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Review

A Reappraisal of Pacific-type Orogeny and Subduction Erosion

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ABSTRACT

The accepted concept of orogeny is based on the Theory of Plate Tectonics and implies two types of orogeny: collision-type (C-type) and Pacific-type (P-type). Pacific-type orogenic belts are directly linked with Pacific-type convergent margins (PCM) existing over subduction zones, where oceanic lithosphere is submerged under intra-oceanic arcs or active continental margins. PCMs are major sites of new crustal growth through juvenile arc magmatism and accretion of upper strata of the subducting oceanic lithosphere and destruction by subduction erosion. The subduction erosion destroys formerly formed magmatic arcs and accretionary prisms. Related Pacific-type orogenic belts thus keep records of both juvenile crustal growth and subduction erosion. There have been found many sites of ongoing subduction erosion in the Circum-Pacific, but it is harder to find evidence for that of fossil Pacific-type orogenic belts. Recent studies of several accretionary complexes in the Central Asian Orogenic Belt (CAOB), the largest in the world Paleozoic to Mesozoic accretionary foldbelt, have found several probable cases of subduction erosion once happened at active margins of the Paleo-Asian Ocean, an old analogue of the modern Pacific Ocean. Evidence for that comes from magmatic lulls as recorded in U–Pb detrital zircon age distributions of arc-derived greywacke sandstone. The modern and fossil cases of subduction erosion are still waiting for their quantitative estimations in order to contribute to our knowledge about the global balance of crust gains and losses.

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Research Highlights

- Pacific-type convergent margins are main loci of crustal growth and erosion.
- Subduction erosion is responsible for destruction of juvenile crust in Circum-Pacific.
- Evidence of subduction erosion can be found in fossil Pacific-type orogenic belts.
- Signs of subduction erosion found in the Central Asian Orogenic Belt formed by the suturing of the Paleo-Asian Ocean.

1. What is Orogeny?

Dewey and Bird were the first to speculate about orogenic belts based on the Theory of Plate Tectonics and to propose modern analogues of two types of orogeny [1]. That time the Himalayan and Andean mountain belts were defined as world standards of collision-type and Pacific type and orogenies, respectively [2]. The western Pacific convergent margin dominated by multiple accretionary complexes, in general, and the Japanese Islands, in particular, were not considered as a world standard of Pacific-type orogeny because that time most geologists defined the importance of a geological manifestation of orogeny, first of all, mountain building. The Andes are over 4000 m high mountains, but the Japanese Islands are typically less than one kilometer high except for a number of subduction zone related volcanos, e.g., Mount Fuji. Now term "orogeny" means not only mountain building, but also other complex geological processes, such as (i) "pure" continental growth by subduction-related magmatism; (ii) continental crust recrystallization and related formation of regional metamorphic belts; (iii) formation of a new geological structure through folding and mountain building; (iv) mountain building triggered erosion of continental mountain belts by rain and snow to delivery sediments into adjacent oceans (Figure 1) [3–7]. All these processes imply the phenomenon of orogeny as was defined by Miyashiro and co-authors back in 1982 based on the new paradigm of plate tectonics. In average, orogeny takes rather short periods of geological time, usually less than 100 Ma, and then finishes resulting in what we see in geological maps (Figure 2). As orogeny includes several complex geological phenomena, it represents an excellent and convenient term to describe the geological history of this or that particular continent and/or its composing orogenic belts.

It took about twenty years of research to define more precisely what are P-type and C-type orogenies based on the results obtained from modern volcanoes and regional metamorphic belts (protoliths and age of metamorphic rocks and their PT-paths) and taking into consideration the exhumation tectonics, which all have drastically changed the understanding of the two types of orogeny. Nowadays we understand that orogeny is a kind of super complicated geological phenomenon, which study requires extensive and intensive field work including geological mapping and structural geology, laboratory tests on magmatic, metamorphic and sedimentary rocks, geochronological investigations, igneous petrology and geochemistry combined with geophysical observations of the oceanic floor and mountain belts and their underlying upper mantle. Finally, those different knowledges were combined together with the newly proposed concept of orogeny including its two types: Pacific or accretion type and Himalaya or collision type [4]. In this paper we will use terms, P-type and C-type orogenies, respectively. Then it appeared that these two types of orogeny must be defined more precisely. The new focuses were made to (1) understanding the petrogenesis of subduction zone magma, (2) origin and evolution of regional metamorphic belts and exhumation tectonics, and (3) formation of accretionary complex, (4) subduction erosion.

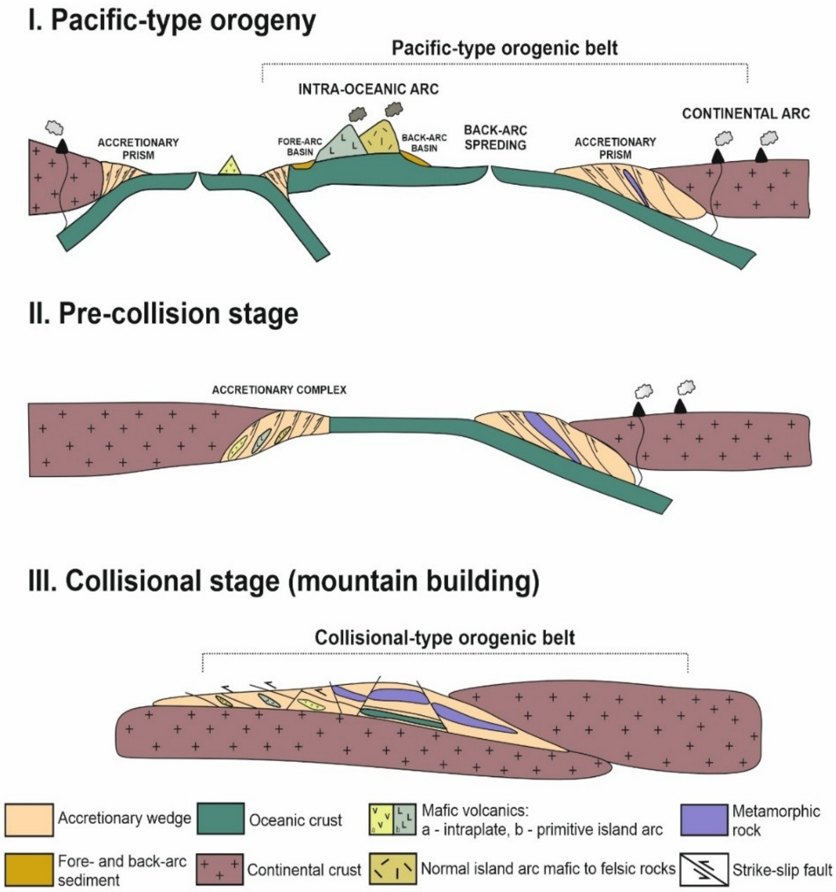

Figure 1. Schemes of Pacific-type and collision-type orogenies based on [8–10].

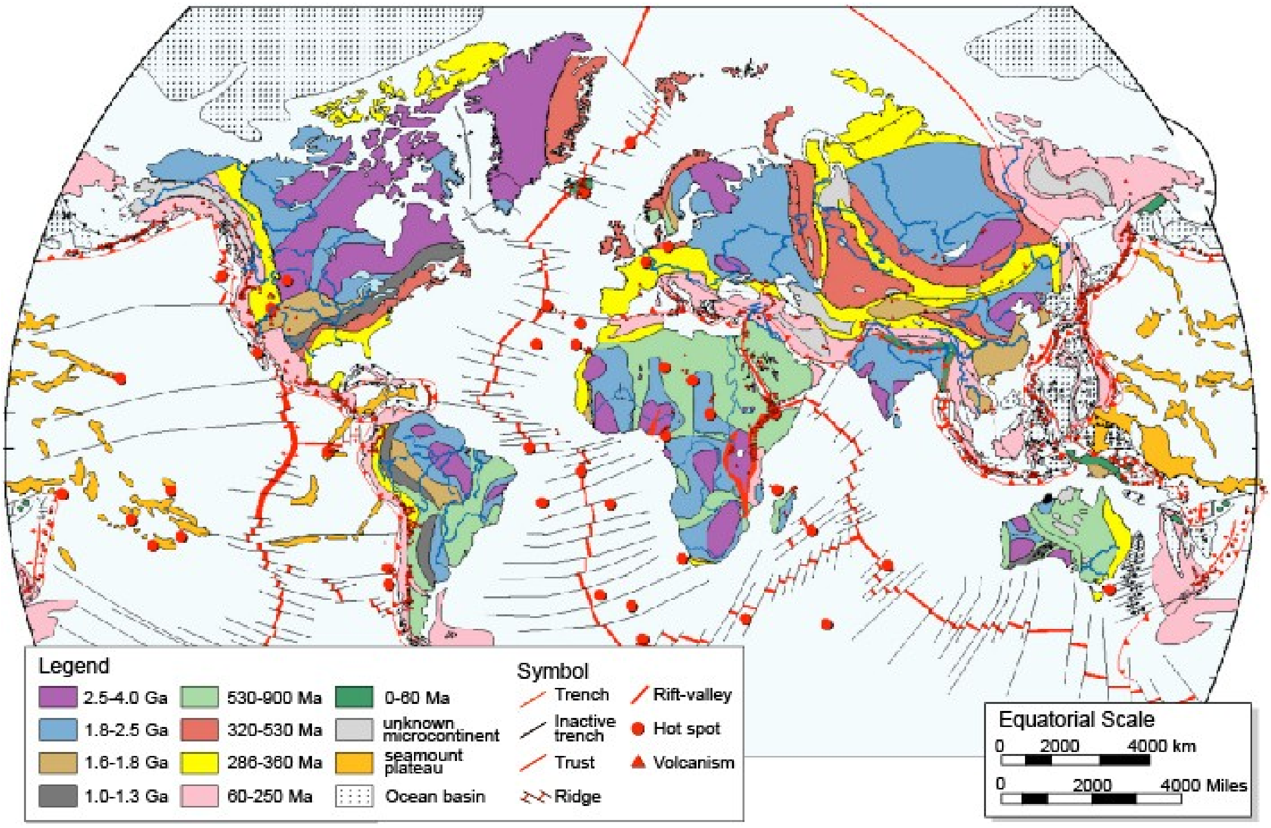

Figure 2. A geologic map of the Earth showing main orogenic belts over the last 4 Ga and illustrating the process of making continents and their dispersion over time modified from [4].

Support for those understandings has come from advanced high-skilled geological mapping [11–14], introduction of Ocean Plate Stratigraphy (OPS) concept with microfossil data [12, 15–18], and scanning microscopy based fossil species identification technology (SEM), age zircon isotope dating by LA-ICP MS [19–22], and P-T-time history of zoned garnet [23–26] and other minerals combined with zoned zircons from surface to mantle depth and return back to the surface. All those data have drastically changed the understanding of the two types of orogeny.

Recently, there have been proposed four types of orogeny: (1) Type 1—Cordilleras (ocean-continent convergence); (2) Type 2—accreted terranes (oceanic plateau/arc/ribbon continent); (3) Type 3—continent-continent collision; (4) Type 4—inverted rift (no oceanic crust) [10]. Such an approach ignores importance of intra-oceanic arcs and their contribution to orogeny. In addition, Types 2 and 4 are just final stages of Types 1 and 3, respectively. So, there still remain two major types of orogeny: Pacific-type and collision-type. However, orogeny is important not only for understanding how mountains grow, but, first of all, by its role in the formation of continental crust through juvenile magmatism, its further transformation by metamorphism and re-melting and final destruction by surface and subduction erosion.

The creation of continental crust can go by two mains groups of processes: magmatic and tectonic [5, 27–32]. The magmatic continental growth starts at subduction zones, mainly through juvenile magmatism of intra-oceanic arcs [33]. More contribution comes from intra-plate continental magmatism linked to mantle plumes and/or rifting zones proving direct "injections" of mantle-derived volcanic rocks into the continental crust. Tectonically the continental crust may overgrow by accretion of the pieces of oceanic plates scrapped off the subducting oceanic lithosphere that then form an accretionary prism or accretionary complex and by exhumed metamorphic rocks forming a non-volcanic arc [5, 15, 30, 34–36] (Figures 1 and 3). All the processes providing net crustal growth, i.e., the increase of the volume of continental crust, are linked only to the P-type orogeny, a focus of this paper.

For the mankind as a whole, study of orogenies has been always very important as such hazards as seismicity and related tsunamis, landslides and rockfalls are directly or indirectly linked to orogeny. In addition, the orogenic belts are major loci of most world largest metallic mineral deposits, including those that have become of crucial value during the late two decades: gold, copper, rare-earths, scandium, yttrium and others.

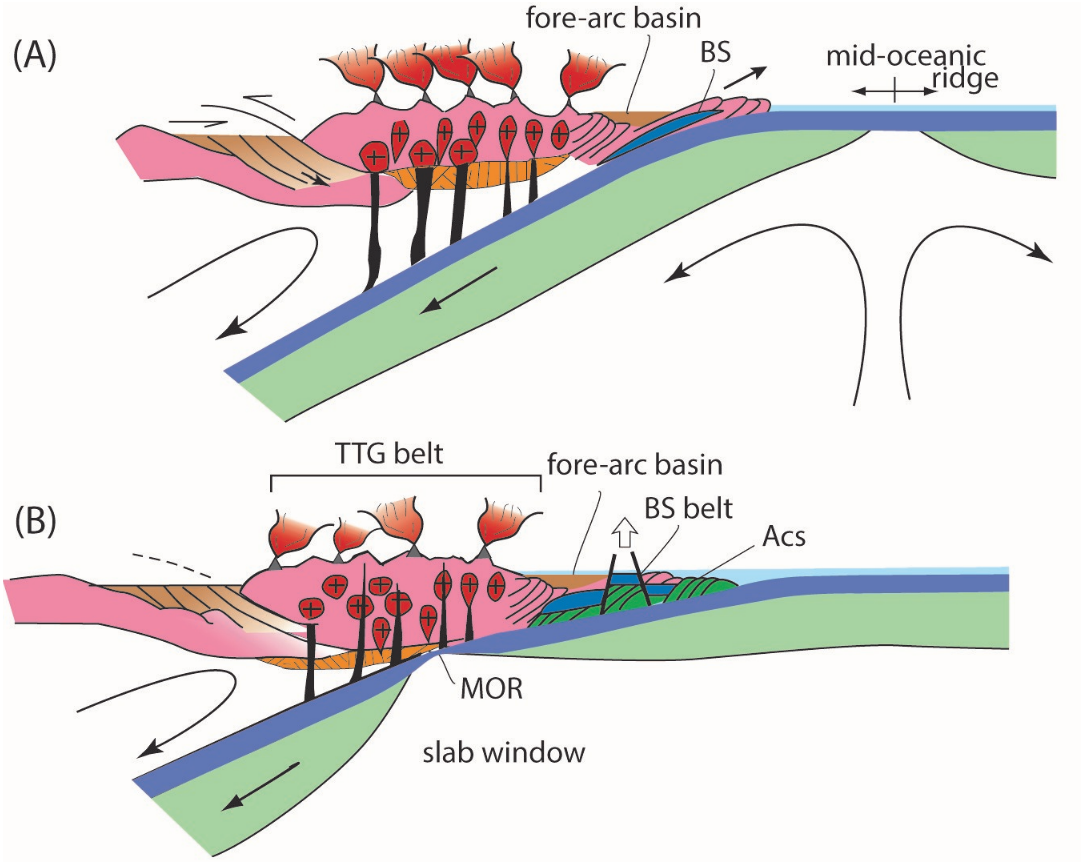

Figure 3. Diagrams illustrating the mechanism of the formation of a Pacific-type orogenic belt [5]. (**A**) Formation of an accretionary complex (AC), regional blueschist and eclogite (BS-EC) metamorphism and exhumation of high-pressure rocks along the Benioff plane, granitoid magmatism by slab-melting. (**B**) Doming of granitoid magmatic arc, growth of fore-arc and formation of non-magmatic arc by emplacement of high-P/T belt (BS belt) underneath and underplating of accretionary complex. MOR—mid-ocean ridge.

2. Pacific-type Convergent Margins and Orogenic Belts

Pacific-type orogenic belts are directly linked with Pacific-type convergent margins (PCM) existing over subduction zones (Figure 1). At subduction zones the oceanic lithosphere is sinking under intra-oceanic arcs or active continental margins. The most important constituents of PCM (from ocean to continent) are accretionary prism, fore-arc basin, metamorphic belt and volcanic arc (Figure 3). The subduction by itself and the related arc magmatism, OPS accretion, ridge subduction and exhumation of metamorphic rocks and serpentinite induce what we call Pacific-type orogeny (PTO). Finally, a related Pacific-type orogen consists of (1) magmatic arc typically dominated by andesitic to felsic rocks, (2) accretionary complex including both accreted and re-deposited units, (3) HP/HT regional metamorphic unit (blueschist, eclogite), and (4) fore-arc basin deposits. A Pacific-type orogen is typically 400–500 km wide, 20–30 km thick, and 2000 km long (see Mesozoic to Cenozoic orogenic belts highlighted in yellow, pink and green in Figure 2). The core of the orogen is occupied by a regional metamorphic belt, which top and bottom borders are cut by paired faults (Figure 3). A narrow fore-arc basin occurs between the volcano-plutonic sequences and the high-P/T regional metamorphic belt, which thickness is less than 2 km. The high-P/T metamorphic belt runs parallel to the batholith belt bounded by a low-P/T metamorphic unit at deeper levels. The general structure of a C-type orogen is similar to that of Pacific-type orogens except the absence of both the magmatic arc and accretionary prism. Collision-type orogen carries no TTG batholith belt but includes large syn-orogenic S-type granitoid belts and smaller post-orogenic A-type granite plutons. A collision-related UHP-HP metamorphic belt is typically 4–5 km thick and twice larger compared to that of Pacific-type. The lateral continuation is variable, depending on the size of the colliding continents. A key point is the protoliths of the metamorphic belt, mafic-andesitic greywacke in P-type belts and peraluminous in C-type belts [2, 3].

Pacific-type orogeny has long been recognized as a contrasting accretionary alternative to continent-continent collisional orogeny. Since the original concept was proposed by [2, 37], there have appeared many new developments though, which make it timely to produce a new re-evaluated model based on new aspects. First, it is substantial growth of tonalite-trondhjemite-granodiorite crust (TTG-type crust). Second is the reductive effect of subduction erosion. In more details, a modern Pacific-type orogen grows in six stages: (1) initial accretion and coeval supra-subduction TTG-type magmatism and HP metamorphism; (2) exhumation of metamorphic rocks to the mid-crustal level; (3) retrograde metamorphism; (4) initial exposure of a high-P/T regional metamorphic belt; (5) exposure of orogenic core; (6) post-orogenic processes including subduction erosion. Accretionary complex is a fundamental constituent of a Pacific-type orogenic belt (Figure 3) [6, 9]. It includes limited ocean floor material, much terrigenous trench sediment, plus island arc, oceanic plateau, and intra-oceanic basaltic material from the ocean. The classic concept of a PTO stresses the importance of new subduction-generated magmatic arcs and accreted oceanic rocks that are added to continental crust along active continental margins.

Figure 3 shows a model for the formation of accretionary complex, its transportation and underplating at depths of 50–60 km and coeval blueschist-eclogite metamorphism followed by exhumation of metamorphosed rocks along the Benioff plane due to the approaching mid-oceanic ridge and initiation of new andesitic crust due to slab melting (Figure 3A). The next stage is tectonic juxtaposition of a high-P/T belt under a fore-arc and underplating of a major accretionary prism derived from the thick trench turbidites that are accumulated after ridge subduction finally resulting in the doming and formation of a non-magmatic arc (Figure 3B). Note that this model ignores the processes of subduction erosion that play an important role in formation and destruction of new/juvenile crust at intra-oceanic arcs during Pacific-type orogeny.

3. P-type Orogeny and Subduction Erosion

Besides the above additional or positive aspects of a PTO, there are, as mentioned above, negative effects of subduction erosion caused by subduction over time. PCMs are very important geological entities because on one hand they are major sites of juvenile crust formation on the Earth, but on the other hand they are places of strong crust destruction through subduction erosion [33, 38–40]. The mechanism of subduction erosion includes destruction of oceanic slab, island arcs, accretionary prism and fore-arc by thrusting, oceanic floor relief (horst/graben), and (hydro)fracturing (Figure 4A). The subduction erosion of intra-oceanic arcs and continental margin hanging walls takes place along almost all PCMs [33, 40–42].

Subduction erosion is a relatively young new concept that is extremely important to discuss the history of the Earth and the processes of formation and destruction of continental crust. In addition, subduction erosion can explain the petrogenesis of granitic magma without delamination of the lower crust. But first of all, subduction erosion plays a very important role of the evolution of Pacific-type orogens, because their components (magmatic arc, fore-arc, metamorphic and accretionary units) all can be transported into the deep mantle (Figure 5). First, accretionary complex grows oceanward to a distance of ca. 200 km toward the trench (Figure 5a). During that stage, a normal magmatic arc often dominated by TTG forms at the volcanic front. Accretion stops after subduction erosion begins and then followed by a landward movement of trench and attenuation of subduction-related magmatism. Subduction erosion occurs every 100 Ma to destroy a major part or the whole arc (Figure 5b). The back-and-forth migrations of the trench and related volcanic front take place during each episode of large-scale subduction erosion. During extensive subduction erosion, the mafic lower crust is transported into the mantle, hence an idea of steady-state delamination of the mafic lower crust is not necessary.

Two basically different types of Pacific-type convergent margins—accreting or growing and eroding or narrowing—have been recognized [42]. The accreting convergent margins form accretionary prisms and grow oceanward. The eroding convergent margins can be recognized by a shortening distance between the arc and the trench (Figures 4B and 5) and direct destruction of accretionary prism, fore-arc prism and magmatic arc that we call tectonic or subduction erosion. Back in the late 1970-ties there were made seismic reflection profiles across the Tonga and Nankai trenches that showed first evidence for the subduction erosion at the western Pacific convergent margins.

The modern convergent margins surrounding the Pacific Ocean are 65% narrowing or eroding, 20% widening or accreting and 15% transform [41, 42]. The subduction of the Pacific plate provides high-rate subduction erosion of the hanging walls of the western Pacific margins, in particular along the Andes active margins and the Nankai trough. Evidence for this comes from the Costa Rica-Guatemala consuming boundary in South America witnessing huge rates of sediment destruction [40] and from the Cretaceous Shimanto accretionary complex of Shikoku Island in Japan [20]. In Guatemala, geologists found gaps of fore-arc sedimentation under ongoing subduction suggesting that periods of accretion alternated with periods of subduction-related sediment erosion. In Shikoku, the accretionary units are spatially adjacent to the coeval granitoids of the Ryoke belt, suggesting that older accretionary complexes have been eroded (Figure 6) [9, 20]. In addition, the U–Pb detrital zircon geochronology of accretionary complexes of the Honshu Island show signatures of cessation of magmatism and trench shifts also suggesting subduction erosion [20]. Another importance consequence and therefore a tool for deciphering histories of fossil P-type orogens is serpentinite mélange and its hosted fragments of both OPS and arc roots. A vertical cross-section suggests that subduction erosion is the most preferred process to mix all those units together, for example, to form serpentinite-dominated mélange belts (Figure 4B).

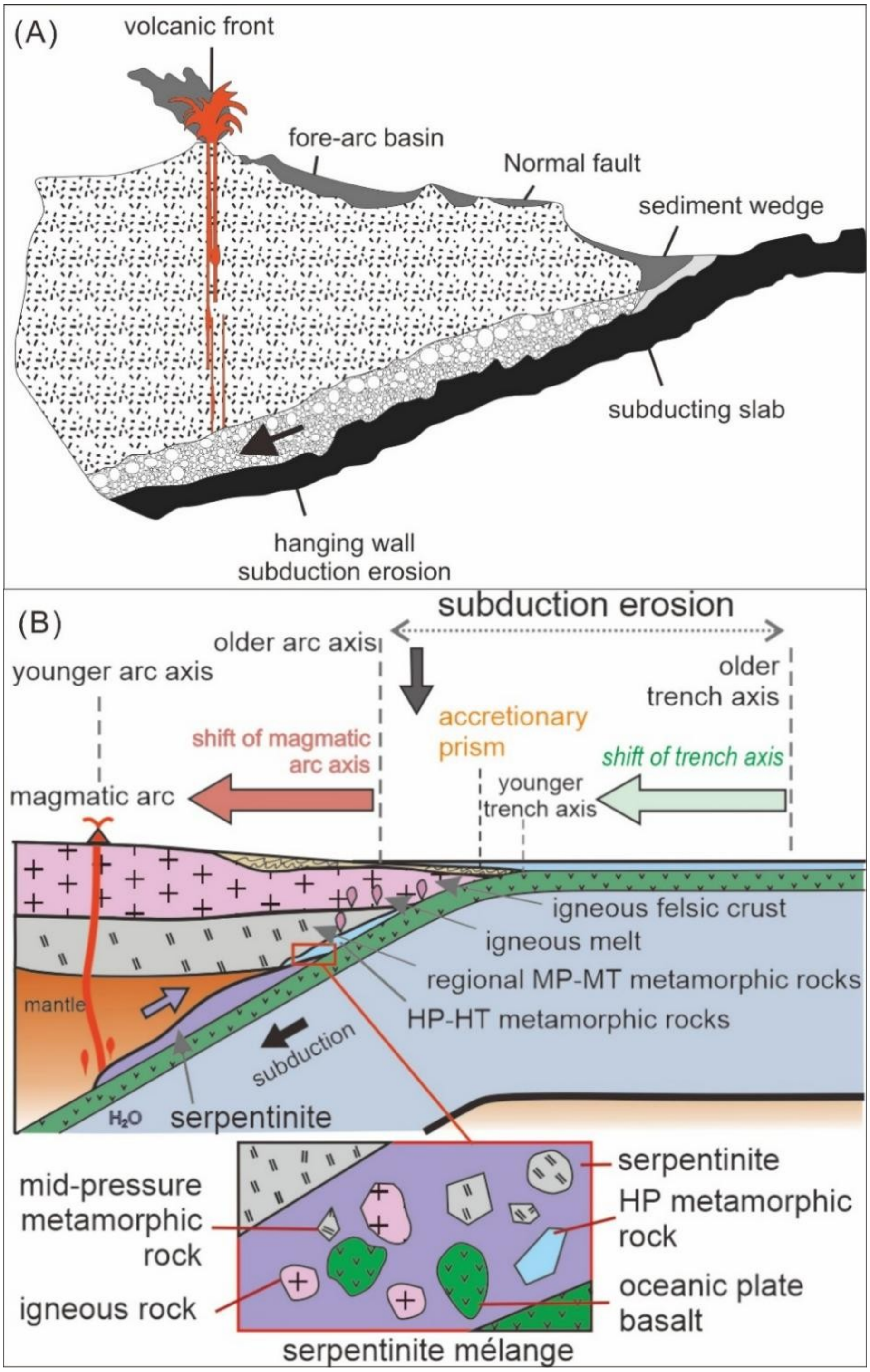

Figure 4. (**A**) A cartoon of subduction erosion illustrating destruction of rocks of the hanging wing of subduction zone and related subsidence, modified from [29]. (**B**) Relationships between subduction erosion, shifts of the trench and arc axes and exhumation of serpentinite mélange carrying pieces of various rocks, modified from [43].

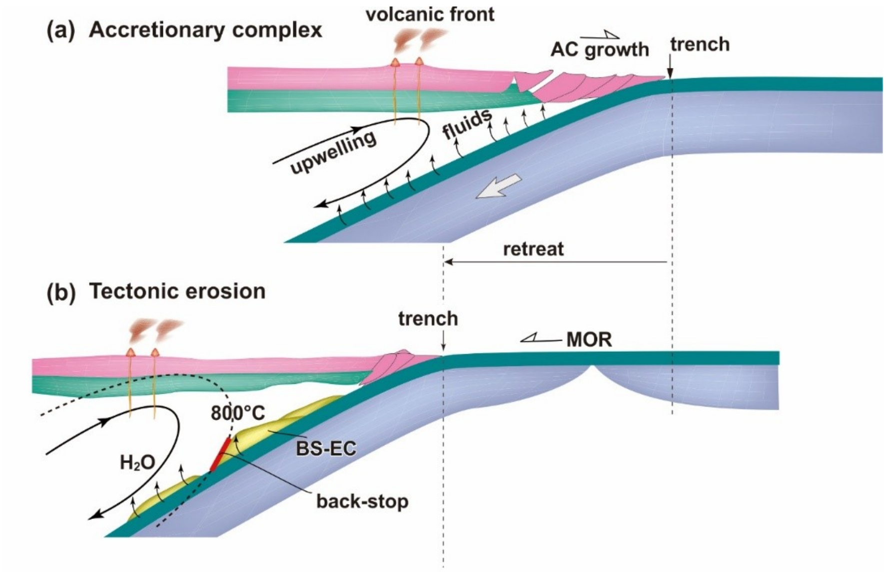

Figure 5. A simplified model for subduction erosion at a Pacific-type convergent margin. AC—accretionary complex, BS-EC—blueschist and eclogite facies metamorphism, MOR—mid-ocean ridge.

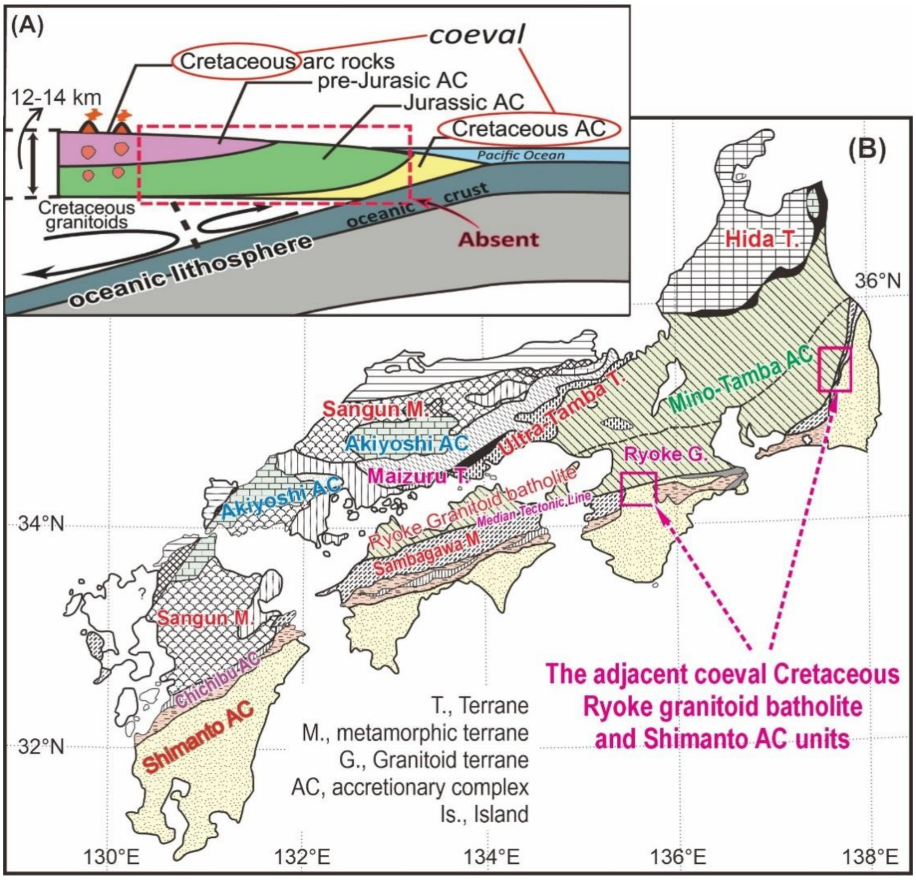

Figure 6. Tectonic scheme of south-eastern Japan modified from [9, 44] including the Cretaceous Shimanto accretionary complex, the Jurassic Chichibu accretionary complex and the pre-Jurassic accretionary units of the Sanbagawa metamorphic terrane. The frames show areas of probable subduction erosion.

4. Examples of Subduction Erosion in Asia

As was noted above the most of the present-day convergent margins around the Circum-Pacific are narrowing [42]. Given that, we are permanently losing the continental crust as the global long-term estimates for crust formation and destruction, i.e. crust volume balance, is 0.55 km^3/year [29]. Therefore, it is important to evaluate the periods and, if possible, volume of created and destructed juvenile continental crust in a historical perspective.

Processes of formation and destruction of continental crust during at least the Phanerozoic can be best studied in a natural lab of continental growth, the Central Asian Orogenic Belt (CAOB) formed by the evolution and suturing off the Paleo-Asian Ocean (PAO), which actualistic analogue is the present Western Pacific region [9, 30]. Accordingly, we suggest that the processes of subduction erosion could have been also active at the Pacific-type active margins of the PAO, which evolution and suturing were responsible for formation of the CAOB [9]. Why we think that this is important? Because the proportions between the recycled and juvenile crust in the CAOB has been hotly discussed since the early 2000-s, but no consensus has been achieved yet [9, 45]. A possible reason is that those arcs were destroyed by surface and/or subduction erosion.

We reconstructed juvenile arcs by having studied Pacific-type orogenic belts of Itmurundy, Tekturmas, Zharma and Char, all in the western CAOB (Figure 7), in Kazakhstan [46]. Most of such studies were made on arc-derived greywacke sandstones that are typically parts of turbidite strata occurring on top of oceanic plate stratigraphy successions. Evidence for an intra-oceanic arc first comes from the unimodal character of the distribution patterns of U–Pb ages of detrital zircons, in which Precambrian ages are so minor in amount that can be ignored. All of them host accretionary complexes with limited or nil presence of igneous island-arc complexes around.

So far, several episodes of subduction erosion have been reconstructed in the early Paleozoic supra-subduction and accretionary complexes of the Middle Tianshan in Kyrgyzstan, central and eastern Kazakhstan and northern Mongolia [46–48]. The U–Pb age patters of detrital zircons from greywacke sandstones of Paleozoic to Quaternary accretionary complexes of the Japanese Islands and the CAOB suggest cessations of magmatism probably linked to subduction erosion triggered shifts of trench axes (Figure 8). Specifically, there have been found signatures of subduction erosion in the Chatkal complex of the middle Kyrgyz Tianshan, in the Tekturmas accretionary complex and ophiolite belt in central Kazakhstan, and in the Zharma magmatic arc Char accretionary zone in eastern Kazakhstan, in the Ulaanbaatar accretionary complex in northern Mongolia and in the Barleik accretionary belt in West Junggar (Figure 7). The evidences are variable—from small to nil outcrops of supra-subduction magmatic formations but abundant arc-derived greywacke sandstones to tectonic juxtaposition of coeval supra-subduction and accretionary complexes [9, 46].

The Chatkal complex includes coeval and spatially adjacent Early Devonian arc granitoids, ophiolites and accretionary units suggesting that a part of the crust was lost [47]: such a setting is similar to that illustrated in Figure 6. The Ulaanbaatar accretionary complex hosts thick greywacke units of averagely andesitic compositions but almost nil outcrops of arc rocks [48]. The Tekturmas and Zharma-Char zones do host outcrops of arc igneous rocks but their size, both volume and area, are by no way can be compared with modern magmatic arcs of the Circum-Pacific [46, 49]. The detrital zircons from the arc-derived greywackes of all the localities mentioned, Tekturmas, Zharma-Char, Ulaanbaatar, Barleik (Figures 7, 8), show U–Pb age distributions without Precambrian ages and positive epsilon Hf suggesting that intra-oceanic arcs once existed in the Paleo-Asian Ocean, but later were almost partly or completely eroded [46, 48]. In addition, the U–Pb detrital zircon distributions show magmatic lulls at intervals of 20–60 Myr suggesting subduction erosion and shifts of magmatic arcs and related cessations of magmatism (Figures 4, 5 and 8) similarly to the Aleutian arc [50].

Figure 7. General outlines of major magmatic arc belts of the CAOB of different ages and locations of accretionary complexes carrying signs of subduction erosion (see below).

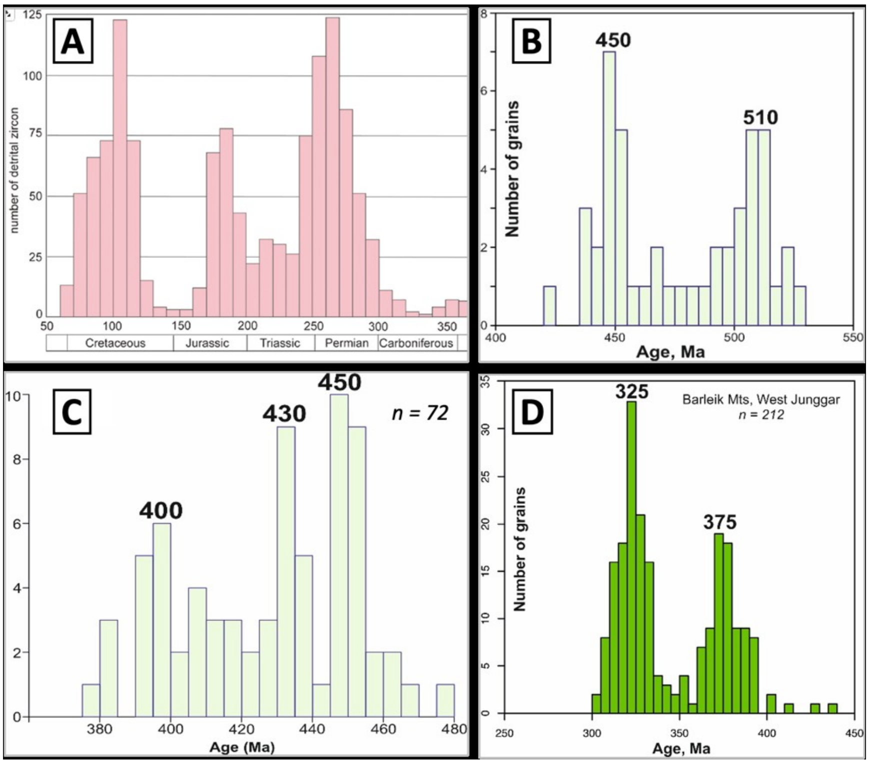

Figure 8. U–Pb age patters of detrital zircons from greywacke sandstones of Paleozoic to Quaternary accretionary complexes of the Japanese Islands (**A**) [51] and the CAOB suggesting cessations of magmatism: (**B**) Tekturmas AC (Ordovician-early Silurian); (**C**) Zharma-Char zone, eastern Kazakhstan (early Carboniferous-Serpukhovian); (**D**) Barleik AC in West Junggar. Note, that in the CAOB the occurrences of supra-subduction formations are very limited in space and ranging from medium sizes (Zharma and Tekturmas) to small sizes (Char zone, Barleik). Based on data from [46, 49, 52].

A special question if and how the composition of subduction-related magmatism changes in cases of subduction erosion. At the moment, no special studies have been devoted to this problem. A general understand of mine is that such magmas should have typical characteristics of subduction-related magmatic rocks, i.e. variable magmatic series (tholeiitic, calc-alkaline, alkaline), crystallization trends, depletion in HFSE, etc. However, we may expect that if tectonically eroded material is involved into magma generation, then the parental magmas would have more enriched isotope composition, for example, in respect to whole-rock Sm–Nd isotope systematics, i.e. they would have lower epsilon Nd values. However, this question requires more focused research in future.

5. Conclusions

Pacific-type convergent margins are main loci of juvenile crust formation on one side and strong plate interactions on the other side that may result in subduction-related destruction of volcanic arcs and accretionary prisms. Related Pacific-type orogenic belts thus keep records of both juvenile crustal growth and crust destruction by subduction erosion. There have been found many sites of ongoing subduction erosion in the Circum-Pacific, but it is harder to find evidence for that in fossil Pacific-type orogenic belts. Recent studies of accretionary complexes of the Central Asian Orogenic Belt, have found several probable cases of subduction erosion that might take place at Pacific-type convergent margins of the Paleo-Asian Ocean, an old analogue of the modern Pacific Ocean. Evidence for that came from magmatic lulls as recorded in U–Pb age distributions of detrital zircons from arc-derived greywacke sandstones. The modern and fossil cases of subduction erosion are still waiting for their quantitative estimations in order to contribute to our knowledge about the global balance of crust grains and losses that is important for developing advanced prognoses on search and exploration of new metallic and non-metallic mineral deposits.

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Conflicts of interest

The author declares that she has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

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