic Barrovian isograds should therefore be carefully re-examined. The well-documented SHRIMP chronology of spot-dating zoned zircons with index minerals from low-P in the core, through HP–UHP in the mantle to low-P on the rim clearly shows that the slow exhumation speed of 23–40 My from mantle depth to mid-crustal level was followed by mountain building with doming at latest stage. Extensive hydration of the UHP–HP unit occurred due to fluid infiltration underneath, when the UHP–HP unit intruded the low-grade to unmetamorphosed unit at a mid-crustal level. Most deformation textures such as mineral lineations, porphyroblasts, pull-apart, or boudinaged amphiboles, formed during extensive hydration at the late stage do not constrain the progressive stress regime. The P–T–t time path determined by thermobarometry using mineral inclusions in garnet and forward modeling of garnet zoning, independent of the matrix minerals, indicates an anticlockwise trend in the P–T space, and follows an independent P–T change in the metamorphic facies series. This is consistent with the numerically calculated geotherm along the Wadati–Benioff plane. Collision-type orogenic belts have long been regarded as being characterized by the intermediate-pressure type metamorphic facies series. The kyanite–sillimanite is an apparent type facies series formed by the late-stage extensive hydration. In contrast, the original high-P to ultrahigh-P type facies series with an anticlockwise kink-point at around 10 kb is a progressive type. A collision-type regional metamorphic belt crops out as a very thin unit sandwiched between overlying and underlying low-P or weakly metamorphosed units. The metamorphic belt has an aspect ratio (thickness vs width) of 1:100, and it extends for several hundreds to a thousand km. It resembles a thin mylonitic intrusion from the mantle extending from 100 to 200 km depth into the crustal rock unit. The underlying unit is thermally metamorphosed in the andalusite–sillimanite type facies series. The major reason for the misunderstanding of the progressive metamorphism in collision-type orogenic belts is the underestimation of the role of fluids derived from the underlying low-grade metamorphic unit, when juxtaposed at a mid-crustal level. The circulation of fluids along the plate boundaries is more important than a P–T change.

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1. Introduction

Our understanding of regional metamorphism is pivoted on information from experimental petrology combined with thermodynamics, structural and petrological studies of regional metamorphic belts from microscopic to map scale, and the paradigm established by plate tectonics (e.g. recent works by Brown 2010–this issue, Omori et al.,...
Although the plate boundaries as well as the information from geophysics, much larger canvas, particularly incorporating processes in consuming plate boundaries by combining information from geology and petrology in modeling mountain building processes along consuming plate margins should be a progressive metamorphism. However, this was proved wrong by subsequent studies as progressive metamorphism ranged from low-T high-P type facies series covering blueschist through eclogite to coesite and diamond facies metamorphism. Recently, similar results were also obtained from the Pacific-type regional metamorphic belts (Aoki, 2009). Therefore, metamorphic petrology systematized through the generally accepted models of England and Thompson (1984) and Spear et al. (1990) faced new challenges. The new discoveries warranted a restructuring of the basic framework of metamorphic petrology in terms of the geodynamics and tectonics of regional metamorphic belts. A paradigm shift in this field should be able to address: (1) progressive regional metamorphism; (2) retrogressive and probably hydration metamorphism; (3) geochronology; (4) metamorphic textures and structures and the estimation of stress; (5) P-T path; (6) metamorphic facies series; (7) exhumation tectonics and (8) the behavior of metamorphic fluid. Most of these themes are now facing several new challenges and drastic revision of previous concepts based on technological and conceptual advancements. In this paper we synthesize the traditional ideas and concepts of metamorphic petrology and evaluate the recent observations, finally leading to the proposal of some new concepts.

2. A brief historical review of regional metamorphism

In this section we provide a brief overview of the existing major concepts including salient assumptions on regional metamorphism.

2.1. Metamorphic rocks exposed on the surface indicate absence of fluids

If excess fluid enriched in water is always available during metamorphism, a chemical equilibrium must prevail, and hence high-grade metamorphic rocks cannot be present on the surface of the Earth. Zeolite facies minerals such as clays are the stable assemblages under the surface, at temperature and pressure conditions prevailing in the wet region. However, exposed regional metamorphic belts such as those of Alps, Himalaya and other areas show the presence of high temperature minerals such as plagioclase and pyroxene on a regional scale. The common presence of anhydrous high-T minerals in regionally exposed metamorphic belts suggests disequilibrium under surface environment (Fig. 1). A possible explanation for this phenomenon is the absence of fluid during the exhumation from deep crust to the surface.

Mineral isograds have been traditionally constructed to explain the progressive nature of regional metamorphic belts (see example shown in Fig. 2). From low- to high-grade of metamorphism, the change in pelitic mineral assemblages define the isograds, such as for example the chlorite, biotite, garnet, staurolite, sillimanite and kyanite isograds in the collision-type Scottish Highland (Barrow, 1893; Fettes, 1979) (Fig. 2), and chlorite, garnet, biotite and oligoclase in the Pacific-type Sanbagawa belt, Japan (Higashino, 1990). These isograds can be explained by P and T increase, which promote hydration reactions at given chemical composition. Interpretation was that excess fluid was present during the P-T increase leading to the completion of chemical equilibria promoting the progressive metamorphism (Fig. 1a,b). However, after the thermal peak (P-T maximum) the recrystallized metamorphic belts return to the surface. If there is no fluid, the mineral assemblages formed at specific P-T conditions should remain frozen and will not undergo any change (Fig. 1c). The presence of high-grade mineral assemblages in the exposed metamorphic belts has been taken to indicate the absence of fluids after the thermal peak, a speculation that has been well demonstrated in petrology and supported by empirical considerations. Therefore, even though the logic is somewhat circular, most petrologists endorsed this concept.

2.2. Meaning of mineral isograd

As shown typically in the case of Scottish and Appalachian metamorphic belts, the appearance of anhydrous minerals seems to be common with increasing metamorphic grade. Therefore, in a given rock system, such as pelitic or mafic, the mineral assemblages indicate dehydration reactions at the high-T side to expelling fluids at the higher-grade side. This process is envisioned as progressive metamorphism and records a P-T increase during regional metamorphism. Therefore, the mineral isograds preserve the P-T structure during the maximum-P-T conditions.

However, if we consider the texture of metamorphic rocks, the margin of amphibole or garnet is often replaced by low-temperature minerals, which indicate minor hydration and recrystallization following the peak metamorphic conditions. Thus, hydration recrystallization was considered to be minor during the exhumation of regional metamorphic belts. It was thus considered that high-grade metamorphic rocks could be transported to the surface without any significant hydration–recrystallization.

As will be discussed in detail later, this notion was wrong. The late-stage retrogression was extensive to obliterate almost all progressive mineralogy at high grades, hence we need to reconsider the basic concept of metamorphism and metamorphic belts.

2.3. Exhumation model

Almost all regional metamorphic belts were considered to be generally stable within the stability field of plagioclase. Plagioclase occupies more than 50% modal content among the mineral assemblages in psammitic to pelitic sedimentary rocks and metabasites. The upper stability limit of plagioclase in both metabase and metasedimentary rocks is up to 12 kbar (Miyashiro, 1973, 1994a,b). Therefore, transportation depth of regional metamorphic belts was considered to have never exceeded the bottom of continental crust (ca. 35 km).
Based on this assumption, it was generally held that continental crust cannot subduct into mantle and would only underplate leading to crustal duplication as in the case of the model proposed for Himalayas (England and Thompson, 1984). Advances in experimental petrology led to the compilation of an exhaustive database on the thermodynamic properties of most of the rock-forming minerals (e.g. Helgeson et al., 1978, Holland and Powell, 1998). Using this database, metamorphic $P$–$T$ paths have been traced by the continuous change in the composition of minerals such as garnet that are assumed to be in equilibrium with the matrix minerals. If chemical equilibria were perfectly maintained, then the radiometric ages derived from key minerals provide valuable insights into the exhumation mechanism of regional metamorphic belts.

One of the best examples for widely cited exhumation model is the Himalayan metamorphic belt proposed by England and Thompson (1984). We will now consider the tectonic history of this belt. The estimated horizontal movement is about 70 to 80 km/My from computations based on the northward migration of Indian continent at the rate of 7 to 8 cm/year (England and Thompson, 1984). If the subduction angle is 30°, the leading edge of the continent would reach Moho depths within 1 million year (Fig. 3a). Therefore, thermal calculation justifies the instantaneous overlapping of two continental crusts (Fig. 3b). In this calculation, it was assumed that the temperature at the surface of the subducted continental crust was zero degree centigrade. The surface of the subducted crust is heated up through time by the overlying lower crust of Asia, to an estimated temperature of 500 °C. The geotherm on the top surface of the Indian continent is thus gradually heated up to attain a steady state geothermal gradient which is a function of time (Fig. 3b). In this case, a time span of only 5 million years is sufficient to attain such a state.

Because the subducted continental crust is expected to have large buoyancy, this crust must uplift right after the duplication of the two blocks following isostatic requirements (Fig. 3a, right upper panel). The present day surface exposure of the Himalayan regional metamorphic belts exhibit a continuous sequence from very low grade (300 °C) to high grade (700 °C), suggesting that the belt exposes the subducted Indian crust from surface to the lower structural level. The protoliths of Himalayan metamorphic rocks still preserve some of the lithostratigraphy derived from the Gondwana continental assembly, and the paleontological records are also consistent with this inference (Gansser, 1964; Lefort, 1975). Therefore, the Asian continental crust, which constitutes the upper part of duplicated continents, seems to have been significantly eroded, the debris from which now constitute the voluminous Bengal fan deposits within the Indian Ocean. Judging from Fig. 3b, the surface regions which recrystallized below 300 °C were not heated up above by the high-temperature Asian lower crust, and the exhumation must have been extremely fast and short that occurred within a few million years.

We now consider the $P$–$T$ architecture of the subducted Indian crust. The Indian crust was transported to a depth of ca. 45 km within 1 million year. The fast rate of subduction means that during the initial stage of subduction, only the pressure must have increased with temperature remaining nearly constant (Fig. 3c). At the depth of 45 km, the subducted crust stays for a considerable time when $P$ must be constant whereas $T$ must gradually increase. This is due to the fact that heat transfer occurs only by conduction which is a very slow process as compared to the speed of the plate movement (England and Thompson, 1984). It should be noted that due to isostatic rebound, metamorphic belts slowly uplift leading to temperature increase vis-à-vis pressure decrease to exhume the metamorphic belts to the surface by buoyancy. Simultaneously, extensive erosion occurs on the surface (Fig. 3c). As expected in such a model, a clockwise rotation of the $P$–$T$ path occurs which matches well with the $P$–$T$ time path deduced from chemically zoned garnets (Spear, 1993). This model has been supported by several petrological studies and Ganguly et al. (1998) estimated the average exhumation speed of metamorphic belts in the Himalaya based on the diffusion velocity of trace elements from zoned garnet (see also Tirone and Ganguly, 2010-this issue for recent models on garnet diffusion). The results were also consistent with an extremely rapid exhumation.

Fig. 1. Schematic diagram of regional metamorphism in subduction zones. (a) The formation of protolith. Accretionary complex formed at trench and gradually decreased its water contents during subduction (shown with change in density of dots in the metamorphic belts in the diagram from a and b). As most prograde metamorphic reactions are dehydration with excess aqueous fluid, chemical equilibration is achieved at prograde to peak stages. (b) On the contrary, most retrograde reactions during the exhumation stage are hydration reactions, which cannot proceed without sufficient water being supplied from outside the system. For this reason, it has long been believed that metamorphic rocks exposed on the surface preserve near peak stage of the metamorphic mineral assemblages (c). However, recent studies have clearly revealed that metamorphic belts have undergone recrystallization with a large amount of water infiltrating at the mid-crustal level (d).
Fig. 2. (a) Map view of metamorphic zoning and mineral isograd on the Scottish Highland. (b) The appearance and disappearance of index minerals in pelitic rocks with increasing metamorphic grade (Fettes, 1979). Intermediate-pressure type metamorphic facies series in Scottish Highland has been called as Barrovian and regarded to be the world standard of progressive metamorphism in the regional metamorphic belts. (c) AFM ternary expression of the progressive disappearance of staurolite. Staurolite-bearing assemblages change to an assemblage of sillimanite + garnet + biotite (right) with the disappearance of staurolite due to temperature increase (center). (d) The appearance and disappearance of index minerals in a model pelitic rock with increasing metamorphic grade along prograde P–T path of the Kokchetav UHP metamorphic rock (after Masago et al., 2010–this issue). Compare (b) and (d) to evaluate the late stage of hydration to mask the stability field of progressive HP minerals at highest grades.
3. A revolutionary change in the concepts of metamorphism

3.1. Discovery of UHP metamorphic rocks

The attractive models proposed for the formation and exhumation of the Himalayan regional metamorphic belts provide a typical case of the systematization of metamorphic petrology and illustrate the consistency between theoretically predicted model and the field and petrologic data. Hence, metamorphic petrologists and geologists widely applied the Himalayan model for other regional metamorphic belts formed by continent–continent collision employing a similar petrological, tectonic, geochronological method. This template study thus became a common currency over the world and similar models for different regional metamorphic belts in space and time were proposed.

However, the discovery of UHP metamorphic rocks from Alps (Chopin, 1984) marked a historic change in our concepts on regional metamorphism and cast the first shadow of doubt on the Himalayan models. Chopin’s (1984) report of coesite-bearing white schist from the highest grade of the Penninic nappe in the Italian Alps was followed by further similar findings such as the discovery of coesite from Norwegian Caledonides (Smith, 1984). Thereafter, ultrahigh-pressure metamorphic rocks have been reported from a number of collisional orogenic belts over the world (see Zhang et al., 2009 and references therein), and new reports continue even today adding to the number of UHP localities, which already exceed 25 (Fig. 4). Although there is a general consensus that UHP metamorphic rocks are remarkably exotic in terms of $P$–$T$ condition, many people still consider the England and Thompson (1984) model for Himalayan metamorphic belts as an acceptable model.

3.2. Mode of occurrence: coherent, allochthonous or autochthonous?

Following the discovery of UHP rocks, one of the main topics of debate was the mode of occurrence of the metamorphic belts. The pressure conditions of UHP rocks range from 30 to 70 kbar, which is clearly outside the stability field of plagioclase, the stability of which denotes pressures of only less than 12 kbar. This led to a contradiction in the conceptual framework of regional metamorphism. One possibility is that UHP rocks were caught up within low-pressure regional metamorphic belts as tectonic blocks. The second view is that it is similar to gravel within conglomerates or olistostrome (Wang et al., 1992). The third possibility is that the regional metamorphic belt itself was subjected to high-pressure to ultrahigh-pressure metamorphism followed by hydration–recrystallization along intermediate-$P$ series below 12 kbar (see a summary by Wang et al., 1992). Among these three interpretations, most people believed the former two cases, possibly because UHP rocks were derived from eclogites which were thought to be derived from ophiolites. Another reason for this contention was due to the fact that the major portion of regional metamorphic belts was derived from psammitic to pelitic or orthogneiss which do not exhibit the HP–UHP metamorphic conditions.

![Fig. 3. Classic model for continent collision orogeny of England and Thompson (1984).](image-url)
However, continued studies on UHP metamorphism revealed that the possibility (3) mentioned above is the most viable scenario. A detailed case study was reported by Katayama et al. (2000) who analyzed zircon inclusions separated from pelitic and psammitic rocks from diamond-grade Kokchetav UHP regional metamorphic belt using laser Raman spectrometry. More than 20 minerals were identified within the zircons. Metamorphic mineral zoning was established based on the mineral inclusions in zircons, and the results clearly demonstrated that the psammitic and pelitic metamorphic units of Kokchetav must have undergone regional metamorphism under HP–UHP conditions. These metasedimentary rocks comprise more than 90% of the belt, and therefore the metamorphic belt itself must have been subjected first to HP–UHP facies series and was later affected by intermediate-pressure metamorphism within Moho depth (Katayama et al., 2001; Masago et al., 2010–this issue). This study, and similar other works were a turning point on the concept of collision-type regional metamorphism.

3.3. Concept of regional metamorphism faces serious challenge

Following the Kokchetav research, similar results were obtained from the Dabie–Sulu Triassic collisional orogenic belts in South China (Liu et al., 2002; see Zhang et al., 2009 for a recent review). Moreover, coesite was also discovered in granitic gneiss from the western part of Himalayan belt, the Pakistan and Indian Himalayas (Kaneko et al., 2003). This led to a drastic change in concept and it became apparent that most of the collisional metamorphic belts must have suffered first HP–UHP metamorphism during the prograde stage (e.g. Nishimiya et al., 2010; Santosh and Kusky, 2010), followed by exhumation up to mid-crustal level when hydration obliterated part of the progressive metamorphic history through replacement by intermediate facies series recrystallization.

The prograde and retrograde metamorphic history and the time gap between these two episodes were clearly identified through spot analysis of zircons from UHP rocks using SHRIMP method pioneered by Katayama et al. (2001). The history recorded from the core and margin of single zircon grains provided new insights into the markedly different $P$–$T$ conditions; for example, a diamond-bearing core against graphite and plagioclase bearing rim. Thus, two independent metamorphic episodes were distinguished with ca. 20 to 30 million years difference between the two events. This has been confirmed not only in Kokchetav, but also in other UHP terranes including the Dabie–Sulu and Himalayas (Wang et al., 1992; Tabata et al., 1998; Liu et al., 2002; Kaneko et al., 2003; Sachan et al., 2004; Zhang et al., 2009). The time gap reaching 20 to 30 million years indicate extremely slow exhumation rate.

The Kokchetav and Dabie–Sulu examples, among other terranes, finally led to the understanding that HP–UHP metamorphism was not an exotic phenomenon and represents part of a progressive metamorphic cycle association with the deep subduction of continental margins followed by late-stage hydration–recrystallization during exhumation. The information so far available indicates that UHP metamorphic rocks are generally restricted to Phanerzoic orogenic belts, and no typical Archean and Proterozoic examples have been reported, except minor exceptions for latest Proterozoic examples from Brazil and Africa (Caby, 1994; Campos Neto, 2000; Parkinson et al., 2002).

Fig. 4. Global distribution of UHP metamorphic rocks (partly modified after Parkinson et al., 2002). Numbers below the localities represent ages in Ma.
3.4. Impact on the Pacific-type orogenic belts

The new findings from collision-type regional metamorphic belts such as those of Kokchetav were soon extended to the Pacific-type orogenic belts such as the Sambagawa metamorphic belt in Japan (Ota et al., 2004; Aoki et al., 2007, 2008, 2009). At the highest metamorphic grade for Sambagawa belt in the Shikoku island of SW Japan, an amphibolite mass of approximately 10 × 4 km² is exposed with a relict mineral assemblage corresponding to eclogite facies, the pressure conditions of which are markedly higher than the already described surrounding amphibolite facies rocks (below 12 kbar). However, these eclogites were considered as tectonic blocks occurring along fault zones (Takasu 1989). More recently, eclogite facies mineral assemblages were widely mapped over the entire mass (Ota et al., 2004). Moreover, small eclogite bodies were also reported from the surrounding Sambagawa metamorphic rocks (Aoya and Wallis, 1999). These findings radically revised the traditional concepts of progressive Sambagawa metamorphism along HP intermediate facies series below 12 kbar, which represents only a later stage hydration-recrystallization after exhumation and emplacement at mid-crustal level. Thus, the high-pressure progressive metamorphism might have occurred at an earlier stage.

4. New paradigm

The framework of concepts on the dynamics of regional metamorphism underwent rapid changes in the recent years and in this section we summarize some of the crucial aspects.

4.1. Intermediate facies series

One of the aspects to be evaluated is whether or not the kyanite-sillimanite type characterizes metamorphism in collisional orogenic belts. Miyashiro (1961) defined three independent metamorphic facies series and two intermediate groups between the three. The type localities listed by Miyashiro (1961) are the Franciscan, Sambagawa, Scottish Highland, New Zealand and the Ryoke belt (Miyashiro, 1973). Based on the description of regional metamorphic belts, it was pointed out that the intermediate-pressure type metamorphic belts characterize the collision type. On the contrary, high-P to high-pressure-intermediate variety denotes the Pacific-type subduction, also low-pressure type paired with HP type. Furthermore, the metamorphic facies series were employed to define a clockwise P-T path (Fig. 5). The finding of UHP metamorphic rocks from several regional metamorphic belts proved that Miyashiro’s generalizations do not hold true. Regardless of whether the orogeny is collision-type or Pacific-type, the regional metamorphic belts display progressive metamorphism under HP to UHP conditions. Also, the P-T-time path is not clockwise, but anticlockwise as will be shown in a later section.

4.2. Re-examination of mineral isograd

We will now examine the question whether it is possible to reconstruct the progressive metamorphism during subduction. Major minerals of pelitic and psammitic metamorphic rocks in collisional belts are plagioclase, quartz, biotite, muscovite and amphibole which are obviously not the products of the prograde high-pressure metamorphism during subduction as discussed before. If so, what were the minerals and their composition, the stable mineral assemblages and reactions during the progressive stage? Can these be retrieved? Compared to pelitic and psammitic schists, metabasites are massive and more competent and therefore, the central portion of a metabasite body tend to preserve the progressive stage of metamorphism even if the unit witnessed late-stage hydration-recrystallization. Thus careful field investigations, mapping and detailed sampling is essential to trace the signature of progressive metamorphism as illustrated in the case of Kokchetav and Dabie–Sulu. However, the volume of metabasites is small and generally less than 10% of the total volume of rocks exposed in such belts. The remaining 90% is composed of para- or orthogneiss. The matrix minerals of metasedimentary rocks have recrystallized under mid-crustal level. The rare metabasites, even though occurring as thin units, locally preserve jadeite + coesite + garnet, as in the case where they are enclosed within metacarbonates (Ogasawara et al., 2002). In some cases, metamorphosed sandstones surrounded by metacarbonates preserve similar UHP assemblages. The stable HP and UHP minerals are preserved within zircon crystals and include coesite, diamond, garnet, jadeite and silica-rich phengite. These minerals and mineral assemblages are different from the matrix-forming minerals in psammitic and pelitic rocks. In this case, UHP metamorphic belts were generated by subduction of passive margin sediments down to 100 or even 200 km depth, dehydrated, and dried at maximum depths. Thereafter they exhumed along the Benioff plane up to mid-crustal levels of 10 to 15 km depth, where extensive hydration and recrystallization occurred when most of HP–UHP minerals disappeared except those occurring as inclusions within robust minerals such as garnet and zircon (Masago et al., 2010-this issue). This critical observation refuted the generally accepted notion that the composition and assemblages of matrix minerals are the basic starting point (e.g., Spear, 1993) to understand regional metamorphism. Some of the fundamental concepts thus collapsed warranting a new framework of metamorphism.

4.3. Tracing prograde metamorphism from zoned garnet

Garnet in pelitic and psammitic metamorphic rocks is the only major rock-forming mineral, which may have been stable during prograde metamorphism. Nevertheless garnet was not in equilibrium with matrix minerals. Since zoned garnet has been regarded as the ideal mineral to draw pressure-temperature change through time, garnet solid solution chemistry has been used most frequently to estimate P–T path and a large number of papers have been published. However, some of the underlying concepts were erroneous. We cannot use matrix minerals at all, because of the late-stage extensive hydration-recrystallization. Is it
possible to reconstruct prograde change of mineral assemblages from pelitic and psammitic regional metamorphic rocks? There are two ways to estimate the prograde P–T path from the zoning of garnet.

The inversion using Gibb’s method (e.g., Spear et al., 1990; Okamoto and Toriumi, 2001; Inui and Toriumi, 2002; Okamoto and Toriumi, 2004) starts from a provided initial condition and traces solid solution chemistry of garnet and other equilibrium minerals to reproduce the prograde P–T change. This method is a feasible approach, although if the prograde garnet and other minerals have been lost during retrogressive metamorphism this method cannot be used. On the other hand, Gibb’s method does not include enthalpy for the calculation and uncertainties derived are minimal. Another method is a forward modeling of the mineral assemblage by extensive thermodynamic calculation using an internally consistent thermodynamic database of the minerals such as Holland and Powell (1998). The calculation predicts equilibrium mineral assemblages in P–T–X space. Even though the matrix minerals, except garnet, are totally retrograded, the prograde P–T path can be estimated from mineral inclusions in garnet grain and composition of garnet near by the inclusion. If some geothermobarometer could be applied to the inclusion and garnet, the estimate will become more quantitative (Omori and Masago, 2004; Masago et al., 2009). However, such a forward calculation needs enthalpies of phases, which is a parameter with a large uncertainty. Both the methods have advantages and disadvantages and therefore if these are used in combination, a realistic P–T path can be obtained.

4.4. The Sambagawa metamorphism

With increasing metamorphic grade, the minerals in pelitic schist range from chlorite, garnet and biotite to oligoclase. These minerals have long been believed to be the products of progressive metamorphic reactions. That is, these minerals were formed by the dehydration reactions by plate subduction with resultant pressure–temperature increase to reach P–T maximum under which oligoclase was formed at maximum-P and T (Fig. 6). The estimated P–T conditions were 12 kbar, 600–700 °C. The contradiction then was that oligoclase is not stable under these conditions.

If all minerals except garnet were formed during hydration recrystallization at later stage, the progressive metamorphism in the Sambagawa belt needs to be re-examined, particularly using zoned recrystallization at later stage, the progressive metamorphism in the underlying the regional metamorphic belts such as those of the Shimanto belt contain large amounts of hydrous minerals, indicating that the reaction between glaucophane and actinolite has a gentle, positive slope. The idea of a clockwise P–T path was derived from the concept of underplating where an accretionary complex is transported to about 15 km depth by descending oceanic plate and underplated against the hanging wall. In this case, the transportation to 15 km depth takes only 0.2 million year if the subduction speed is 10 cm/year. Since this time span is geologically very short, the resultant scenario is only pressure increases at constant temperature. However, once accreted to the hanging wall, then temperature increases at constant depth since the hanging wall is always of higher temperature being part of the mantle wedge.

However, the reaction mentioned above is not dehydration, but a hydration reaction and substantial volume of water is necessary to generate actinolite through the consumption of glaucophane. Metamorphic belts require the supply of large amounts of water from outside. Therefore, this texture can be explained by pressure decrease at constant temperature instead of isobaric temperature increase (Fig. 7). Important process here is the infiltration of water-rich fluids, similar to the case of eclogite at highest grade. The lower grade units underlying the regional metamorphic belts such as those of the Shimanto belt contain large amounts of hydrous minerals, indicating the infiltration of large volumes of hydrous fluids during the exhumation from depths to shallow levels. The structurally intermediate units of the Sambagawa belt contain eclogite facies rocks that show the highest P–T grade (Banno et al., 1978; Banno and Sakai, 1989; Ota et al., 2004) (Fig. 8). These are remarkably hydrated and recrystallized to amphibolite. Below the structural intermediate level, lower pressure and temperature rocks are present which are more hydrated and recrystallized than those in the highest-grade metamorphic core at the structurally intermediate level (Fig. 8). The source of fluids would have been the underlying low-grade metamorphic rocks of the Shimanto belt (Fig. 8).

4.5. Re-examination of metamorphic age

If continent–collision-type regional metamorphic belts were formed by overlapped continental crust, the clockwise P–T–t exhumation of regional metamorphic belt must have occurred within an extremely short time span. From the beginning of subduction through transport to great depths and final exhumation to the shallow levels must have occurred within a few million years as calculated by the numerical simulation of overlapping continental crust (see Fig. 3).

On the contrary, zircon U–Pb SHRIMP ages clearly indicate a much longer time span than that predicted above. For example the SHRIMP age of zircon, which contains coesite inclusions, shows 48 Ma at 100 km depth in the Pakistan Himalaya (Kaneko et al., 2003). After return from
this depth to the mid-crustal level (15 to 10 km depth), the extensive hydration recrystallization occurred at 25 Ma, as plagioclase occurs as inclusions the zone developed in the zircons at this stage. These results show that it took about 23 million years for the return journey from UHP depths to the Barrovian recrystallization depths. Moreover, the drill core data of Bengal fan deposit in the Indian Ocean (ODP Leg 116) show that the mountain building in the Himalayas began since 8 Ma (Derry and France-Lanord, 1996). This is grossly inconsistent with the exhumation rate of regional metamorphic belts from mantle depths to mid-crustal level. Therefore, mountain building of the Himalayas seems to be unrelated to the event of regional metamorphism.

Similarly, the time span for transport from mantle depths of 100 to 200 km to the mid-crustal level took about 30 million years (Katayama et al., 2001) (Fig. 9). The time span for the subduction and exhumation is one order of magnitude higher than that envisaged in the crustal duplication model. Obviously, the field observations refute the model of continent duplication as discussed earlier in Fig. 3.

In the case of Himalayan metamorphic rocks, most of the radiometric ages of K–Ar and Ar–Ar concentrate at about 25 Ma derived from phengite or muscovite (Searle, and Freyer, 1986; Hubbard and Harrison, 1989; Copeland et al., 1991; Guillot et al., 1994). According to the previous speculation, 25 Ma is the timing when the high temperature regional metamorphic belts pass through the depth equivalent to 400 °C by the exhumation of deep-seated regional metamorphic belt to the mid-crustal depth. Therefore, peak metamorphism must be much older than 25 Ma. Recent observations suggest that the concept of closure temperature might be wrong, and that the K–Ar dates may represent recrystallization ages at the above depths by extensive fluid infiltration underneath. One way to test the closure temperature is the spot analysis of white mica formed during...
the progressive stage and which now occurs as mineral inclusion within garnet or zircon and compare with the spot analysis of white mica from matrix in the same rocks. In the case of Himalayas, if matrix white mica yields 25 Ma ages from eclogite facies rocks, then the white mica inclusions within zircon and garnet must be 48 Ma. If such is the result, then the popular interpretations based on closure temperature would be wrong. This idea needs to be tested in future studies.

In the case of Sambagawa metamorphic belt, a similar problem exists as that in the Himalayas. The age of prograde eclogite facies metamorphism is SHRIMP date of 120 Ma (Okamoto et al., 2004). On the contrary, the ages obtained from white mica are 60 to 80 Ma by K–Ar and Ar–Ar ages (Itaya and Takasugi, 1988; Takasu and Dallmeyer, 1990). Whether the 60 to 80 Ma age represents the time of hydration recrystallization at mid-crustal level or the much older white mica under UHP conditions at 120 Ma was reset at 400 °C due to closure temperature effects need to be examined by spot analyses of mica inclusions in garnet.

5. Re-examination of metamorphic facies series

It has been previously believed that one metamorphic rock records one metamorphic facies. The concept of metamorphic facies series was formulated by integrating the distribution of low to high-grade facies rocks in regional metamorphic belts (Miyashiro 1961, 1965) (Fig. 10a).

In general terms, metamorphism begins with increasing pressure and temperature from the surface condition to P–T maximum at depth and thereafter the return to surface. Thus, the rocks in regional metamorphic belts could have been subjected to several metamorphic grades (Fig. 10b). de Roever and Nijhuis (1963) proposed the pioneering concept of plurifacial metamorphism based on the observation that one metamorphic rock preserves several facies under the microscope such
as zoned Ca–Na amphibole and Ca–Na pyroxene. The clockwise P–T time path connecting several metamorphic facies has become a fashion since 1980 from the analysis of regional metamorphic belts over the world. Since one rock specimen preserves several metamorphic facies in cases where high-grade metamorphism has operated, Miyashiro’s proposal of metamorphic facies series needed redefinition. Thus to avoid confusion, the highest T at given P condition for each rock was connected to draw the P–T path and was defined as the metamorphic facies series (Spear et al., 1990) (Fig. 10b).

The metamorphic facies series thus defined is again clockwise in P–T space; with increasing depths the temperature gradient tends to increase. If we consider the facies series characterized by clockwise P–T path at depths over 10 kbar along consuming plate boundary, the temperature must increase beyond the solidus of basalt or peridotites, and slab must be partially melted. Thus the subducted materials above oceanic crust together with the sediments on the top will be melted almost completely. However, observation from natural examples along the modern subduction zones does not support this, because arc magmatism behind the trench is not in conformity with the idea of slab-melting in the case of old slab >25 Ma (Defant and Drummond, 1990; Drummond and Defant, 1990). Seismological observations also do not indicate any slab-melting at great depths.

The P–T change along the descending slab has been calculated numerically (for example, Peacock 1996) (Fig. 11a). The results clearly indicate an anticlockwise trend, instead of a clockwise path. Such a trend is commonly recognized by geophysicists who consider plate boundary as a thermal boundary layer and it is well recognized that geothermal gradient is not constant with increasing depth. For example, the Kokchetav HP–UHP units show an anticlockwise path (e.g. Masago et al., 2009) (Fig. 11b) and the slope of the estimated P–T curve changes at about 13 kbar and 700 °C to a much straight path with no significant increase in temperature up to 40 kbar. This trend appears to be common not only in continent collision zones but also in Pacific-type orogenic belts (Inui and Toriumi, 2002, Aoya et al., 2003; Okamoto and Toriumi, 2004; Masago et al., 2009).

6. Re-examination of textures

6.1. Metamorphic texture

Regional metamorphic rocks contain a variety of textures related to prograde metamorphism, recrystallization and deformation. For example, albite porphyroblasts often include a variety of minerals defining internal deformation fabric. Elongate minerals such as amphiboles define mineral lineations. Boudin or pull-apart textures are also common which indicate extension and breakdown of the elongated minerals into several fragments, all of which have long been considered to have been formed during subduction, i.e., progressive textures. Also common are snowball garnets which entail the rotation and growth of inclusion minerals, as well as pressure shadows. Other microstructures include shear folds, deformation of radiolarians and rounded cobbles and crenulation fold within mica-rich domains. These textures offer information on the direction of stress and its relative magnitude under the assumption of boundary conditions and initial state.

In the Sambagawa belt, mineral lineation and crenulation fold axis of mica, boudin or pull-apart texture of mineral grain or elongated minerals, and radiolarian deformation, among other features indicate E–W extension, which is parallel to the orogenic belt (e.g., Toriumi, 1982). This elongation coincides with the direction of metamorphic fluid flow in which the elongated minerals have grown. These structures have long been considered to form during progressive metamorphism through subduction during the Cretaceous time and relative plate motion. However, all of these mineral textures and deformation were not formed during progressive recrystallization, but were generated at a later stage after the emplacement at mid-crustal level by the addition of fluids underneath (Toriumi, 1982, 1985 and Toriumi and Noda, 1986).

Albite porphyroblast appears at the highest grade in the Sambagawa belt and the zone in which abundant albite is present has been termed as the spotted zone. Empirically, this zone corresponds to the biotite zone at the highest grade. The timing of formation of the porphyroblast in relation to the progressive or retrogressive metamorphism is important to discuss the origin of the metamorphic texture. This texture appears restricted only to the highest-grade portion because its development has been traditionally linked to progressive metamorphism at the highest, and therefore, the deepest conditions. However, the albite porphyroblasts include even retrogressive minerals developed at lower pressure conditions during hydration (Toriumi, 1975). Therefore, the timing of the formation of these porphyroblasts must be after the emplacement of the Sambagawa belt into the mid-crustal level. Presumably, large amounts of fluids infiltrated into the Sambagawa belt, which promoted extensive scale of recrystallization at 80 to 70 Ma. The texture and deformation of the rocks in this belt also indicate lack of preservation of the progressive stage. An E–W extension strain is derived from the deformation pattern of gravels in metaconglomerate schist and the recrystallized age of white mica by K–Ar method. The conglomerate schist in Oboke area has been considered to be a part of the Sambagawa metamorphic belt from deformational patterns. However, LA-ICPMS U–Pb detrital zircon age separated from quartz porphyry cobble in the conglomerate indicates 92 ± 4 Ma (Aoki et al., 2007). This age represents the timing of consolidation of the acidic magma for the protoliths of gravels. Therefore, the sedimentary age of conglomerate must be younger than 92 Ma. On the other hand, the Sambagawa progressive metamorphism is dated as 120 Ma (Okamoto et al., 2004) clearly indicating that Oboke conglomerate is not a part of...
the Sambagawa metamorphic belt. Hence, the so-called Sambagawa belt must be divided into two different metamorphic belts. When the Sambagawa metamorphic rocks were emplaced at mid-crustal level, above the Shimanto belt, both Sambagawa and Shimanto shared the same history of recrystallization and deformation with E–W extension. The microfabrics of the Sambagawa schist are remarkably similar to the deformation patterns associated with low-grade metamorphism in the Shimanto belt. This shows that the metamorphic texture of the Sambagawa schist does not correspond to the progressive stage, but is related to retrogressive hydration stage. The major texture of the Sambagawa schist was formed during the retrogressive hydration stage at 80 to 70 Ma when Sambagawa was juxtaposed to the Shimanto belt. The metamorphism of basic and pelitic schist in the Shimanto belt. This shows that the metamorphic texture of the Sambagawa schist does not correspond to the progressive stage, but is related to retrogressive hydration stage. The major texture of the Sambagawa schist was formed during the retrogressive hydration stage at 80 to 70 Ma when Sambagawa was juxtaposed to the Shimanto belt. The metamorphism of basic and pelitic schist in the Shimanto belt reached up to blueschist facies. The zircon U–Pb chronology yielded 84 Ma for the protolith age, and the abundant grained white mica yielded K–Ar ages around 60–65 Ma for the metamorphism (Aoki et al., 2008). It is difficult unequivocally define the textures or fabric formed during progressive stage of metamorphism, and to differentiate the earlier stage of exhumation from mantle depths to the mid-crustal level with the presently available information except in specific cases. One such example is a relict eclogite formed at the highest grade of the Sambagawa metamorphism. The elongation axis of the omphacite and related textures show orogen-verticak vertical S–S slide. The disposition of the Sambagawa belt shows a structurally intermediate position, vertical to the strike of the orogenic belt, and pre-dates the development of the E–W lineation (Toriumi and Kohsaka, 1995; Yamamoto et al., 2004). There are minor rocks in outcrop scale or microscale, which show the texture or deformation during the exhumation from the mantle depths. However, all of those do not preserve the progressive stage of subduction. The deformation fabric during progressive metamorphism must be restricted to mineral inclusions within garnet and zircon. The snowball garnets may provide one of the tools to reconstruct the three-dimensional movement of the progressive deformation.

7. Discovery of top and bottom boundary of regional metamorphic belts

One of the fundamental requirements is to define the top and bottom boundaries of the regional metamorphic belt, although this has not been resolved in most cases. Metamorphic petrologists have often neglected the presence of discontinuous boundary by simply assigning a continuous gradation into the lower grade rocks gradually without considering a discontinuous gap above and below the metamorphic units, although structural geologists had predicted the presence of a clear boundary. On outcrop scale, a sharp boundary cannot be identified between the two units because of mode of deformation and metamorphic grade do not show any marked difference. The maximum thickness of regional metamorphic units such as the Sambagawa reaches up to 2 km. The pressure gradient within the belt remained unresolved. Among the models proposed for the Sambagawa, a structural break is commonly noted along the boundary of the metamorphic zone such as in the Kanto Mountains (Hashimoto et al., 1992).

UHP–HP belts often exhibit remarkable pressure difference within the belts. Detailed studies in the Kokchetav unit covering 250 km×20 km helped in identifying nearly horizontal top and bottom boundary (Kaneko et al., 2000). Locally, tectonic windows are present revealing the underlying unmetamorphosed units because the bottom boundary is
nearly flat (Kaneko et al., 2000). And more interestingly, a contact metamorphic aureole in the unit underlying the Kokchetav UHP–HP unit was also identified. This contact aureole is divided into four zones and the metamorphic grade progressively increases towards the boundary. Metamorphic facies series belong to andalusite–sillimanite type and contact aureole reaches up to 600 °C at 2 kbar (Terabayashi et al., 2002). Metamorphic zircon separated from contact zone yielded SHRIMP U–Pb age of 501 ± 10 Ma which coincides with the age of the extensive hydration and recrystallization stage within the HP–UHP units (Katayama et al., 2001). This observation indicates that the contact metamorphism was a result of the emplacement of the HP–UHP units into upper crustal level at 6 km depth. Thus, a new concept of the exhumation of diamond-grade metamorphic rocks and their high temperature solid intrusion emerged, similar to magma intrusion. This idea clearly demonstrated that a radical change from the traditional concept of buoyancy-driven upward exhumation and erosion of regional metamorphic belts is undoubtedly wrong.

A suite of 7000 samples were collected from the Kokchetav from which 350 were analyzed by electron microprobe and zircons separation performed from 250 samples to evaluate the detailed P–T structure. The study yields maximum pressures of 60–70 kbar at 900–1000 °C (see a summary by Maruyama et al., 2002). Metamorphic units within the 2 km thick belt were sub-divided into five mineral zones with the structurally intermediate zone showing the highest grade. The metamorphic grade decreases both upward and downward with a pronounced pressure gradient with only 5–6 kbar at the boundaries. However, the boundaries of mineral zones are continuous without any sharp structural breaks, indicating ductile deformation to emplace those mineral zones upwards after the thermal peak. Overall thermobaric structures show symmetric pattern with an axis at the structural intermediate. However, the thickness of each mineral zone is not symmetric above and below. The deformation structure indicates that the structurally intermediate zone moved from south to north (Kaneko et al., 2000; Fig. 12c).

In the case of Pacific-type metamorphic belts such as the Sambagawa, the method to define top and bottom boundaries had already been proposed by Isozaki and Itaya (1990). The precise ages were measured from radiolarian microfossils and K–Ar dating of fine-grained white mica separated from low-grade metamorphic rocks along the outcrop scale. Later, Nishimura (1990) used the crystallization index of carbonaceous material in the outcrop scale to precisely fix the boundary in meter scale. The importance of defining top and bottom boundaries had been pointed out in earlier studies with the boundary defined either top or bottom, or both for forty examples of regional metamorphic belts from different regions of the world (Maruyama et al., 1996).

8. Chaotic state arising from the concept of nappe tectonics

The Penninic nappe of the Alpine metamorphic belt is the best example where the top and bottom boundaries are well defined with the intermediate zone enclosed within overlying and underlying unmetamorphosed units (Fig. 12a). However, the origin of UHP–HP unit has not been well understood largely due to the confusion arising from the concept of nappe tectonics (Fig. 13). In the following section we briefly address this problem.

In this metamorphic belt, there are three tectonic slices demarcated by horizontal faults (Coward and Dietrich, 1989; Maruyama et al., 1996). The structurally lowest unit, the Helvetic nappe which constitutes the basement of Europe has been classified as an allochthon that has never moved after its formation. The overlying unit (Penninic nappe UHP–HP unit), which was metamorphosed in the Eocene to Miocene, moved from south to north and was thrust over the allochthon. Thereafter, the topmost unit, the Austro-Alpine unit or nappe which is considered as a basement of Africa, was again thrust over on the top. Although this has been the prevailing view, it is more reasonable to consider that the structurally intermediate unit, the Penninic nappe, was tectionally inserted into the overlying and underlying units because this structural intermediate unit is the only unit that was subjected to the Eocene–Miocene HP–UHP conditions of metamorphism. In the prevailing concept, the reconstructed three units are assumed to have possessed a horizontal relationship as shown in Fig. 13. However, a prominent gap is evident between units H and P in Fig. 13, a marked discontinuity in terms of lithology, stratigraphy and geochronology. These three are not continuous each other and lithostratigraphically different before nape-stacking (Fig. 13).

Underneath the Kokchetav HP–UHP unit, a well-developed contact metamorphic aureole has been defined with andalusite–sillimanite type facies series (Terabayashi et al., 2002), clearly demonstrating that the exhumation of regional metamorphic belts was not buoyant uplift as proposed by England and Thompson (1984) but a high temperature intrusion into shallow crustal level as discussed in the previous section. Moreover, the emplacement depths were shallower than 12 km (4 kbar) and the highest temperature recorded from the margin of metamorphic belts is 600–650 °C. This indicates that the innermost domain of the metamorphic belts must have witnessed much higher temperatures, albeit lower than 1000 °C, when these rocks were at nearly 200 km depth. Due to this reason, when the metamorphic belt was emplaced, large volume of fluids must have infiltrated with the local development of migmaitite.

From the structural analysis of the interior of the Kokchetav metamorphic belt, the root zone was estimated to the south, with a northward movement as a sub-horizontal tectonic slice during exhumation. The average exhumation speed was extremely slow, 5 mm/year, as estimated by Katayama et al. (2001). There was no mountain building on the surface until the metamorphic unit was emplaced at depths shallower than 12 km. The major period of formation of sedimentary basin was after the doming stage, and developed by high angle normal faults after extensive hydration, equivalent to the post-orogenic mountain building stage. Post-collapse orogenic granites intruded into the metamorphic belt (Katayama et al., 2001). Traditionally, the main stage of orogeny was regarded as the exhumation or uplifting of regional metamorphic belt, which was also regarded to be the major mountain building stage. However, we consider that this concept is incorrect, as exhumation of regional metamorphic belt to the mid-crustal level occurs much earlier and without mountain building. The mountain building stage is a post metamorphic event through doming as first proposed Maruyama (1990) and Maruyama et al. (1996) based on wedge extrapolation model. A similar scenario was also recently proposed by Santosh et al. (2009a) to explain the metamorphic belts in the Cambrian collisional orogen of Gondwana in southern India.

9. A new model of exhumation

9.1. “Intrusion” of regional metamorphic belts

The model proposed by England and Thompson (1984) marks the pioneering tectonic synthesis to explain the formation of continent collisional type orogenic belts and their exhumation employing metamorphic petrology as a powerful tool. If the double crustal model they envisaged is valid, the structural bottom of the regional metamorphic belts must continue to higher-grade metamorphic rocks up to the Moho depths, and underlain by mantle peridotites. On the contrary, the units underlying the regional metamorphic belts are composed of weakly metamorphosed or unmetamorphosed rocks. Moreover, the thermobaric structure of the interior of the regional metamorphic belts does not support the model, which predicts unidirectional continuous pressure temperature increase to the bottom. As mentioned in previous sections, the well-examined metamorphic belts such as Kokchetav always show structural intermediate position for the highest-grade units as well as the Himalaya and Alps. The three-dimensional structure indicates marked thermal and baric gradients within the thin (2–3 km)
high-grade unit without any fault boundaries inside, suggesting that
ductile deformation prevailed after the peak metamorphic conditions
and the high-grade metamorphic unit 'intruded' into the weakly meta-
morphosed or unmetamorphosed geological units. The average exhu-
mation speed was extremely slow from mantle depths of 200 to 100 km
to the mid-crustal levels of 10 to 15 km, at about 4 mm/year (Katayama
The present day ongoing uplift rate measured in Himalayas, Taiwan and outer Indonesian non-volcanic arc shows only a few cm/year. The exhumation rate of HP–UHP units up to the mid-crustal depth is one order of magnitude slower.

9.2. Mountain building

The mountain building stage is the second step triggered by doming which occurred after the emplacement of regional metamorphic belts into the mid-crustal level and the development of high angle normal faults surrounding the dome generating large sedimentary basins. The best-documented example is the Himalayan mountain building caused by Indian collision against Eurasia (Fig. 14). The initiation of collision of India against Eurasia started at 50 Ma and UHP metamorphism occurred at 48 Ma (Kaneko et al., 2003). The UHP–HP unit was emplaced from mantle depth to the mid-crustal level at 25 Ma but the mountain building stage has not yet begun. At 8 Ma, the Himalayan metamorphic belt uplifted by doming and extensive development of secondary normal faults together with corresponding formation of Indus–Bengal submarine fan deposit (Fig. 14). Thus, the formation of large folded mountain belts occurs as the final stage of exhumation and is unrelated to the main stage of exhumation of the metamorphic belts from mantle depths to the mid-crustal level. The Himalayan mountain belt was reactivated since the last 1 million year possibly in response to the southward jump of plate boundary and buoyant continental crust was underplated beneath the higher Himalayas to push up the Himalayan mountain chain (Sakai, 2002).

9.3. Dynamics of extrusion

The aspect ratio of regional metamorphic belts shows ca. 1:100 in the case of the Himalayan metamorphic belt, the thickness in only a few km whereas the belt continues over 1000s of km along the strike with 200–300 km width. Thus, regional metamorphic belts are thin and platy which are cut by paired faults: normal fault on the top and reverse fault on the bottom, and the belt is extruded above the Benioff thrust on the consuming plate boundary. The exhumation velocity is one order of magnitude smaller than the plate movement, which has been proposed by Maruyama (1990) and Maruyama et al. (1994, 1996). These features can be attributed to the following three processes. (1) Subduction angle changes from deep to shallow through time. The subducted wedge-shaped continental material at depths was extruded by shallowing of the subduction angle. (2) The rheology shows marked contrast in the
units above and below the regional metamorphic belts. The regional metamorphic belt is composed of quartzofeldspathic material which turns ductile at temperatures above 350 °C, whereas the overlying wedge mantle is composed dominantly of olivine and the underlying unit is eclogitic oceanic crust and peridotites which behave as brittle below 1000 °C. (3) Rheological change during exhumation of quartzofeldspathic regional metamorphic belts. The regional metamorphic belt moves along the Benioff thrust up to mid-crustal level and becomes stagnant at depths of 10 to 15 km because the quartzofeldspathic materials transform from ductile to brittle by the temperature decrease at this stage, becoming harder. The 350 °C temperature divide corresponds to the brittle–ductile transition for the quartzofeldspathic material at mid-crustal depths of 10 to 15 km. Thus, regional metamorphic belts, which behave ductile fluid, are inserted between the overlying rigid mantle wedge and the underlying rigid slab. When the subduction angle turns to shallower, then the stress field changes to trigger the wedge to extrude into mid-crustal level. This is the most essential dynamic process controlling the exhumation of regional metamorphic belts.

9.4. Regional metamorphic belts brought up by buoyancy uplift?

The density of quartzofeldspathic rocks is about 2.8 g/cc which is lower than that of peridotites (3.2 to 3.3 g/cc for depths up to 50 to 60 km at which stage amphibolite transforms to eclogite with a density 3.3 to 3.4 g/cc) (Komiya et al., 2002; 2004). These values continue to a depth of 250 km with a maximum of 5% variation. Below 250 km depth, K-hollandite (density 4.7 g/cc) and stishovite (density 4.3 g/cc) become stable. Above 90 kbar, the density of a quartzofeldspathic rock is larger than the mantle material (Irfune et al., 1994) and therefore buoyancy does not aid in the exhumation of regional metamorphic belts from depth. On the other hand, it turns to become a strong slab-pull force.

Between 0 and 70 kbar, a quartzofeldspathic rock is buoyant than mantle peridotites or eclogites. However, the small density difference would not help the uplift of regional metamorphic belts as a plume within overlying mantle wedge (Fig. 15). More difficulties for the buoyancy uplift mechanism include the size of regional metamorphic belts and three-dimensional shape which is extremely different from the mushroom shape predicted in buoyancy-driven models. Moreover, as discussed in a previous section, the aspect ratio of the metamorphic belt is around 1:100, and is quite different from the plume shape, and platy. If size is too small, even though density difference is large enough, buoyancy uplift is not effective. Thickness of about 1 to 3 km is extremely small compared to the whole crust in space. Simple calculation never supports that it can penetrate into mantle wedge (Fig. 15). With regard to boundary conditions, OA and OB behave as either as a free slip or frictional boundary surface. In a typical case of angle AOB shown in Fig. 15, the initial conditions are alpha equals 30°, beta equals 5°, and 0.5°, it would lead to exhumation of material from 60 km depth to the surface either along a free slip boundary or frictional boundary.

To move material from a depth of 120 km to the surface, around 80% deformation is required at the wedge triangular region. The average deformation speed would depend on the deformation speed in the wedge region. Deformation speed within the wedge is assumed to be constant. Exhumation speed must be faster at the deeper regions and tends to be slower near the surface. In the above example, the exhumation speed at 120 km depth reduces to one third near the surface and the material during the exhumation is stretched five times (free slip) to 20 times (frictional slip) along the exhumation direction. In the laboratory experimental studies performed by Chemenda et al. (2000) to understand the exhumation mechanism of Himalayan regional metamorphic belts, paired faults were clearly reproduced and the model of wedge extrusion well illustrated.

9.6. Second stage uplift and mountain building

Wedge extrusion mechanism can exhum the regional metamorphic belts along Benioff thrust from mantle depths to the mid-crustal level. However, another mechanism is necessary from there to move the material to the surface. This is the second stage process of doming and mountain building by domal uplift of the unit, which is sandwiched as the core of the regional metamorphic belt. The typical example is the Himalayan mountain building, which started since 8 Ma triggered by the southward jump of plate boundary. Along the new plate boundary, continental crust began to subduct underneath the Himalayas and jacked up part of higher Himalayas (Takada and Matsuura, 2002) (Fig. 16).

9.7. Modern analogue of regional metamorphic belts and exhumation mechanism

It is interesting to examine why regional metamorphic belts were generated episodically and exhumed to the surface to through time. During the last 500 million years along the circum Pacific region such as Japan and California, glaucope-bearing regional metamorphic belts were formed and exhumed to the surface every 100 My on an average (Maruyama et al., 1996). New orogenic belts were formed underneath and/or oceanward through time episodically. In the case of continent collision-type regional metamorphic belts, although the occurrence and timing vary among different cases, our synthesis shows that about 30 collision-type orogenic belts were formed on the Phanerozoic earth by continent collision (Fig. 4).

In the case of continent collision, the formation and exhumation of regional metamorphic belts appear to be related to the size of continent. For example, the size of continents to form UHP units shows a wide range from India, North China, and Western Europe to small continents such as Madagascar and Java Island in Indonesia (Liou et al., 2000, 2002; Parkinson et al., 2002). In the case of the continents smaller than the size of Madagascar or arc, we do not normally see any example of UHP metamorphic belts. We examine this aspect in more detail below.

Whether the subducted continental crust is accreted to the hanging wall without subduction into deep mantle, or returned back to the surface depends on a number of factors including size (buoyancy) of the continent and the degree of coupling between the subducting slab and the overlying continental crust. The descending Pacific plate immediately before the trench outer wall of the Japan Trench in NE Japan is bent to generate horst and graben structures. The grabens have a maximum depth of 500 m and are a few km wide, which are then filled by quartzofeldspathic trench turbidites. These sediments are being subducted into the deep mantle together with Pacific MORB crust (Miura et al., 2003). Buoyancy derived from graben filled sediments would not be effective because of the relatively small size or volume. However, in the case of intraoceanic arc subduction, such as the Kyushu–Palau paleo-arc and Amami plateau (paleo-arc) with thickness less than 20 km, subduction proceeds into deep mantle without any accretion (Kodaira et al., 2000; Yamamoto et al., 2009). In the case of Izu Mariana arc with a thickness of continental crust of
about 30 km, at least some of the intraoceanic arc tends to be accreted which indicates adequate buoyancy to overcome the coupling force exerted by descending slab. Note that buoyancy depends on the volume, hence if the collision of arc is not vertical or tangential to the trench, but parallel to the trench, even 20 km thick arc crust can be accreted to the hanging wall, a process that was presumably common in the Archean.

We now consider the stress system that promotes the exhumation of UHP–HP metamorphic belts using modern analogues. Regions of our interest are shown in Fig. 17 which is a world map to show the distribution of plate boundary. The ongoing exhumation area of regional metamorphic belt must be along the active consuming plate boundary. In the case of collision-type regional metamorphic belts, the best modern analogue is the non-volcanic outer arc in Timor–Tanimbar region of Indonesia (Fig. 18). Along the non-volcanic arc from Timor through Tanimbar to Salem, a U-shaped non-volcanic outer arc continues over 2000 km. Miocene glaucophane-bearing regional metamorphic belts are exposed in southwestern part of this region for about 700 km long and in the northwestern part for over another 600 km, although not in the central part (Ishikawa et al., 2007; Kaneko et al., 2007). To the west of the N–S trending non-volcanic arc, a forearc basin (Weber Deep) is developed with a depth of up to 7000 m. The region itself is underlain by strong extensional state (Charlton et al., 1991). On the contrary, the domains to the north and south are underlain by strong N–S compressional state (Fig. 18).

The metamorphic belts towards the SW part, particularly the southwestern end, correspond to the late stage of collision orogeny...
and the island itself is uplifted as a dome showing the development of a number of normal faults on the island to uplift Quaternary reef limestone above 1300 m. The top of the folded mountain in the Timor reaches 2960 m and shows the highest elevation speed over the world, 0.4 to 0.6 cm/year for the last 0.5 million years on an average. To the east of the outer arc, the elevation rate tends to be small. In the case of Laibobar Island, 700 km away from Timor, the top boundary of glaucophane-bearing metamorphic belt is exposed above the sea level (which is a normal fault) and the Quaternary reef has not been uplifted for the last 1 million year. The difference in terms of uplift clearly shows the time difference in the stage of orogenic evolution, and confirms that domal uplift has not been initiated to the east. On Laibobar Island, minor normal faults were identified which indicate that the domal stage may have started very recently. However, the Timor Island has already been uplifted vertically over 1300 m. Under the Taninbar Island, which is the easternmost portion of the non-volcanic arc, domal uplift has not yet begun and the leading edge of the subducted Australian continental plate is being broken off from the subducting oceanic lithosphere (Osada and Abe, 1981) (Fig. 18b). The boundary of break-off between continental lithosphere and oceanic lithosphere is characterized by high seismicity, vertical to the seismicity in the Benioff plane (Osada and Abe, 1981). The seismological characteristics suggest slab break-off and that the buoyant continental lithosphere cannot subduct deeper than the present, a constraint posed by the more dense older oceanic lithosphere which exerted a higher slab-pull force leading to the slab break-off. To the west under the Timor Island, the continental lithosphere is already released from oceanic slab and hence the free buoyant subducted continental slab promotes exhumation of regional metamorphic belts as shown in Fig. 18.

Thus, the process of exhumation is related to slab break-off and resultant change in the subduction angle from deep to shallow thereby promoting the subducted wedge to remove to arc-trench gap (Fig. 18b) (Maruyama et al., 1996). Taninbar illustrates the stage just after slab break-off and complete release of slab. On the other hand, the case of Timor shows a further advanced stage of second domal uplift. On the contrary, 100 km north of Timor, the volcanic arc has already shut down its magmatic factory to the north of volcanic arc, and a south dipping back thrust is developed (Hamilton, 1979; Harris, 2006; Nugroho et al., 2009). The active back thrust disappears to the northeastern end of Timor indicating that the entire region from the north of the volcanic arc to the trench is underlain by the strong N–S compressional state (Fig. 18).

On the other hand, to the west of Timor, the Indo-Australian plate is completely separated from the descending oceanic slab, which is sinking down into deep mantle. The subduction angle of the Australian continental lithosphere has turned shallower thereby pushing up the entire Timor Island. The continued uplift of Timor Island starting from 0.5 Ma has resulted in the present day peak of the mountains reaching over 2960 m. We now consider ongoing example from the Pacific-type orogenic belts. Whether continent collision-type or Pacific-type regional metamorphic belts fundamentally record the same structural pattern; that is, a sandwich structure and two-step exhumation process followed by extensive mountain building at the latest stage. This suggests that a similar mechanism operates to exhume the regional metamorphic belts regardless of their category as collision or Pacific-type. As mentioned in an earlier section, the fundamental control is exerted by the change in subduction angle to shallow values. In the case of Pacific-type, the shallowing subduction angle and the approach of mid-oceanic ridge to the trench are well-studied. It is considered that in the circum Pacific orogenic belts, mid-oceanic ridge subduction has occurred once every one hundred million years on an average (Engbretson et al., 1985).

Some of the youngest Pacific-type orogenic belts occur in the Olympic Peninsula, southwest of Seattle near Vancouver (Fig. 19a) (Maruyama et al., 1996). This is the region of Quaternary uplift cut to the east by active normal fault, and to the west by active reverse fault. These two faults seem to be paired and sandwich the thin `platy' geologic unit 20 km >100 km in space. The core of this wedge-shaped package contains low-grade lawsonite-bearing schists formed at about 11 km depth (Brandon and Calderwood, 1990). The wedge extrusion here started in the Miocene to expose the deep-seated portion of an accretionary complex. Apatite fission track age shows 7 to 11 Ma (Brandon et al., 1988; Brandon and Calderwood, 1990).

The Juan de Fuca plate subducting underneath the Mt. Olympus is very young, ca. 5 Ma (Engbretson et al., 1985). To the west, the N–S trending active Juan de Fuca ridge is present which moves eastward at the rate of 3 cm/year and which will finally subduct after few million years. Considering the last 20 million year movement of the mid-oceanic ridge, the age of subducting slab underneath is gradually

![Fig. 17. World map showing ongoing orogeny along the active consuming plate boundaries of the Earth. Six examples are marked, the details of which are explained in later figures.](image-url)
younging through time. The subducted oceanic slab bends rather suddenly at 40 km depth of the Benioff plane, which would considerably promote the wedge to extrude upward as shown in a present day cross section in Fig. 19.

History of plate subduction in this region supports an approaching ridge through time to remove the wedge to the surface. In the case of the well-studied Pacific-type blueschist belts of Sambagawa belt in Japan, the emplacement of deep-seated eclogite blueschist belt to the mid-crustal level occurred at 70 to 80 Ma which is almost identical to the ridge subduction of the Kula-Pacific. The transport to the surface occurred afterwards, at about 50 Ma. The example of the Sambagawa indicates that the transport to shallow surface level was after the event of ridge subduction. The Juan de Fuca plate has only a 20 to 30 km thick lithosphere because of the very young age. Therefore at depths of 25 to 50 km, a number of small earthquakes occur within the slab mantle. These earthquakes are derived by dehydration reaction, similar to the well-studied case in Japan (Hasegawa et al., 2009; Maruyama et al., 2009; Omori et al., 2009). The regional metamorphic belts emplaced at mid-crustal level under the forearc region could have been infiltrated by abundant dehydrated fluid — both deep subducted sediments and from the downgoing slab.

We now examine the case of SW Japan. The age of the Philippine Sea Plate subducting underneath SW Japan arc is highly variable depending on the place (Fig. 20). For example, under Kyushu, a very old portion of the oceanic plate (older than 100 Ma) together with 4 remnant island arcs are being subducted (Seno and Maruyama, 1984; Maruyama et al., 2009). On the other hand, in the central Honshu and Kanto regions, the oceanic lithospheric is older than 48 Ma as deduced from the age of boninite in the Ogasawara arc (Seno and Maruyama, 1984). The Philippine Sea plate subducts at the intermediate region from Kanto to Kyushu and the Shikoku Palece–Vera Basin has an age of 8 to 30 Ma. The youngest part is the region marked by Kinan Sea Mount chain, which is being subducted just under the Kii Peninsula. Kii Peninsula is the region where most remarkable uplift is ongoing since the Quaternary. Therefore, the central part of the Kii Peninsula has been severely eroded exposing the structural bottom under the Sambagawa belt. Thus, the Shimanto belt is in direct contact with the Median Tectonic Line to the north, with the Sambagawa belt missing in the Central Kii Peninsula. An evaluation of the uplift rate in SW Japan shows that the eastern and western parts were less eroded and the central part of the Kii has been most uplifted. Therefore, apparently, the age of subducting plate is critical; if it is young, the hanging wall seems to be selectively uplifted and eroded.

In the case of NE Japan, the Cretaceous Pacific Plate is being subducted under the arc. The E–W cross section of NE Japan arc at Sendai brings out subducted sediments from high-resolution of seismic tomography made by Hasegawa et al. (2009). The subducted sediments are present below the Benioff plane at 40–80 km depth.

Fig. 18. Ongoing exhumation of continent collision type metamorphic belt in Timor–Tanimbar region of Indonesia (partly modified from Maruyama et al., 1996). (a) An outline of tectonic environment of the Indonesian region. Note the contrasting stress field between the west (compressional) and the east (extensional). (b) Cross section along A–B in the extensional environment. Forearc region is underlain by the compressional stress field whereas the back arc side is dominated by extension to form the 7000 m deep Weber Basin. Beneath the arc, slab break-off is ongoing. (c) Western side N–S cross section of the Timor Island. Note the location shown on (a). The entire region is underlain by strong N–S compressional stress field and the back thrust is developed on the back arc side. Oceanic slab has been disconnected with the resultant buoyancy of continental lithosphere. The regional metamorphic belt exposed on the surface is in the second stage of exhumation by doming associated with a number of high angle normal faults.
together with hanging wall of already-accreted sediments. The hanging wall of metamorphosed unit under BS–EC conditions may be promoted to uplift along the Benioff plane carrying fragments of mantle wedge by anticlockwise convection in the wedge corner triangle (Fig. 21). If this process is ongoing, the exhumation of UHP–HP belt may occur in the case of old-slab subduction.

In the area where younger plates are being subducted in SW Japan, local differences of uplift are also observed. For example, along the strike of orogenic belts, topographic depression appears periodically from east to the west. The Ise Bay, Kii Strait and Bungo Strait were tectonically subsided whereas the intermediate region in Kii Peninsula and Shikoku were elevated.

Recently, microearthquakes termed as tremors have been precisely recorded by the recently established seismic network in Japan. This has helped to carefully monitor the fluid derived from Moho depths and to trace the ‘day-to-day’ movement of fluids (Obara, 2002; 2009). The results show two regions where no tremors were observed beneath the Kii Strait and the Ise Bay (Fig. 22a). In spite of the fact that subduction-related dehydration occurs commonly beneath shown by slab-seismicity, the fluid has not come out above the Moho depth. The following is a speculation to explain this enigma. Above the Benioff plane in these two regions, high-pressure–low-temperature regional metamorphic belts are being extruded and emplaced at mid-crustal level. These units absorb the dehydrated fluid released from underneath to produce hydrous minerals. On the contrary, in the intermediate regions such as Kii Peninsula and the central part of Shikoku, hydration completed to extract excess fluids above the depth, with the second stage of doming to form high angle secondary normal faults. In future, the youngest blueschist belt may appear in both Kii and Shikoku if this interpretation is correct. We compare two cross sections across eastern Shikoku with no tremors, and central Kii Peninsula with frequent tremors (Fig. 22b). Along the eastern Shikoku section, a topographic anomaly (high) close to the sea level, has been speculated to be due to the presence of subducted seamount underneath (Kodaira et al., 2000). An alternate interpretation is that the subducted accretionary complex was tectonically extruded after blueschist facies metamorphism up to mid-crustal level to push up the foregoing portion, which is now close to the sea level (Fig. 22). The Kii Peninsula and Central Shikoku are now underlain by second stage of doming as supported by the tectonic uplift above 350 m for the last 0.17 Ma at Muroto cape (Yoshikawa et al., 1964). Average uplift rate is 2 mm/year. The sharp V-shaped notch at the south of Muroto Peninsula probably was formed by high angle normal fault along the

Fig. 19. Ongoing Pacific-type orogeny in the Cascade region in the western North America (partly modified by Brandon and Calderwood, 1990). (a) Tectonic environment of the Cascade region showing the distribution of subduction zones and subducting young Juan de Fuca plate. Note the location of the youngest lawsonite-bearing schist at Mt. Olympus. (b) E–W cross section showing the uplift of Mt. Olympus which is cut on the top by normal fault and on the bottom by reverse fault. Extensive hydration could be present underneath shown by the nest of frequent seismicity from the underlying Juan de Fuca plate.
Fig. 20. (a) Index map showing the age variation of Philippine Sea plate. Western Philippine Sea on the north is as old as 100–40 Ma. The eastern margin, which subducts under the Kanto region, is older than 48 Ma. The central part of Philippine Sea that subducts underneath SW Japan is as young as 30–17 Ma. (b) Cross section along A–A’ (modified after Park et al., 2002). Regional metamorphic belt seems to be exhumed along the splay faults, which may explain the recent remarkable uplift in the Kii Peninsula. Also shown is the top boundary of subducting Philippine Sea plate. The presence of cold seep indicates low-temperature springs enriched in nutrients. Cold seep is the surface expression of splay fault, and the abundant nutrients feed biological communities.
coastal lines, supporting the idea of domal uplift. Such domal uplift cut by high angle normal faults suggests the underplating of a buoyant mass of accretionary complex below to push up the above. The buoyant mass could be younger spreading ridge, or rising large volume of quartzofeldspathic accretionary complex. A similar process seems to be ongoing under the Kii Peninsula. Thus, SW Japan might expose the youngest blueschist belt in future.

10. Relationship to orogeny

Regional metamorphic belts occupy the orogenic core and are hence the most important element of an orogen. The process to produce regional metamorphic belts is complex including generation of the metamorphic belt, subsequent exhumation, emplacement at mid-crustal levels, and finally mountain building which exposes the regional metamorphic units to the surface. Large-scale orogenic belts regionally affect the already existing continental crust causing widespread sedimentation in the surrounding regions, accompanied by arc magmatism to increase the volume of continental crust. Thus, regional metamorphism is one of the most important processes in orogeny.

Orogeny is not an instantaneous phenomenon, but a process that lasts over a long time of the order of a hundred million years. In the case of Himalayas, the subduction started at 50 Ma. The beginning of UHP to HP metamorphism started at 48 Ma (Kaneko et al., 2003), which is very close to the timing of subduction initiation, and it took 23 million years from UHP metamorphism at mantle depths to the mid-crustal level exhumation at 25 Ma where extensive hydration-recrystallization occurred. Furthermore, dome like uplift and mountain building started only after 8 Ma with a large time gap reaching 15 million years. From the time of initiation of metamorphism to mountain building, it took a total of 40 million years. Subsequently the plate boundary shifted leading to the rise of the Himalayan mountains since 1 Ma ago. Mountain building is still going on at present (Fig. 23).

In the case of Pacific, taking the Sambagawa belt as an example, subduction and underplating of accretionary complex from trench up to 60–70 km depth took only 1 million year, based on the computations of relative plate motion during the Cretaceous time (Engebretson et al., 1985; Maruyama and Seno, 1986). Regional metamorphism has its peak at 120 to 125 Ma as demonstrated by zircon SHRIMP age (Okamoto et al., 2004). Exhumation and emplacement at mid-crustal level occurred between 80 and 60 Ma, where extensive hydration occurred. Therefore, it took 40 to 45 million years from mantle depths to the mid-crustal level. Thereafter, dome-like second step mountain building began to expose the high-grade regional metamorphic rocks to the surface by 50 Ma (Isozaki and Maruyama, 1990). From the second stage mountain building, the uplift rate is estimated as 4 mm/ year, converting 10 to 12 km uplift during 20 to 30 million years. Thus, the Sambagawa orogeny has taken 70 million years from its beginning to the surface exposure of regional metamorphic rocks.

Pacific-type orogeny in the Sambagawa metamorphic belt during the Cretaceous is yet another process. In this case, folding and underplating of accretionary complex from trench up to 60–70 km depth took only 1 million year, based on the computations of relative plate motion during the Cretaceous time (Engebretson et al., 1985; Maruyama and Seno, 1986). Regional metamorphism has its peak at 120 to 125 Ma as demonstrated by zircon SHRIMP age (Okamoto et al., 2004). Exhumation and emplacement at mid-crustal level occurred between 80 and 60 Ma, where extensive hydration occurred. Therefore, it took 40 to 45 million years from mantle depths to the mid-crustal level. Thereafter, dome-like second step mountain building began to expose the high-grade regional metamorphic rocks to the surface by 50 Ma (Isozaki and Maruyama, 1990). From the second stage mountain building, the uplift rate is estimated as 4 mm/ year, converting 10 to 12 km uplift during 20 to 30 million years. Thus, the Sambagawa orogeny has taken 70 million years from its beginning to the surface exposure of regional metamorphic rocks.

![Fig. 21. A schematic illustration of 3 domains of metamorphic–metasomatic factory (MMF), subduction zone magma factory (SZMF) and big mantle wedge (BMW) under NE Japan across Sendai (Maruyama et al., 2009, based on seismic tomography work by Hasegawa et al., 2009). The double seismic planes (hatched) cause a large pulse of dehydrated fluid from the descending Pacific-slab leading to viscosity contrast among MMF, SZMF and BMW. Counter-flow convection in the mantle wedge begins immediately above 200 km depth and moves toward a volcanic front obliquely to release an arc magma under the volcanic front. The boundary between MMF and SZMF corresponds to the culmination point of frequent seismicity at 60 km depth. The enlarged figure shows a contrasting convection flow for MMF and SZMF, the former promoting exhumation of subducted sediments as shown by yellow color including fragments of wedge mantle peridotites (Alpine peridotites).](image-url)
the northernmost foothill of the mountain belts consisting a major portion of the batholith belts. If this is the case, Pacific-type orogeny may have had two stages of mountain building at the initial stage and at the final stage.

Fig. 23. Tectonic evolution of the Himalayan region from 60 Ma to the present (modified after Kaneko, 1997). Before the Indian collision, Pacific-type orogeny prevailed to form paired belts, Cretaceous huge batholith belt on the north associated with contemporaneous BS belt on the south. The Indian continent subducted underneath the southern margin of Eurasia at 50 Ma, the regional metamorphism started from 48 Ma and proceeded to progressive HP–UHP metamorphism, followed by slab break-off to trigger the exhumation of UHP–HP belt into mid-crustal depth by 25 Ma by wedge-extrusion process. Asthenospheric upwelling by delaminated slab heated the bottom of thickened continental crust under Tibet, caused eclogite melting at the Moho depth and erupted adakite lava-flows. Also shown is the top boundary of the UHP–HP unit called STDF (South Tibetan Detachment Fault). The bottom boundary is MCT (Main Central Thrust). An extensive hydration occurred at 25 Ma at mid-crustal level. Second stage doming started around 8 Ma to cause mountain building to transport huge amounts of sediments to the Indian Ocean.

Fig. 22. (a) Distribution of tremors at the Moho depths in SW Japan (Obara, 2002). Note the absence of tremor in Kii Strait and easternmost part of Shikoku and in the small region near Ise Bay. Also shown is the isodepth contour of the top of the Philippine Sea plate. (b) Schematic cross section along A–B and C–D. A–B is the cross section for the tremor-absent region whereas C–D is the tremor present region. Absence of tremor can be explained by the dehydrated fluids were all absorbed to hydrate the exhumed and water unsaturated regional metamorphic unit. Tremor is observed after the saturation of exhumed regional metamorphic belt shown along C–D cross section.
11. Himalayas and Andes: a comparison

In the Himalayas, a 50 million years long history exists prior to the final collision-type orogeny (Fig. 23). At present, within the Indian Ocean near the spreading ridge, prominent seismicity records compressional stress. Therefore, the plate boundary is delineated not along Main Frontal Thrust in the Himalayas, but within the Indian Ocean (Engdahl et al., 1998), which corresponds to the northern boundary of the Indo-Australian plate. If the plate boundary shifts completely from MFT to Indian Ocean, the Himalayan Mountain Range would not be a mobile orogenic belt, which means the end of collision orogeny.

On the other hand, in the central part of the Andean Mountain Belt, mountain building has definitely begun since Miocene at about 25 Ma (Ramos and Aleman, 2000). This was caused by continent subduction of South America underneath the Andean mountain range known as A-type subduction to jack-up the Andean mountain. This process corresponds to the mountain building at the initial stage of Pacific-type orogeny (Fig. 24). However, regional metamorphic belt has not yet been emplaced into the core of the Andean mountain, and extensive scale of felsic volcano-plutonism has not yet occurred. Moreover, subduction zone volcanism itself is absent in about one third of the entire Andean region (Gutscher et al., 1999). These observations suggest that the Andean mountain range is underlain by a mountain building stage, but has not yet reached the activated time dominated by extensive volcano-plutonism and exhumation of regional metamorphic belts in the forearc region. Presumably, the Andean belt is still in the initial stage over the entire 70 million years long Pacific-type orogeny. However, Andean mountain range is wide enough so that a regional provincialism might be present. For example, at the southern end of the Andean belt, mid-oceanic ridge began to subduct underneath where TTG granite intruded near the trench only 50 km from the trench. Therefore, this local area may have been in the stage of a peak Pacific-type orogeny (Fig. 24c). But the regional metamorphic belt has not yet been exposed on the surface. Comparing the Sambagawa orogeny, the stage at the southern end of the Andean belt is the stage before the doming uplift and after the exhumation of regional metamorphic belts at mid-crustal level. Nevertheless, the overall stage of the whole Andean belt has not yet reached the second mountain building stage. In future, a few mid-oceanic ridges would reach to the trench to promote the orogenic activity (Fig. 24c).

11.1. Mountain building is unrelated to the exhumation of HP–UHP belt

In collision orogeny, formation of huge mountain belt is restricted to the final stage. On the other hand, the Pacific-type is marked by two stages of mountain building — the first stage is characterized by the tectonic uplift of volcanic front with simultaneous HP–UHP metamorphism by A-subduction from the backside down to 60 to 100 km depth. The second mountain building occurs at the end of orogeny as discussed before.

Regardless of collision-type or Pacific-type, the mountain building is unrelated to exhumation of regional metamorphic belts. Mountain building to expose the orogenic core occurs by the domal uplift of the sandwiched units with the core of regional metamorphic belts at the end of orogeny. However, at this period, tectonically eroded portion reaches only 10 km. Formation of folded mountain accompanied by active erosion generates the remarkable topography of mountain belts, but corresponding to only about 3 kbar change in metamorphic pressure. It is important to note the extremely large pressure gradient from 25–70 kbar down to 3–5 kbar recorded in regional metamorphic rocks, are absent in terms of vertical movement on the surface. This is due to extremely slow exhumation of regional metamorphic rocks from mantle depths to mid-crustal level and because of the very thin sheet-like solid intrusion of the metamorphic belt along Benioff thrust. Therefore, there is no manifestation on the surface in terms of vertical movements.

There is an essential difference between collision-type and Pacific-type orogens (Fig. 25). In the case of collision reflecting the different mechanism of uplift, only the pressure drops at near-constant temperature at temperature after the metamorphic pressure reaches the peak. On the other hand, both pressure and temperature decrease together in the case of Pacific-type. This may be due to the fact that oceanic plate subduction was simultaneously ongoing when the HP–UHP units are being removed tectonically to the mid-crust, although need to verify in future (Fig. 25).

12. Concept of paired metamorphic belts

In 1961, Miyashiro proposed metamorphic facies series and paired metamorphism based on the geology of Japan. These two concepts helped the establishment of plate tectonics in 1968. However, the concept of paired metamorphic belts has been considerably modified since then (Santosh and Kusky, 2010; see also Brown, 2010-this issue). For example, collision-type regional metamorphic belts are not paired at all. No counterpart of low P high T metamorphic belt is present. Also, granitic batholith belt is absent in general. In the case of Alps and Himalayas, minor post-orogenic granites intruded at the end of the orogeny. It should be noted that oceanic plate subduction is a necessary phenomenon prior to the final collision of continents in the case of collision-type orogeny. Therefore, Pacific-type accretionary complex must have been formed to the north of collision type orogeny in the case of Himalayas. In this case, proportional to the total length of subducted oceanic plate, size of accretionary complex and size of batholith belts must vary. To the north of the Himalayan Mountain Range, a huge batholith belt and small glaucophane-bearing metamorphic belts are observed both of which are ca. 100 Ma old and formed prior to the Himalayan collision (Maruyama et al., 1996). These paired rocks would belong to Pacific-type orogen, and not to the collision type. On the other hand, there is no batholith belt in the Alps. In the case of collision type orogen, there is no heat source to produce high-T low-P type metamorphic belts.

In the case of Pacific-type orogenic belts, the presence of low-P and high-T regional metamorphic belts is rather exceptional. If present, both belts were not exhumed to the surface at the same period. For example, in the Sambagawa–Ryoke paired metamorphic belt, regarded as the world standard, the Ryoke belt runs side by side with the Median Tectonic Line (MTL) on the map view, with Ryoke in the north and Sambagawa in the south, in general. But in the three dimensions, the Ryoke belt rests above the Sambagawa with a sub-horizontal fault called as paleo-MTL (Isozaki and Maruyama, 1991). The boundary fault was formed at 15 Ma when Japan Sea opened and the upper Ryoke belt was thrust over the Shimanto–Sambagawa and Jurassic accretionary complex from north to southward. Thereafter, in Kii Peninsula and Shikoku, particularly the regions towards the eastern part were preferentially uplifted to erode out the upper Ryoke belt. As a result, the apparent distribution of the Sambagawa to the south and Ryoke to the north appear to give an impression of paired belts. Yet, on the western margin of Shikoku, whole Kyushu and Kanto plain, top and bottom relationship of the Ryoke and Sambagawa are preserved very well. The apparent arrangement of paired belt is also recognized in New Zealand and Celebes. Hida, Sangun and Hidaka are also exceptional examples of paired belts over the world. In the case of Pacific-type orogenic belts, huge TTG belts on the continent side are paired with low-temperature high-pressure type regional metamorphic belts oceanward. In this case, batholith belt is paired with high-pressure low-temperature regional metamorphic belts, and not with low-pressure high-temperature metamorphic belts. Finally we conclude that Miyashiro’s concept of paired metamorphism is correct, but incorrect for the simultaneous uplift to expose paired belts.
13. Fluids and regional metamorphism

The major cause of regional metamorphism has long been considered as an effect of the increase of $P$ and $T$. However, the evolution and migration of fluids have been highlighted in recent studies and perhaps played the most crucial role (e.g., Santosh et al., 2009b). The zircon crystals formed during metamorphism include high-$T$ low-$P$ minerals such as magmatic origin at the core e.g., quartz, albite which are mantled by the newly grown zircon during the increased $P$–$T$ conditions. This in turn includes coesite, jadeite and diamond in the

![Tectonic map of Andean orogenic belt showing E–W cross section (A–B, C–D). Also shown is the distribution of thrust on the eastern foothill of the Andean mountain belts (Ramos, 1999). Subducting mid-oceanic ridge is present only at the southern margin of the Andean mountain. As shown in A–B cross section (Ramos et al., 1996), a series of thrusts push up the Andean belts by A-subduction of South American continent underneath the Andean belt. Regional metamorphic belts may have been formed along the southern margin of Andean belt, but have not yet been exposed to the surface (shown along cross section C–D). Red triangles denote volcanoes.](image-url)
The discovery of UHP metamorphic rocks and their petrologic and tectonic characteristics have revolutionized the concepts of regional metamorphism, particularly focusing on the evolution and migration of fluids. The link between earthquakes and metamorphism in consuming plate boundaries became increasingly apparent. In these zones, subducted hydrated slab dehydrates with increasing pressure and temperature and the fluid liberated would remarkably influence the rheological properties and stress fields (Peacock, 1993, Omori et al., 2002, 2009; Hacker et al., 2003 etc.). In other words, the birth of fluid and its transportation translates to triggering of earthquake, based on the concept of dehydration embrittlement (e.g., Meade and Jeanloz, 1991; Omori et al., 2009). Metamorphic petrologists can study the fossil evidence for earthquake within regional metamorphic belts and evaluate the dynamics of orogenic movement. Subduction zones along which frequent earthquakes occur are in fact the location of ongoing progressive metamorphic reactions (Maruyama et al., 2004; Omori et al., 2009).

15. Fluid circulation characterizes the plate boundary

Distribution of earthquakes is confined only to the plate boundary (Fig. 27a). Fluid circulation is restricted only to the plate margin of consuming plate boundary from which fluid moves deep into the earth’s interior at least covering the whole upper mantle down to 660 km depth. In the divergent boundary, fluids come up from mid ocean ridge magma, which in turn originated at 410 km through a curtain-like mantle upwelling (Zhao, 2004). Fluids may have been derived from the Earth’s interior to the surface through superplumes (see Maruyama et al., 2009; Santosh et al., 2009b). This observation indicates that regional metamorphism occurs only along the plate boundary where earthquakes occur. For the other regions such as under the continents and within ocean plate, no free fluids are available except hotspots and hence no recrystallization proceeds. Even under the continents in the lower crust or below the Moho, even if temperature conditions exceed 700 °C, no metamorphic recrystallization must prevail if fluid is absent. A contrasting picture emerges in the distribution of earthquakes between mid-oceanic ridge and continental rift. In the former case, earthquakes are present down to 660 km depth, but in the latter, only at depths shallower than 30 km along the transform fault boundary. Earthquakes are generated at depths shallower than 15 km. These contrasting differences in depths correspond to...
16. Metamorphic recrystallization in the whole mantle

If the circulating fluid is the only factor to cause regional metamorphism as documented clearly in UHP–HP metamorphic rocks and zoned zircon which contains quartz, graphite, albite inclusions in the core and rim, with mantle including diamond and coesite and/or jadeite, the site of ongoing recrystallization in the whole mantle scale could be envisaged as shown in Fig. 27. The cross section of the Earth is schematically shown cross-cutting Pacific and African superplume together with the western Pacific triangular zone with double-sided subduction zones, to make it clear for circulating fluids to recrystallize the mantle and related rocks. According to the double-sided subduction, the upper mantle in the western Pacific triangular zone is being recrystallized most predominantly among whole upper mantle region, and by the same reason the lowermost mantle could preserve the lowest temperature of ca. 2300 °C at CMB (core–mantle boundary) (Maruyama et al., 2007).

In addition, the two sites of rising superplume could bring recrystallization from the top by the presence of fluids derived from liquid outer core, because of the presence of light elements such as C, H, O, and S, which occupy ca. 10% of the outer core, and are oversaturated in the growing solid inner core (Maruyama, 1994; Maruyama et al., 2007). Below the mid-oceanic ridge down to ca.30–40 km depth, rising mantle flow would release migmatic melts to cause the recrystallization to reset the isotope equilibration.

On the other hand, the fluid-absent zone such as the bottom of cratonic continents would not be recrystallized even at T over 700 °C, nor will there be any isotopic re-equilibration. Hence the radiometric ages remain as before. If this is true, the orogenic peridotites may retain old mantle convection history even at CMB level, preserved in within mineral inclusions of zircons.

17. Subduction zone geotherm through geologic history and the shrinking forbidden zone

The subduction zone geotherm must have changed through time, according to the cooling Earth since its birth at 4.6 Ga in the planetary space. This issue has long been considered by several authors based on the P–T estimates of regional metamorphic belts over the world, either Pacific-type or collision-type. Here we summarize the concept based on the results presented in Maruyama et al. (1996) and Maruyama and Liou (2005).

Since the pioneering work by de Roever (1957), several authors have tried to confirm the geothermal gradients at subduction zone through time, and all of them recognized a clear trend of secular variation with time (Fig. 28). The maximum T limit for regional metamorphism has been less than 900–1000 °C throughout Earth history. However, the maximum-P condition increased from 2.0 GPa before 1000 Ma to >6.0 GPa after 630 Ma. Most metamorphic terranes older than 1000 Ma show maximum-P conditions less than 1.0 GPa, indicating that Precambrian metamorphism occurred within crustal depths and slab-melting to produce TTG (tonalite–trondhjemite–granodiorite) rocks that dominate the continents (Martin, 1993). This is because a wide P–T field of slab-melting lies above the wet solidus of hydrated MORB (Fig. 28).

All recognized UHP belts are younger than 630 Ma, and the subduction zone metamorphism to form UHP belt became possible only after the temperatures became cold enough to inhibit slab-melting (Fig. 28). It should be pointed out that the subduction zone
geotherm is nearly parallel to the wet solidus of MORB (Maruyama and Liou, 1998). This probably caused the sudden appearance of UHP–HP belts after 630 Ma.

Following the secular change of subduction zone geotherm, as recorded in regional metamorphic rocks shown in Fig. 28, the forbidden zone in P–T space at low-T and high-P side has reduced through time. The region was wide enough to cover a major part of P–T space below MORB wet solidus before 1000 Ma, but got rapidly reduced towards the low-T side after 630 Ma. This change allowed lawsonite eclogite to appear first since 520 Ma along the eastern margin of

Fig. 27. a): Global distribution of earthquakes (shown by dots) and plate boundaries (modified after Seno, 1995). The distribution of earthquakes shows an excellent correlation with the plate boundary such as mid-oceanic ridges, continental rifts and transform faults. The upper mantle beneath the western Pacific shown as shaded region is dominated by water supplied by double-sided subduction zones from the east and from the south (see Maruyama et al., 2007). b): The cross section of the Earth along the solid curve in a), indicating ongoing recrystallization of mantle by fluid circulation (blue color). Recrystallization, which corresponds to ongoing regional metamorphism, may be highly restricted as shown by the cross section. Even in the deep mantle recrystallization may be possible only by fluid migration from the liquid outer core. See more details in the text.
Unfortunately the Japanese scientific community lost him from Japan in 1965 as he spent the latter half of his academic years in U.S.A, developing his field to cover whole Earth, particularly ocean-floor petrology. We Japanese would like to appreciate his highly intelligent and thoughtful works written in Japanese first before the articles in English were published. All of these contributions educated Japanese, and developed understanding of the consuming plate boundary around Japan and the whole Earth.

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References


Australia (Watanabe et al., 1997). Another example is from Guatemala (Tsujimori et al., 2006).

18. Postscript

It has already passed nearly 30 years since coesite-bearing UHP rocks were first reported from collisional belts in Europe, but several debates continue. The UHP belts constitute only a very minor component among the various metamorphic belts of the world. However, this trivial “noise” has radically revised many of the concepts and framework of metamorphic petrology established over the last 100 years and expanded the realm of metamorphic petrology to include many subjects including deep Earth geophysics. One of the major advancements in metamorphic petrology was the understanding of the role fluids and the critical role they play in mineral transformation. Indeed, crustal rocks subjected to extreme metamorphic conditions were the key for this paradigm shift, with newer information on ongoing processes in active plate boundaries adding more fuel to the debate.

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Prof. A. Miyashiro was a pioneering worker who systematized metamorphic petrology, combined with tectonic settings, back in late 1950s. He was born in Japan, and contributed to Earth Science in Japan.


