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REVIEW ARTICLE
Origins of Japan—the 'Big Picture' Revisited: A Review of New Plate Tectonics Research

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This review essay mainly compares two articles by G.L. Barnes on Japanese geology, previously published in *Japan Review* (2003, 2008), with a series of articles on 'New Paradigms' in Japanese plate tectonics published in *Chigaku zasshi* in 2009–2010. The first purpose is to update and add new details to flesh out the previous *Japan Review* overviews. A discussion about collisional and accretionary tectonics then follows, outlining problems of interpretation by scholars coming from different academic backgrounds (Alpine geology and subduction-zone geology). This text is highly technical, based on the previous offerings which should be read first.

Japanese geologists are forging ahead in determining new ways to measure and interpret geological processes in a subduction zone. The Japanese archipelago, composed of twenty seven geological belts, is affected by movement of four different plates: two oceanic plates subducting under the main islands, and the islands themselves apportioned between two continental plates. The 500 million year history of the formation of the Japanese landmass is of great general and theoretical interest but not well covered in formal textbooks. Thus, scientific papers such as the *Chigaku zasshi* offerings in Japanese as well as those in English published in the prominent geology journals must be synthesized to gain an understanding of this region. Since these subduction-zone movements have given rise to modern volcanoes and earthquakes, that understanding forms a crucial background for disaster management.

New research mentioned herein includes zircon-dating of sediments in accretionary complexes, identification of "second continent" formations in the mantle, and tectonic erosion/accretion alternation.

Keywords: Japanese geology, plate tectonics, palaeogeography, structural geology, accretionary complex, collision tectonics, tectonic erosion

Introduction

This author has previously published two articles in *Japan Review* that recounted the formation of the Japanese islands.[1] Beginning around 2007, several articles have since appeared

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[1] Barnes 2003, 2008.

in scientific journals that are again changing our understanding of the geological origins of Japan. In addition to reviewing this new research, my self-appointed task is to assess whether my previous coverage of this topic remains accurate in light of these new findings. In short, I can say yes, but several points need modifying. In addition, I offer a brief consideration of the overall problem of accretionary versus collision tectonics. Readers unfamiliar with geological terminology are advised to read the earlier *Japan Review* articles, which have extensive explanations of fundamental concepts plus glossaries for particular terms. The present review builds on these earlier presentations, even as it amends the information contained therein.

Here I survey a series of thirty five articles published in three parts under the title "Nihon rettō keiseishi to jisedai paradaimu" 日本列島形成史と次世代パラダイム (Geotectonic evolution of the Japanese Islands under New Paradigms of the Next Generation) in three issues of the *Chigaku zasshi* 地学雑誌 119:2 (2010), 119:6 (2010), and 120:1 (2011). All articles but one are in Japanese with English titles and abstracts, and most illustrations have captions in both Japanese and English. Free PDFs of these articles are available via the *Chigaku zasshi* website, or directly from J-Stage (Japan Science and Technology Agency). The English abstract for each article gives a good indication of content, while every issue has its own preface in Japanese, in addition to an overview in English by Kasahara et al. (2010), cited in the bibliography below. References herein to articles in the *Chigaku zasshi* (CZ) series other than the English overview will be cited only by CZ volume, issue and page numbers, keyed to the dates of publication above. Several of the findings of these original reports have been synthesized by Isozaki et al. (2010), which is drawn on here together with further sources in English; these are footnoted by author and date as usual, and appear in the bibliography below.

The *Chigaku zasshi* collected papers contain an overwhelming wealth of new findings, new ideas, and new concepts as well as historical perspectives—in the form of original papers, review articles and historical reviews. Overall, the authors emphasize the importance of Pacific-type (or Miyashiro-type) orogeny—that is, mountain building through subduction rather than through collision, the latter getting more press through the formation of the Alps and Himalayas. They emphasize that during the first two billion years of earth's existence, continents were formed exclusively through such subduction orogeny.[2] This is still the main mechanism for continental growth, but this understanding is now tempered by the concepts of tectonic erosion and second continent formation, the latter of which forms the substance of the "new paradigm."

The concept of Pacific/Miyashiro-type orogeny has been challenged by French geologists since the 1980s, with their experience in Alpine geology. A new article by Charvet continues to dismiss this concept in favour of Alpine-type collision orogeny in an island arc, insisting on collision as a major factor in the formation of the Japanese landmass.[3] Charvet objects to several aspects of Pacific/Miyashiro-type orogeny, but presents his viewpoint as argument by assertion. Much detail, both old and new, is included but nothing that clearly supports his assertions. I cannot rebut his work in detail here, but I include below instances of collision in Japan that show that the proponents of Pacific/Miyashiro-type orogeny have

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[2] Maruyama et al., CZ 120:1, pp. 115–223.

[3] Charvet 2013.

an open mind about collision—as they are open to any new developments—but that they demand a firm grounding in the data and not unsubstantiated assertions.

New Paradigms and Challenges

The newest understanding

In 2010, Japanese geologists announced to the world that they had identified the driving force that makes the Pacific Ring of Fire so tectonically active.[4] The key words here are "tectonically active." They do not refer to the volcanic eruptions and earthquakes common in the Ring of Fire but to rifting: particularly, what is called "second continent" formation and its role in causing continental rifting. This finding links interaction between the subducting slab of oceanic floor and the overlying continental plate in a kind of boomerang effect.

Previous Japanese research concentrated on identifying the nature and contents of Accretionary Complexes (ACs): those materials scraped off the ocean floor during subduction and accreted, together with trench deposits, to the continental plate edge in one form of accretionary tectonics—a major mechanism of continental growth. In contrast, the new research proposes that more often than not, the ocean floor grinds away the edges of continental plates through tectonic erosion, rather than adding to them through accretion. The eroded materials contain much granite previously produced through subduction zone magmatism; these granitic materials are carried down by the subducting slab to between 520 and 660km deep, where they equilibriate and consolidate to form "second continents." The heat from naturally radioactive elements in granite in second continents causes the formation of magma plumes in the overlying mantle, which rise to break up the earth's surface crust. These are much larger than the magma extrusions produced through any individual volcano, and these plumes act especially to break up supercontinents. The many rifted basins in the East Asian region, such as Lake Baikal and the South China, Philippine, Bohai 渤海 and Japan Sea basins, are thought to be caused by such superplume activity from the second continent region.

Thus, subduction is not just something that happens at the edge of continents: subducted materials affect the very coherence of the continents that overlie them. However, whether the second continent revelation constitutes a new "paradigm" within plate tectonics research is arguable, though the authors can certainly claim credit for making many aspects of subduction and rifting—and indeed their linkage—more understandable through this model. In time we might see the second continent model join the long stream of Japanese contributions to plate tectonics through identifications of the earthquake zone along the downgoing oceanic slab (now called the Wadati-Benioff Zone) by Wadati in 1935, of paired metamorphic belts by Miyashiro in 1961, of the Volcanic Front concept by Sugimura in 1965, of Pacific-type orogeny by Matsuda and Ueda in 1971, and of the Accretionary Complex concept by Kanmera in 1976.[5]

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[4] Kasahara et al. 2010.

[5] As listed in Isozaki et al., CZ 119:6, pp. 999–1053; see also Isozaki et al. 2010.

Revisions to understanding

Additional new information can be highlighted with reference to Isozaki et al., who have identified several "mistakes" in past research that are best "forgotten."[6] These mistakes are given in Table 1 (left hand column) along with the revised understandings (right hand column). Many of those corrections will be revisited in the section below on "Updates."

X Mistaken research results X	O Corrections O
X–That all of Japan formed and developed off the North China craton	O–Instead, most of the Japanese landmass formed off the South China craton
X–That the most important faults are the Median Tectonic Line (MTL) and Fossa Magna	O–Instead, the sub-horizontal faults separating the various Accretionary Complexes (ACs) are the major structuring agents of the Japanese landmass
X–That the origin of the MTL can be traced to a Cretacous strike-slip fault running along the continental edge and connected with the Tanakura Tectonic Line (TTL)	O–The Paleo- and Neo-tectonic lines operated differently at different times, with only the latter being a shallow strike-slip fault related to the TTL
X–That the Japan Sea opened (like French doors) from the middle, anchored at fixed points at the sides	O–Instead, the Japan Sea basin rifted along two strike-slip faults, E and W, and the Japanese landmass moved directly away from the continent
X–That the most important faults in Japan are steep angle normal faults	O–Instead, the most important are the sub-horizontal faults separating ACs
X–That Japan's several strike-slip faults are over 1000km long and some parts of Japan moved up along them from the area of Vietnam	O–Instead, the strike-slip faults are relatively shallow, recently activated, and affect the local landmass
X–That Japan is composed of strike-slip fault bounded terranes that do not share a common genesis	O–Instead, it is composed of sub-horizontal thrust sheets that formed successively in similar subduction environments
X–That when ACs were not forming, the oceanic plate was subducting very obliquely	O–The absence of ACs is more likely due to loss of ACs through tectonic erosion
X– That the growth of ACs occurred continuously seaward	O–ACs formed intermittently
X–That once arc crust is formed, it is not destroyed and continental growth continues seaward	O–Instead, arc crust can be destroyed through tectonic erosion, and rather than growing in size, the landmass can be reduced in size
X–That when an arc collides with an orogenic zone, continental crust is not increased	O–Granite basements of arcs can be subducted, as is currently occurring with the Izu Arc

Table 1. Revisions in Japanese plate tectonics research: "mistakes" as drawn from Isozaki et al. (CZ 119:6, pp. 999–1053) with corrections given by the author. X (batsu) indicates "wrong," O (maru) indicates "correct."

Exportable research results

Isozaki, Maruyama and Yanai argue that Japanese geology is now in its latest stage of development: that of "exporting science" (after non-science, colonial science, and independent science), explained as the ability to provide new indigenous research technologies to other countries.[7] One of these exports is using U-Pb (radioactive uranium decaying into stable

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[6] Isozaki et al., CZ 119:6, pp. 999–1053.

[7] Isozaki, Maruyama and Yanai, CZ 119:2, pp. 378–91.

lead) dating and LA-ICP-MS (Laser Ablation Inductively Coupled Plasma Mass Spectrometry) analysis of zircon crystals in Accretionary Complexes to reconstruct the subduction record.[8] Zircon crystals reside in the AC protolith (that is, AC sediments/sedimentary rocks before being metamorphosed) and igneous rock fragments incorporated into the AC; some zircons are detrital because they have come from already eroded and disappeared granite bodies and sandstones that have been recycled into these AC. By investigating where they came from, the nature of the inner continent behind the subduction zone where the AC was forming can be ascertained.

A second export involves using seismic profiling to reconstruct both second continent regimes and the three-dimensional nature of ACs.[9] Germane to this is the need to establish the importance of faults according to their structural roles, with tectonic unit boundaries taking priority over other faults which are perhaps more recent, more visible, and account for current re-arrangements rather than fundamental geotectonic arrangements. In assessing the relationship between geological belts, it is necessary to recognize the three-dimensional forms of regional metamorphic zones. This allows assessment of continuity in relationships between adjacent belts from unmetamorphosed ACs through to High Pressure/Low Temperature metamorphic belts.

Finally, the revised view on granite destinations is exportable (Isozaki et al. 2010): namely that arc batholiths can disappear through tectonic erosion, leading to second continent formation; that tectonic erosion contributes to the formation of serpentinite belts (transformed mantle rock), which are later exhumed to the surface; and that there is significant subduction of buoyant continental crust in the Izu-Bonin 伊豆–ボニン Arc.

Updates to "The Big Picture"

In the following section, the new Japanese research will be compared with what was published in *Japan Review* in Barnes 2003 and 2008. The dating conventions are: Ga = billion years ago, Ma = million years ago.

• I reported that accretionary tectonics have been a relatively unknown compositional aspect of the Japanese islands by non-geologists, who usually think of Japan as a volcanic archipelago. In fact, the geological belts of the Japanese landmass are almost entirely composed of ACs with some continental fragments, but many overlie and are intruded by igneous masses. Worldwide, the survival of Accretionary Complexes is rare, making Japan an exemplary case. The more common process is the loss of continental and oceanic crust through subduction-erosion.[10] ACs are estimated to have formed during one third of the time since subduction began, while erosion occurs during the other two thirds;[11] today, 75% of subduction zones around the world are eroding, while 25% are accreting.[12] The Japanese islands therefore are valuable resources for studying ACs as phenomena of crustal growth, especially in a world where continental crust is now decreasing in mass.[13]

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8 Isozaki et al., CZ 119:6, pp. 999–1053; Nakama et al., CZ 119:6, pp. 1161–72.

9 Isozaki et al. 2010.

10 Maruyama et al., CZ 120:1, pp. 115–223; Tsujimori, CZ 119:2, pp. 294–312; Ueda, CZ 119:2, pp. 362–77.

11 Suzuki et al., CZ 119:6, pp. 1173–96.

12 Yamamoto, CZ 119:6, pp. 963–98.

13 Yamamoto, CZ 119:6, pp. 963–98.

- ACs which do not survive are tectonically eroded from the over-riding plate by the subducting plate—along with granitic continental crust. These materials are taken down into the mantle where they are understood to form second continents.[14] It is estimated that five to seven times the amount of continental crust that exists on the earth's surface is contained in these submerged second continents.[15] Isozaki et al. propose that accretion and erosion along the continental edge occurred alternately.[16]

- I took pains to emphasize that the present day Japanese Islands have only existed as islands since ca. 15 million years ago. It now appears that at least five series of "Japan" arcs (defined by granite basements) have been created, among which some "proto-Japan" arcs have existed as continental arcs and others as archipelagos similar to modern Japan.[17] Three previous arcs have been subducted and lost to second continent formation, except for blocks of granite and metamorphic rocks incorporated into—and therefore surviving in—existing serpentinite mélanges.[18] Serpentinite is the mantle rock peridotite after it has absorbed water, thus becoming soft and acting as a trap for other rocks pushed into it (forming a mélange) as the downgoing slab scrapes against the mantle.

- The initiation of subduction in the Japan area has been pushed back from 450Ma to 520Ma.[19] U-Pb dating of zircons has revealed clusters of dates when granite batholiths underlying arc formations in subduction zones were created at 520–400Ma, 280–210Ma, and 190–160Ma; these have all been eroded away except for current small exposures.[20] The Ōmi 青海 serpentinite mélange in the Hida 飛騨 Marginal Belt (Hida Gaien) represents the earliest subduction phase,[21] while several other serpentinite belts contain granite fragments dating to 450Ma and 250Ma.[22] The Cretaceous batholiths, dating to 110–90Ma and 80–60Ma still exist in the San'yō 山陽 and San'in 山陰 districts, respectively.[23]

- Further zircon datings reveal seven periods of continental erosion whose materials were eventually recycled into the proto-Japan area: 2500–1000Ma (Paleo- to Mesoproterozoic), 1000–800Ma (Neoproterozoic), 520–400Ma (Cambrian-Silurian), 280–210Ma (Permian-Triassic), || 190–160Ma (Jurassic), 110–90Ma (mid-Cretaceous), || and 80–60Ma (Late Cretaceous-Paleogene).[24] The double lines here indicate when there was a major change in the source of the erosional materials: the first at 200Ma when the North and South China cratons collided, and then at ca. 80Ma after the formation of the Cretaceous granite batholith, which kept earlier continental materials from flowing into the proto-Japan area.

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[14] Senshū, Maruyama and Rino, CZ 119:6, pp. 1215–27.
[15] Kawai et al., CZ 119:6, pp. 1197–1214.
[16] Isozaki et al. 2010, pp. 95–100.
[17] Isozaki et al. 2010, p. 102, Figure 12-c.
[18] Isozaki et al., CZ 119:6, pp. 999–1053.
[19] Kunugiza and Gotō, CZ 119:2, pp. 279–93; Santosh and Senshū, CZ 120:1, pp. 100–114.
[20] Nakama et al., CZ 119:6, pp. 1161–72.
[21] Matsumoto et al., CZ 120:1, pp. 4–29.
[22] Suzuki et al., CZ 119:6, pp. 1173–96, Figure 5.
[23] See Isozaki et al. 2010: Figure 6 cont.
[24] Isozaki et al. 2010, p. 89.

• In Figure 5 and text of Barnes 2003, I represented the then current understanding that the Hida Belt was affiliated with the North China craton (ancient continent) and the Oki 隠岐 Belt derived from the South China craton. The dates of detrital zircons in the Oki Belt are now understood to be as old as the Hida Belt, matching the date of the North China craton at 2.0–1.8Ga when the craton resided in the center of the former supercontinent Nuna/Columbia. Conversely, detrital zircons recovered in Japan from the South China block date only to ca. 1Ga when that craton resided in the center of the next supercontinent, Rodinia.[25] Thus both the Hida and Oki Belts are now thought to derive from the North China craton.

• Upon the break-up of Rodinia, subduction began at ca. 520Ma, as represented in rocks from the Hida Marginal Belt representing an early island arc. The oldest sedimentary unit, a felsic tuff bed, has been identified at 472Ma, indicating the existence of explosive volcanoes at that time.[26] The next oldest sedimentary unit is the South Kitakami 南部北上 Belt, comprised of shelf sediments post-dating 444Ma.[27] Other "oldest" units in the Hida Marginal Belt are these: oldest ophiolite 520Ma, oldest granite 520Ma, oldest metasomatism 520Ma, oldest blueschist 450Ma.[28]

• One of the more fascinating aspects in studying the early geology of Japan is the reconstruction of paleogeographic maps. Those presented in Barnes 2003/2008 have now been updated in Isozaki et al., with commentary (Section 7).[29] These give a more dynamic view of the units being discussed here.

• The collision and unification of the North and South cratons is represented on the continent by the Qinling-Dabie-Sulu 秦峰–大別–蘇禄 suture, which covers a large extent in China and crosses into the Korean Peninsula. Four tiny parcels of mid-temperature/pressure metamorphic belts claimed to correlate with this suture zone have recently been found at widely separated locations in Kyushu 九州, near the Noto 能登 peninsula and in eastern Tōhoku 東北.[30]

• I noted that the exhumation of high pressure/low temperature metamorphic belts was a common phenomenon in subduction tectonics. There now exists a clear model for how AC materials, subducted to depths that result in blueschist facies metamorphism, are then "squeezed up by insertion" during non-accretionary, erosive periods.[31] Moreover, the current crystalline contents of these metamorphosed units represent not the peak pressure/temperature of metamorphism but a retrogressive crystallization as the unit dehydrated during exhumation.[32]

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[25] Santosh and Senshū, CZ 120:1, pp. 100–114; Nakama et al., CZ 119:6, pp. 1161–72.
[26] Nakama et al., CZ 119:2, pp. 270–78.
[27] Shimojō et al., CZ 119:2, pp. 257–69.
[28] Isozaki et al. 2010, Figure 12.
[29] Isozaki et al. 2010, Figures 11–14.
[30] Ōmori and Isozaki, CZ 120:1, pp. 140–51.
[31] Ueda, CZ 119:2, Figure 9-B.
[32] Isozaki et al. 2010, p. 89.

- I referred to the Japanese archipelago as a “mature island arc” in contrast to the Izu Arc. Six stages of continental crust growth are now recognized in Pacific-type orogeny, with different parts of Japan used to represent stages 3, 5 and 6.[33]

- Ophiolites, which are remnants of oceanic floor, are scattered throughout the Japanese islands. These are likely to have been formed in back-arc or fore-arc positions around previous proto-Japans (similar to the existing oceanic floor in the Japan Sea formed 20–15Ma) rather than representing oceanic floor from the Pacific Ocean plate predecessors. The oldest ophiolite in Japan, however, at 600Ma, is thought to derive from a passive margin setting of oceanic plate (similar to the current Atlantic Ocean shores) before subduction began.[34]

- The Sanbagawa 三波川 Metamorphic Belt is shown as cutting through the middle of Kyushu in Figures 7 and 9 of Barnes 2003. This belt has been discovered to incorporate at least two different ACs, formed and metamorphosed at different times; the geographical extents of these separate components have now been revised.[35] The two parts are now referred to as the Sanbagawa Metamorphic Belt sensu stricto and the Shimanto 四万十 Metamorphic Belt (MB). Rocks of the Shimanto MB have been discovered in northern Kyushu on the western side of the Nomo 野母 Tectonic Line in Nagasaki 長崎 prefecture, indicating substantial displacement of south western Japan southwards along the fault, perhaps as part of the Japan Sea opening.[36]

- The Median Tectonic Line, one of the major constructional faults running through western Japan, was earlier believed to have shifted Outer Zone strata (on the southern rim of Japan) more than 1000 miles northwards from off the southern China coast to their present position in Japan. This interpretation of “the once popular but unrealistic strike–slip fault-controlled tectonics in SW Japan” has now been discarded in favour of in situ sub-horizontal stacking of ACs.[37] The MTL is now discussed in two chronological senses: the paleo-MTL, which was a mechanism of arc shortening during the opening of the Japan Sea basin; and the neo-MTL, which is a Quaternary strike-slip fault that demarcates the boundary of the Nankai 南海 fore-arc sliver.[38]

- Because NE and SW Japan are subducting differently aged and differentially hydrated plates (Pacific and Philippine, respectively), their volcanic eruption patterns and chemistries are completely different.[39]

- The history of the Izu Arc was previously presented as a collision with Honshu 本州 after 15Ma in five separate (intermittent) accretion events.[40] The juncture of the Izu Arc with Honshu, involving the Philippine Plate, the North American Plate (northeast Honshu) and

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[33] Maruyama et al., CZ 120:1, pp. 115–223.

[34] Isozaki et al., CZ 119:6, pp. 999–1053.

[35] Aoki et al., CZ 119:2, pp. 313–32; Otoh et al., CZ 119:2, pp. 333–46.

[36] Kōchi et al., CZ 120:1, pp. 30–39.

[37] Isozaki et al. 2010; Itō and Satō, CZ 119:2, pp. 235–44.

[38] Isozaki et al. 2010, p. 95.

[39] Katayama et al., CZ 119:2, pp. 205–223.

[40] Hirata et al., CZ 119:6, pp. 1125–60.

the Eurasian Plate (southwest Honshu), is now recognized as a triple trench junction.[41] This onshore triple junction is twinned with the offshore triple trench junction of the Philippine, North American and Pacific Plates.

Recent seismic studies on the Izu Arc indicate that buoyant material such as an island arc can be easily subducted if less than 25km thick.[42] The bending of the geological belts in the Kantō 関東 syntaxis at 5Ma was ostensibly caused by crust greater than this thickness, accompanied by the accretion of crustal blocks now marooned as the Tanzawa 丹沢 and Misaka 三坂 mountains. The majority of the Izu Arc, subducted since 17Ma, amounts to about 700–800km in length.

One of the reasons Izu Arc materials were intermittently accreted is the angle of the arc meeting Honshu: perpendicular (orthogonal); when an arc collides obliquely, it subducts smoothly, as is currently the case with the Kyushu-Palau Ridge subducting under Kyushu.[43] In contrast, an intra-oceanic arc that did not subduct but accreted in the Triassic exists in the Maizuru 舞鶴 Belt.[44]

- I reported that the Japan Sea opening took place between 19 and 15Ma; completion of rifting is now dated to 16Ma.[45] The whole rifting process has now been extended to include a series of processes: a superplume causing arc volcanism at 39–37Ma and resulting in general uplift; the beginning of normal faulting and seawater intrusion ca. 33Ma; rifting far enough to begin ocean floor formation ca. 20Ma; and further arc volcanism between 20–15Ma accompanying rifting.[46]

I also reproduced Matsuda and Otofuji's 1984 palaeomagnetic data in understanding the opening of the Japan Sea as NE and SW Japan rotating down from the continent like French doors opening outwards.[47] This model is now rejected in favour of movement (like an opening drawer) directly away from the continent along two transform faults: the Tanakura 棚倉 Tectonic Line in Tōhoku and the Ululun Tectonic Line running down the west of Kyushu;[48] this movement was accomplished with very little rotation, leaving SW and NE Japan microplates as the largest of thirty one separate continental blocks rifted from the continental edge.[49] Yanai, Aoki and Akahori (Figure 7) propose a reconstruction that packs these blocks back into the area of the current Japan Sea, where many remain marooned there today. The portions of north eastern and south western Japan were widely separated, while the Outer Zone is shown in approximate position circa 20–25Ma. They estimate that 150km of crust separated the current Inner and Outer Zones and was lost (via thrust movement) when these were brought into their present positions.

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[41] See Isozaki et al., CZ 199:6, Figure 2.

[42] Yamamoto et al. 2009.

[43] Isozaki et al. 2010, p. 95.

[44] Isozaki et al. 2010, Figure 13-c.

[45] Nakama et al., CZ 119:6, pp. 1161–72.

[46] Yanai, Aoki and Akahori, CZ 119:6, pp. 1079–1124.

[47] Barnes 2003, Figure 8b.

[48] Isozaki et al. 2010, p. 95.

[49] Yanai, Aoki and Akahori, CZ 119:6, Figure 3.

Geotectonic "Belt" Descriptions

The tectonic units that make up the Japanese landmass are traditionally called "belts" (*tai* 帯); elsewhere these may be termed "terranes," but the imported term "terrane" is avoided because it too often implies an exotic (allochthonous) origin and is testimony to the nature of "colonial geology" in Japan.[50]

Figure 1 presents a compilation of information on these various tectonic belts, several newly identified; equivalencies are clarified for those tectonically rearranged belts which have different names in different parts of the country but are of the same origin. Other more minor belts appear in the Japanese geological literature but are not included here. Notes to the map include the caution that the granite belts and their contact-metamorphic aureoles (Ryōke/Gosaisho 領家/御斉所) are very different from most other belts, which began as Accretionary Complexes and have undergone varying degrees of regional metamorphism. The continental fragments (Hida, Oki Belts) are also of a completely different origin than the ACs that make up the majority of the Japanese landmass. Finally, the South Kitakami Belt is noted for being the only example of very thick ancient shelf sediments.

All of these geotectonic "belts" are fault-bounded. Considerable work has been expended in identifying the kinds of faults that separate each type of unit and how important they have been in constraining the developmental sequence of the Japanese landmass.[51] Interestingly, the big, recently active faults such as the Median Tectonic Line (neo-MTL), Itoigawa-Shizuoka 糸魚川–静岡 TL, Fossa Magna, Kantō (Tone 利根) TL, and the Tanakura 棚倉 TL are classified as steep-angle normal strike-slip faults of minor fourth class significance, as they are boundaries of microplates which were activated relatively recently in the opening of the Japan Sea.

The more significant class one and two major faults are low-angle normal or reverse (thrust) faults that occur between the continental craton/suture fragments and an AC, and between an AC and a high-pressure metamorphic belt. Because the faults are low-angle, the relationship between neighbouring belts is sub-horizontal, meaning that faults define the tops and bottoms of stacked units. The geological belts are thus layers, not blocks (as they appear to be in surface outcrop on a map).

A full N-S cross-section of the archipelago has been constructed through Shikoku 四国, Chūgoku 中国 and the Oki 隠岐 Ridge, showing the sub-horizontal layering in the Inner Zone, and a slightly oblique layering in the Outer Zone.[52] The MTL has traditionally been considered the boundary between these two zones, but this needs clarifying following the separate identifications of the paleo-MTL and neo-MTL: it is the paleo-MTL that separates the Ryōke granites of the Outer Zone from the Sanbagawa Metamorphic Belt of the Inner Zone.[53] The major Tectonic Lines that structure the Japanese landmass—from oldest to youngest, north to south: Nagato-Hida, Ōsayama 大佐山, Ōmi 青海, Ishigaki-Kuga, Butsuzō, and Aki 安芸—are essentially sub-horizontal thrust faults which represent previous subduction planes.[54]

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[50] Isozaki et al., CZ 119:6, pp. 999–1053.

[51] Isozaki et al., CZ 119:6, pp. 999–1053; Yanai, Aoki and Akahori, CZ 119:6, pp. 1079–1124.

[52] Itō and Satō, CZ 119:2, pp. 235–44.

[53] Isozaki et al., CZ 119:6, pp. 999–1053.

[54] Isozaki et al. 2010, Figure 8.

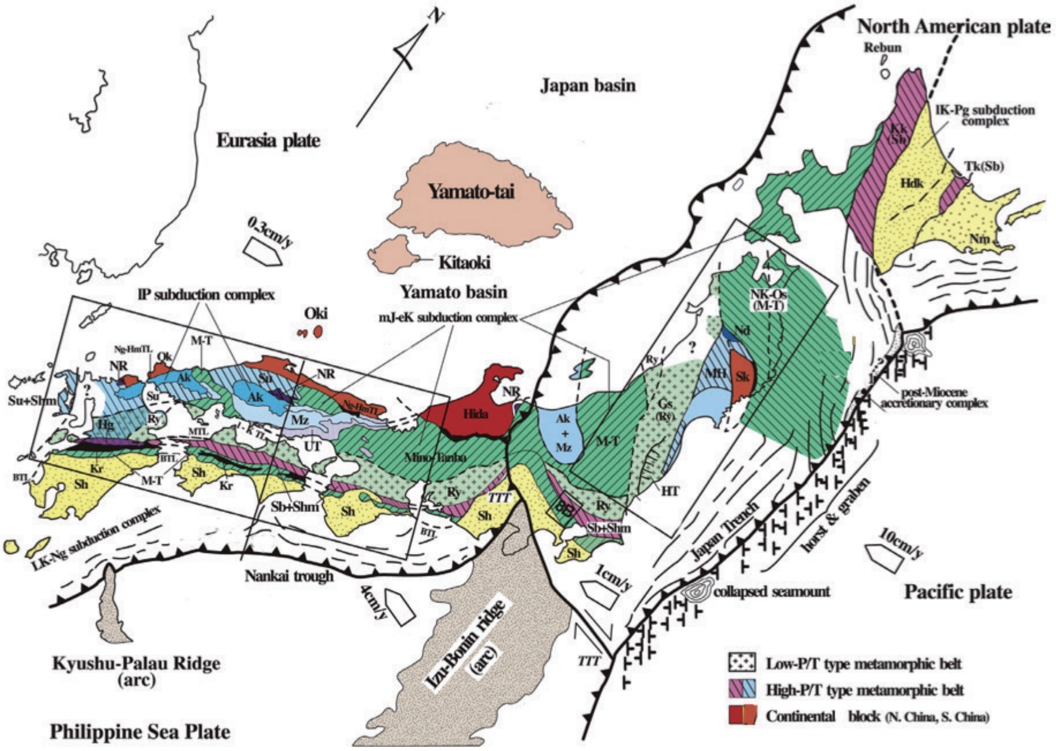

Figure 1. Descriptions of Geological Belts comprising the Japanese landmass (condensed from Isozaki et al., CZ 119:6, pp. 1013–1022; Isozaki et al. 2010, pp. 1013–1022). Tectonic Line (TL) abbreviations: BTL = Butsuzō 仏像, I-KTL = Ishigaki-Kuga 石垣–玖珂, MTL = Median, Ng-HmTL = Nagato-Hida Marginal 長門–飛騨. Other abbreviations: TTT = triple trench junction; IP = igneous province; mJ-eK = middle Jurassic–early Cretaceous; lK-Pg = late Cretaceous–Palaeogene.

Collision Orogeny in Japan?

Charvet states that "the first and main difficulty" with the Pacific-Miyashiro Orogeny model is that it is based on ridge subduction causing nappe (AC) emplacement; he argues that ridge subduction causes tectonic erosion, not accretion.[55] Instead, he insists that "the arrival at the trench of a small block with a lighter crust, and therefore positive buoyancy, like a mature arc or micro-continent is able to induce a collision producing permanent compressive structures."[56]

It seems to me that Charvet has misunderstood the causal sequence of the proposed role of ridge subduction in accretion. Figure 3 in Isozaki et al. (2010) clearly shows that ridge subduction is followed several million years later by AC formation. Isozaki and colleagues do not deny the reality of tectonic erosion at the continental edge, but as I understand it, they argue that the subduction of a hot oceanic ridge will cause both uplift and magma production at the continental edge. The uplift and increased volcanic activity will result in a higher rate of erosion, which supplies sediments to the trench. It is these sediments that are then bulldozed back up into the continental edge to form an AC, long after the ridge has been subducted.

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[55] Charvet 2013, p. 92.

[56] Charvet 2013, p. 94.

Belt	Abbreviation	Nature	Dates (those from detrital zircon in parentheses)	Protoliths of metamorphic belts; Contents of others	Metamorph. Date	Metamorphic facies P = pressure T = temperature	Notable rock types (minor)
Hida 飛騨	Hd	continental fragment	Pre-Cambrian (3.4Ga, 2.6Ga, 2.0-1.7 Ga, 1.1Ga, 580Ma)		280-240Ma		gneiss; Jurassic granite intrusions
Oki 隠岐	Ok	continental fragment	Pre-Cambrian (3Ga, 2Ga, 1.7Ga)	silt, sand	280-240Ma	medium	gneiss; Jurassic granite intrusions
Nagato-Renge 長門 – 蓮華	NR=Kr	serpentinite mélange, includes Hida Gaien & Renge schist	Palaeozoic	metamorphosed component from Ordovician~Devonian AC; includes ultrabasic rock	450-340Ma	lowT/highP crystalline schists occur as tectonic blocks in eastern part	400Ma granitoid gneiss as tectonic blocks in western part
Miyamori-Hayachine 宮守 – 早池峰	MH=NR	Ophiolite + serpentinite mélange	Ordovician (480-470Ma) ophiolite			highP rocks in mélange	
Sangun 三郡	Sn	old name, now split into Renge and Suo schists					
Kurosegawa 黒瀬川	Kr=NR	serpentinite mélange existing as a klippe in Chichibu Belt		same origin as NR and pre-Jurassic serpentinite mélange beneath it			includes early~late Palaeozoic volcanics, sediments & metamorphic rocks
S. Kitakami 南部北上	Sk	thick shelf sediments	post-Ordovician-Mesozoic				440–410Ma arc granites
Nedamo 根田茂	Nd	Accretionary Complex; Permian part same as Ak	Carboniferous-Permian				
Higo 肥後 + locs. In Unazuki 宇奈月, Hitachi 日立	Hg	Qinling-Dabieshan-Sulu suture fragments	(3.7–1.9Ga detrital zircons) in 260–230Ma granites	silt, sand, fossiliferous limestone, Cambrian volcanics	230Ma	medium	Permian-Cretaceous granites
Hitachi-Takanuki 日立 – 高貫	HT (Ht-Tk) = Hg	northeastern fragment of Hg		Cambrian and Carboniferous sediments, volcanics		medP	
Akiyoshi 秋吉	Ak	Accretionary Complex		sandstone, mudstone chert, reef limestone, seamount greenstone and ocean floor basalts	Late Permian	weak	
Suo 周防	Su	Metamorphic Belt		silt, sand, Permian-Triassic AC	240Ma	lowT/highP greenschist-glaucophane schist facies	
Maizuru 舞鶴	Mz	fragment of Palaeozoic island arc; closely related to UT	Permian-Triassic	Permian granite, ophiolite; Permian-Triassic sandstone			

Belt	**Abbreviation**	**Nature**	**Dates (those from detrital zircon in parentheses)**	**Protoliths of metamorphic belts; Contents of others**	**Metamorph. Date**	**Metamorphic facies P = pressure T = temperature**	**Notable rock types (minor)**
UltraTanba 超丹波	UT			Permian-Triassic AC		weak	
Chizu 智頭	Cz	Metamorphic Belt	separated from Suo Belt by zircon dates	Triassic AC	180Ma	lowT/highP greenschist-glaucophane schist facies	silty sandy greenschist
MinoTanba 美濃－丹波	M-T = Ch	Accretionary Complex	end of Triassic-Jurassic				
Chichibu 秩父	outlier of M-T	Accretionary Complex					
Sanpōzan 三宝山	subset of Chichibu	Accretionary Complex	early Cretaceous	seamounts			
N. Kitakami-Oshima 北部北上－渡島	Nk-Os = M-T, Ch	Accretionary Complex	Jurassic				
Ryōke 領家	Ry = Gs	granite batholith and metamorphic aureole	Cretaceous	M-T Jurassic AC + Ak Permian AC + Su Triassic highP metam. + Hg medP metamorphics			lower mylonite
Sanbagawa 三波川	Sb *sensu stricto*	Metamorphic Belt	Cretaceous, 140Ma protolith	early Cretaceous AC	mid-Creta. 120–110Ma peak	lowT/highP greenschist-eclogite facies	silty sandy greenschist, covered w/ eclogite schist
Shimanto 四万十	Shm	Metamorphic Belt divided from Sb *s.s.*	<80Ma protolith (part of Sh-N that metamorphosed)	mid-Cretaceous AC	term. Creta. 60Ma peak	lowT/highP greenschist-eclogite facies	silty sandy greenschist
Kamui kotan 神居古潭	Kk = Sb	Metamorphic Belt			Cretaceous	lowT/highP	
Tokoro 常呂	Tk = Sb	Metamorphic Belt			Cretaceous	lowT/highP	
Gosaisho 御斉所	Gs = Ry	granite batholiths and metamorphic aureole	Cretaceous	Jurassic AC		weak	
Southern Shimanto 南部四万十	Sh-S	unmetamorphosed AC		Palaeogene AC, southern end is Miocene AC			sandstone mudstone (chert greenstone)
Northern Shimanto 北部四万十	Sh-N	unmetamorphosed AC mélange	<80Ma	late Cretaceous			sandstone mudstone (chert greenstone)
Hidaka 日高	Hdk = Sh	Accretionary Complex	Cretaceous	Cretaceous AC	Cretaceous	partially metamorphosed	
Nemuro 根室	Nm	shelf sediments	Cretaceous				

Table 2. Geological belts of Japan (modified from Isozaki et al., CZ 119:6, pp. 999–1054, Fig. 1). Ga = billion years; Ma = million years; '=' means 'equals' or 'is the same as'; AC = Accretionary Complex.

Isozaki et al. make a clear distinction between orogenic boundaries, such as the above Tectonic Lines, and collision sutures. Two arc-arc collision sutures are named as minor constituents of archipelagic formation: the Kōzu-Matsuda 国府津–松田 fault in central Honshu, and the West Hidaka fault in central Hokkaido,[57] while only two instances of continent-continent collision affecting Japan are identified: the major collision of the North and South China cratons at 230Ma, and the current minor colliding of SW and NE Japan to form the Japan Alps.[58]

The one large-scale over thrust sheet that resembles an Alpine nappe occurs along the palaeo-MTL, a thrust fault that was activated between 20–15Ma during Japan Sea opening.[59] Isozaki et al. state:

> By utilizing mid-crustal detachment, the upper crust of the arc (the Cretaceous batholith belt and associated pre-Cretaceous AC + meta-AC units) was horizontally transported ocean wards. Consequently, the enigmatic occurrence of granite batholith unit over the coeval high-P/T meta-AC in western Shikoku was achieved.[60]

By splitting the continental unit (the Japan arc) and over-thrusting one part onto another, the granite batholith unit detached from its basement became "rootless" when over thrust, thus conforming to the formal definition of a nappe: "thrust sheets which have moved more than about 10 km relative to the footwall."[61]

Another example of the differing interpretations by Charvet and Isozaki et al. concerns the status of the North Shimanto Belt.[62] Isozaki et al. identify it as an AC formed 80Ma which partially underwent high pressure metamorphism between 70–60Ma;[63] as the lower crust of a forearc zone, it detached and slid under the main islands along the BTL, a previous subduction plane. Charvet refers to the North Shimanto 北部四万十 Belt as a "continent-type block," which collided and under thrust along the BTL between 80 and 60Ma. However, he does not state where this "Shimanto block" came from and does not define what "continent-like" means in terms of the North Shimanto Belt which is an AC.

Part of the problem here is whether the "docking" of the North Shimanto belt is viewed as accretion or collision. Is this perhaps a false dichotomy? Cloos suggests that the "terms collision and collider should be reserved for bodies whose subduction caused or would cause some kind of rearrangement in the pattern of plate motion, generally the initiation of a new subduction zone and the creation of mountains."[64] These changes only happen in continent-continent collision, which does not occur in "peripheral orogens," such as the Japanese landmass, permanently facing the open ocean at the edge and not being approached by another continental mass.[65] Island arcs and other oceanic bodies do, in a sense, collide with a continental edge (like the Izu Arc is doing now), but since they do not cause

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[57] Isozaki et al. 2010, p. 95.

[58] Isozaki et al. 2010, pp. 83, 93.

[59] Yanai, Aoki and Akahori, CZ 119:6, pp. 1079–1124.

[60] Isozaki et al. 2010, Figure 9 caption.

[61] Ramsay and Huber 1987, p. 521.

[62] Charvet 2013; Isozaki et al., CZ 119:6, pp. 999–1053.

[63] Isozaki et al. 2010, p. 86.

[64] Cloos 1993, p. 734.

[65] Nance and Murphy 1994, p. 51.

the dramatic changes listed here, it is better to consider them cases of accretion, forming "accretionary orogens."

In sum, the very mechanisms Charvet proposes for causing nappe formation (arc-arc and continent-continent collision) are already recognized as instances of collision, and those that are not so recognized (e.g. the Tanzawa and Misaka blocks) can be accommodated under the umbrella of accretionary tectonics—where things do collide but are accreted without rearrangement of plate motion or initiation of a new subduction zone or formation of ACs. If other "small blocks" have arrived to cause AC formation, then where are these blocks now? It seems the issue of terminology surrounding "collision" must be revisited vis-à-vis the mathematical calculation of stress and strain in fault systems within structural geology, and a clearer explanation of how accretionary prisms become Accretionary Complexes.

Conclusions

The worldwide presence of Accretionary Complexes has been recognized as both uncommon in formation and rare in survival. Tectonic erosion by the subducting oceanic plate is the more common process: the subducting plate grinds away at the continental edge, and can push the eroded fragments into the serpentinizing mantle edge while carrying the rest of the slab and trench debris down into the mantle. The eroded and subducted granite fragments are newly hypothesized to consolidate into "second continents," whose natural radioactive heat causes magma plumes to form and break apart the continental crust above them.

In updating the overviews on the formation of the Japanese islands, several previous research results discarded by Japanese scholars were presented above in Table 1 together with my assessments of new understandings and trends. Further important revisions include: five Japan arc-granite batholiths have been detected; the Hida and Oki Belts are now both acknowledged to be derived from the North China craton; the beginning of subduction in the proto-Japan area has been pushed back to 520Ma; portions of the Qinling-Dabie-Sulu suture have been identified in four locations in Japan; the Sanbagawa Metamorphic Belt has been divided into two belts; the Median Tectonic Line acted in two phases, paleo-MTL and neo-MTL which are vastly different in scale; the idea that the Outer Zone moved into place 1000km from the south via the neo-MTL has been discarded in favour of in situ development; and the "French door" model of Japan Sea opening is discarded in favour of a "drawer" model.

Many of the geological belts of Japan have been conceptually reorganized as more information about their contents and relationships is discovered (e.g. the Sanbagawa Belt mentioned above). Table 2 provides an incomplete, but hopefully useful indication of the natures of these belts, which in the main are correlated with Figure 1.

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