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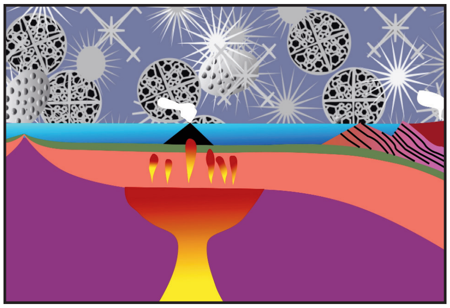

Memories of Pre-Jurassic Lost Oceans: How To Retrieve Them From Extant Lands

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SUMMARY

The information reflected in mid-oceanic sedimentary deposits provides critical constraints for reconstructing past global environmental changes. Available data from extant oceans, however, are limited to the Early Jurassic and younger ages, because older oceanic plates have been subducted. This article explains methods for obtaining information on pre-Jurassic mid-oceanic conditions by conducting fieldwork on older orogenic belts exposed on land. The key point is the identification of ancient accretionary complexes (AC), not along currently active margins but within older orogenic belts in continental domains, particularly by recognizing ocean plate stratigraphy (OPS) that contains mid-oceanic strata, as demonstrated by studies of on-land exposed ancient AC in Japan and elsewhere. In this paper, six examples of retrieved mid-oceanic sedimentary data are introduced, in which significant records on the following unique events in the pre-Jurassic world are archived: 1) the extinction-related Paleozoic–Mesozoic boundary superanoxia (based on data from the Jurassic AC in SW Japan); 2) the Permian Kamura cooling event in the mid-Panthalassa (*ditto*); 3) the Neoproterozoic snowball Earth evidence from the mid-Iapetus Ocean (based on data from the Neoproterozoic–Cambrian AC in Wales, UK); 4) the discovery of enigmatic Ediacaran (Neoproterozoic) microfossils from a mid-oceanic atoll complex (based on data from the Cambrian AC in southern Siberia, Russia); and 5) and 6) Early Archean (3.8 and 3.5 Ga) biogenic signatures in mid-oceanic deep-sea environments (based on data from the Eoarchean AC at Isua in Greenland, and the Paleoarchean one in Pilbara, Western Australia). These results demonstrate the great utility of OPS analysis for understanding pre-Jurassic lost oceans, including the early biological and environmental evolution of the globe.

SOMMAIRE

Les informations enregistrées dans les dépôts sédimentaires médio-océaniques constituent des contraintes logiques qui permettent de reconstituer les changements environnementaux globaux. Cela dit, l'information sur de grands pans de fonds océaniques est limitée aux fonds océaniques Jurassiques précoces et plus jeunes, parce que les fonds océaniques plus anciens ont été subduits. Le présent article explique des méthodes permettant d'obtenir de l'information sur les milieux médio-océaniques pré-jurassiques par des levés de terrain sur des ceintures orogéniques affleurant sur terre. L'idée centrale consiste à circonscrire d'anciens complexes d'accrétion (AC), hors des marges actives actuelles, soit dans les ceintures orogéniques plus anciennes au sein des domaines continentaux, en y repérant des contextes stratigraphiques de plaques océaniques (OPS) qui renferment des strates médio-océaniques, comme ça a été fait lors études d'AC affleurant au Japon et ailleurs. Le présent document décrit six exemples de contextes stratigraphiques de plaques océaniques où on trouve des indices importants des événements pré-jurassiques uniques suivants : 1) l'extinction liée à la superanoxie de la limite Paléozoïque-Mésozoïque (à partir des données d'un AC jurassique dans le sud-ouest du Japon); 2) l'épisode de refroidissement permien de Kamura du Panthalassa moyen; 3) l'épisode néoprotérozoïque de « Terre boule de neige » conservé par l'océan mi-japétien (selon les données de l'AC néoprotérozoïque-cambrien dans les Wales au Royaume-Uni); 4) la découverte de microfossiles édiacariens (Néoprotérozoïque) d'un complexe d'atolls médio-océaniques (selon les données d'un AC cambrien du sud-est sibérien, Russie); et 5 et 6) des signatures biogéniques de milieux médio-océaniques profonds de l'Archéen précoce (3,8 et 3,5 Ga) (selon les données

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d'un AC éoarchéen à Isua au Groenland, et d'un AC paléoarchéen à Pilbara, Australie). Ces résultats montrent la grande utilité de l'analyse de la stratigraphie des plaques océaniques pour comprendre les océans pré-Jurassique, de même que l'évolution des débuts de la vie et des milieux de vie sur Terre.

INTRODUCTION

When geologists explore the deep past, and, in particular, when they try to find evidence of ancient environmental changes and related biological evolution on a global scale, the main source of information is the vast 'archive' found in various outcrops of sedimentary rocks throughout the world. During the earlier half of the nearly 200 years-long history of modern geology, stratigraphy almost always occupied a central position; in other words, the main targets in analyses of the Earth's deep past were fossiliferous Phanerozoic systems and even fossil-poor Precambrian strata deposited mostly in ancient shallow seas. Since the advent of plate tectonics in the late 1960s (Wilson 1966), the traditional viewpoint of geologists has drastically changed (Oreskes 1999), and realistic connotations of igneous, metamorphic, and sedimentary rocks are now perceived in a new unified framework. Oceanographic studies of deep-sea sedimentary rocks, in particular, the numerous samples from ocean floor drilling of more than 2,000 sites, have provided valuable new sets of information concerning the Mesozoic to Cenozoic global environmental changes, and guided us to look at the ancient world from a totally different viewpoint.

In contrast to the continental sedimentary archives, however, sedimentary records from the mid-oceans have a sharp age limit, namely the Early Jurassic. The age spectrum of the world's oceans shows that currently the oldest extant ocean floor is of the Late Jurassic age, which exists along both margins of the Atlantic Ocean, in the western Pacific along the active Mariana trench, and in the Timor Sea (Fig. 1). It seems certain that pre-Jurassic ocean floor also must have existed elsewhere, but that it has all vanished due to subduction. It is thus virtually hopeless to retrieve pre-Jurassic sedimentary records directly from modern oceanic floors, even though oceans have occupied at least 70% of its surface area during the last 700 million years and probably much more before that. The reconstruction of pre-Jurassic environmental changes on a global scale seemed impossible; however, a new approach to pre-Jurassic oceanic sedimentary rocks was recognized and formulated during the 1980s and 1990s in Japan through fieldwork-based geological studies of subduction-related orogenic belts.

This article introduces the fundamental concepts and framework of this approach, which is called "Ocean Plate Stratigraphy (OPS) analysis," for studying on-land exposed ancient orogenic complexes, and the practical procedures in fieldwork for recovering information on pre-Jurassic oceans from data that can be observed on land. Together with the definition

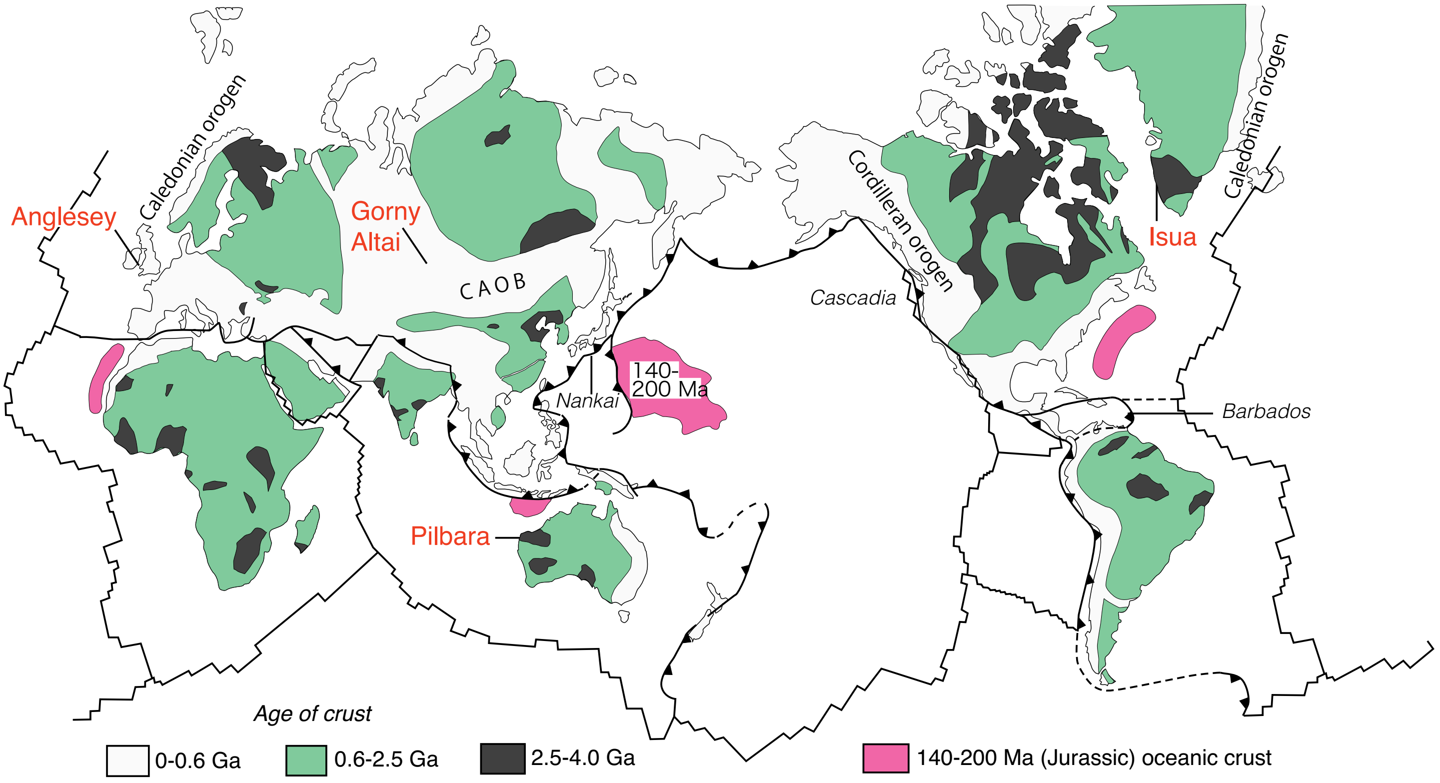


Figure 1. World map showing ages of crusts, with localities and orogenic units discussed in this article.Note that extant ocean floors comprise solely the Jurassic and much younger crust, because much older ones have been already subducted/disappeared. For the Precambrian orogenic belts, Anglesey in Wales and the Gorny Altai Mountains in southern Siberia display mid-oceanic sedimentary rocks, whereas the Isua Supracrustal Belt in western Greenland and the Pilbara greenstone belt in Western Australia expose Archean (the oldest) ones. CAOB: Central Asian orogenic belt.

of OPS and a brief historical review of OPS research, some examples of fruitful results, not only from the pre-Jurassic Phanerozoic but also from the Precambrian, are briefly explained in order to emphasize that OPS analysis will provide useful hints for future research on the pre-Jurassic environments of vast mid-oceanic realms. Although the results to date are still patchy with respect to the entire 4 billion year-long history of the Earth's oceans, possible applications of this research extend further back to the mysterious Precambrian superoceans, not only of the Proterozoic-Archean but also of the Hadean, and even of the early Mars or extra-solar water-hosting super-Earths (Seager 2013; Howard 2013).

OCEAN PLATE STRATIGRAPHY ANALYSIS: HISTORY AND DISCIPLINES

Where to Find

In general, the plate tectonic mechanism called subduction drives nearly 100 km-thick oceanic lithosphere into the mantle, making it disappear eventually from the planet's surface; nonetheless, some material on the top of subducting slab is sometimes tectonically peeled off and accreted to the leading edge of the overlying plate. Such rock packages added to the trench inner wall are called accretionary complexes (AC). Internal structures and material characteristics of modern examples have been fully documented in various active trench environments along the circum-Pacific margins and partly along the Caribbean trench (e.g. Nankai Trough off SW Japan, Cascadia margin off W North America, Barbados margin off Lesser Antilles; Fig. 1) by seismic profiling, deep-sea drilling, and diving submersibles (Westbrook et al. 1984; Hyndman et al. 1990).

Much older Phanerozoic examples of AC have been described mostly from the circum-Pacific domains, such as Japan, Alaska, and California; however, they were generally more deformed and/or metamorphosed than the modern analogues still sitting adjacent to active trenches, owing to the post-accretion overprinting by multiple structural, metamorphic and/or magmatic processes. These domains characterized by ancient AC, blueschist (high-pressure/low-temperature-type metamorphosed AC), ophiolites, and arc granite batholiths, have been recognized as orogenic belts, in particular, as the Cordilleran-type (Dewey and Bird 1970) or the Pacific-type (Matsuda and Uyeda 1972) one, in contrast to the continent-continent collision-type ones like the modern Alpine-Himalayan system. This article emphasizes that we can find pre-Jurassic mid-oceanic sedimentary records either in weakly metamorphosed AC in ancient oceanic subduction-related Pacific-type orogenic belts currently exposed on land or in their remnants stored in much older (post-accretion) collision-type orogens.

Accretionary Complexes (AC) and Ocean Plate Stratigraphy (OPS) in Orogenic Belts

In the modern (post-Triassic) plate tectonic framework, oceanic plates are formed along mid-oceanic ridges, where the surface of the crust is ornamented with mid-ocean ridge basalt (MORB) with pillow structure. Before subduction along an active trench, the top of the oceanic crust has been draped over by relatively thin, deep-sea pelagic sediments (radiolarian ooze). When an oceanic plate eventually arrives at a trench, coarse-grained terrigenous clastic material (turbiditic sand/mud/gravel) covers the above-mentioned oceanic rocks (Fig. 2A). The primary stratigraphy in the trench axis in general, therefore, consists of the following triplet of rocks: pillowed MORB, deep-sea pelagic sedimentary rocks, and trench-fill turbidites, in ascending order. Such a stratigraphic package was named "ocean plate stratigraphy (OPS)" (Isozaki et al. 1990; Matsuda and Isozaki 1991). This tripartite package of rock strata accumulated on an oceanic plate is typically subducted into the mantle, but occasionally it is transferred to the frontal part of the overlying plate to form an AC. Under the sub-horizontal contraction tectonic regime between two relevant plates, the MORB and overlying sedimentary rocks in the trench are incorporated into a layer-parallel shortening structure called a duplex along a pair of reverse faults (top and bottom thrusts) almost parallel to the main décollement (Fig. 2B). Components of all AC in the world, modern and ancient, therefore, can be described essentially in terms of OPS.

The geological connotation of OPS was first summarized in the early 1990s (Isozaki et al. 1990; Matsuda and Isozaki 1991). The OPS of an AC represents a travel log of the oceanic lithosphere from its birth at a mid-oceanic ridge to its demise at a trench. The timing of final accretion is approximated by the depositional age of trench-fill turbidites (Fig. 2A). In addition to the above triplets, fragments from hotspot-type seamounts and capping atoll complexes, oceanic island basalt (OIB) greenstones and reef limestones, are included in an OPS *sensu lato*. The shallow marine limestones accumulated on mid-oceanic topographic highs (Fig. 2C) represents diachronous lateral equivalent rocks of deep-sea chert; therefore OPS is two-fold with $\mathrm{OPS_{deep}}$ and $\mathrm{OPS_{shallow}}$, as will be mentioned later.

The key issue in hunting for pre-Jurassic mid-oceanic sedimentary rocks, therefore, is the identification of OPS in on-land exposed ancient AC, particularly in ancient orogenic belts. Older AC exposed on land are essentially composed of three rock types: 1) basaltic greenstones (lava and volcaniclastics), 2) non-terrigenous biogenic sedimentary rocks (chert, limestone), and 3) coarse-grained terrigenous sandstone/mudstone, each of which exactly corresponds to one component of OPS. These rocks were once called the 'eugeosynclinal assemblage' in the early to mid-20th century.

Basaltic greenstone has geochemistry identical to MORB or OIB and commonly shows pillow structure proving its origin by submarine volcanism. The pillowed basaltic greenstone of MORB affinity is directly covered by fine-grained strata, mostly beds of radiolarian chert that usually total less than 100 m in thickness. In rare cases, thin beds of metalliferous deposits (amber) and micritic limestone (enriched in coccoliths) are also found between the pillowed greenstone and bedded chert. In addition, greenstone with OIB affinity is commonly associated with purely bioclastic shallow marine limestone. Its characteristics indicate that greenstone with interbedded non-terrigenous chert or limestone

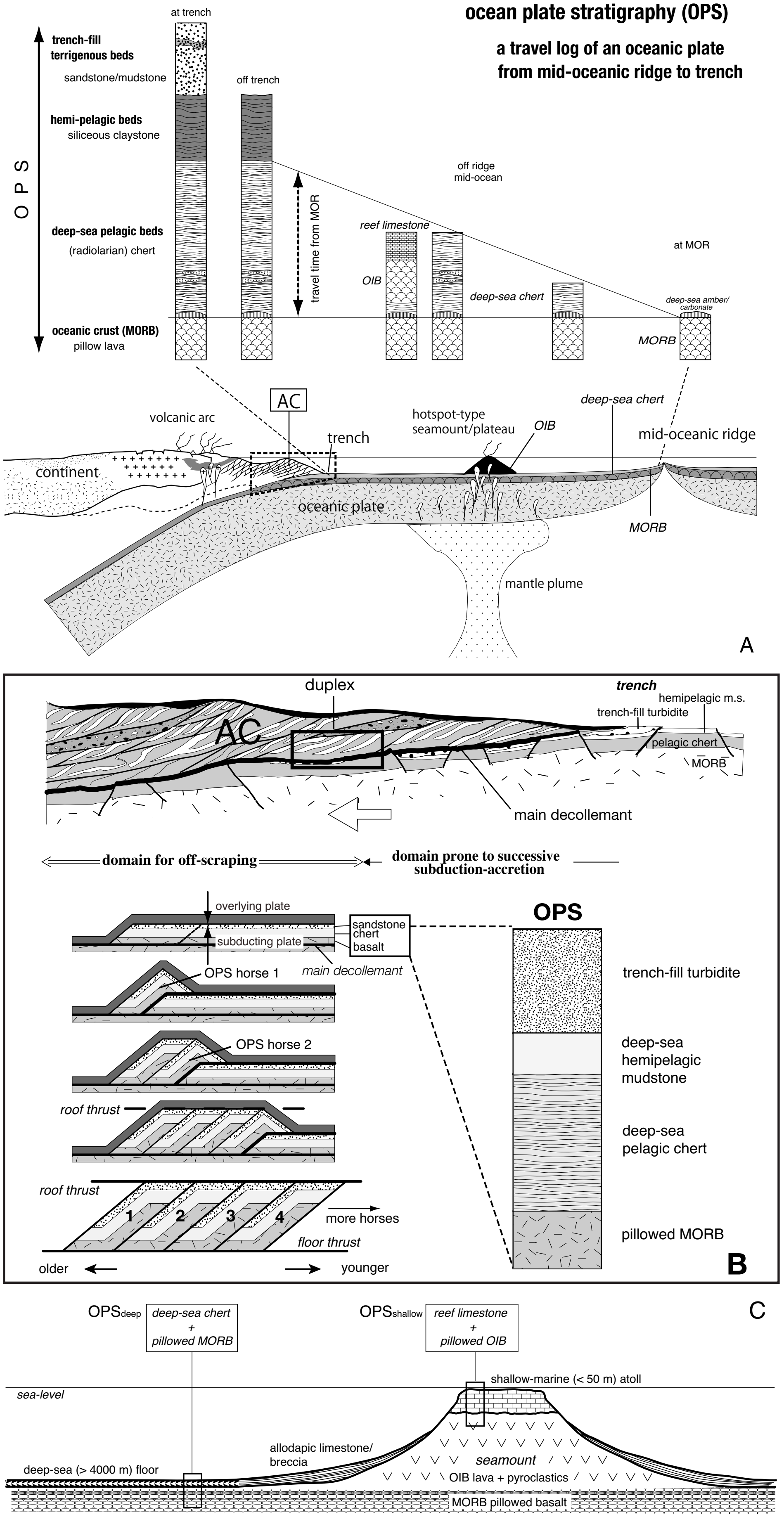


Figure 2. Ocean plate stratigraphy (OPS) of an accretionary complex (AC) (modified from Isozaki et al. 1990; Matsuda and Isozaki 1991; Komiya et al. 1999). A: Schematic diagram showing a simplified transect of a ridge-trench system and the significance of OPS. Note that the travel log of an oceanic plate, from its birth at a mid-oceanic ridge to its demise at a trench, is recorded in the middle part of the OPS. B: Duplex structure that hosts plural OPS units as thrust horses. C: Lateral variations of mid-oceanic sediments, ranging from pelagic chert on deep-sea floor to shallow-marine atoll limestone on the top of hotspot-type seamount. Consequently, AC may contain two contrasting aspects of OPS, i.e. $\mathrm{OPS}_{\mathrm{deep}}$ and $\mathrm{OPS}_{\mathrm{shallow}}$ that record paleo-environments of deep-sea and surface ocean, respectively.

was derived from an oceanic crust, corresponding to the lower and middle parts of the OPS. In contrast, terrigenous clastic rocks consist of coarse-grained rock fragments, quartzofeldspathic grains obviously derived from continental crust, and correspond to the upper part of the OPS. It is noteworthy that these continentally derived clastic rocks dominate in volume, usually more than 80–90% of the entire AC volume, with respect to the other oceanic rocks (Isozaki et al. 1990). Owing to the common formation mechanism, all AC are composed of essentially the same rock types; however, neighbouring look-alike AC units formed at different times can be identified and discriminated from each other by virtue of microfossil dating of each OPS, as demonstrated in the Japanese Islands (Isozaki 1996). In short, OPS can serve as an 'ID' for each AC unit within a long-lived orogenic belt.

Etymology

Before introducing practical details of ancient mid-oceanic sedimentary archives, a short historical summary of the concept OPS is explained here. Readers may understand why it took so long for the concept to be understood and accepted by many geologists, despite the fact that OPS occurs commonly in various orogens in the world, and why it has been so difficult to recognize in ordinary fieldwork.

Immediately after the formulation of plate tectonic theory during the late 1960s, the basic idea of OPS was primarily proposed in the early 1970s as "plate stratigraphy" (Berger 1973) on the basis of the oceanographic studies on the modern ocean floor. Superficial comparison between 'plate stratigraphy' and rocks in the Phanerozoic orogenic belts was preliminarily attempted elsewhere in USA, UK, and Japan during the 1970s (Chipping 1971; Connely 1978; Leggett et al. 1979; Taira et al. 1980); however, the strict identification of ancient mid-oceanic deep-sea sedimentary rocks in land-based fieldwork was not easy, thus the claimed reconstructed stratigraphy was still imaginary or hypothetical, and was not yet recognized in its full extent. Field-based geological studies on AC in on-land orogenic belts during the latest 1970s to early 1980s, in particular, microfossil dating of the non- to least metamorphosed Jurassic AC in SW Japan, validated the deep-sea origin of bedded chert, and refined the concept and strict definition of OPS for AC (Isozaki et al. 1990; Matsuda and Isozaki 1991).

The major breakthrough was made in the study of the bedded chert-bearing Jurassic AC units of the Mino-Tanba belt in SW Japan. Bedded radiolarian chert, composed mostly of fine-grained biogenic silica (radiolarian tests and sponge spicules) without coarse-grained terrigenous clastic rocks, represents one of the characteristic rock types in traditional 'eugeosynclinal' orogenic belts, i.e. AC belts in the modern sense, was long regarded as a potential candidate for an ancient analogue of mid-oceanic deep-sea sediment (Trümpy 1960; Grunau 1965). However, a long-running debate ensued about the original depositional setting of the chert, whether it formed in a mid-oceanic deep-sea environment or in shallow seas along continental margins (Iijima et al. 1978; Sugisaki et al. 1982). The latter hypothesis was suggested because of the apparent 'intimate association' with terrigenous sandstone or conglomerate in orogenic belts.

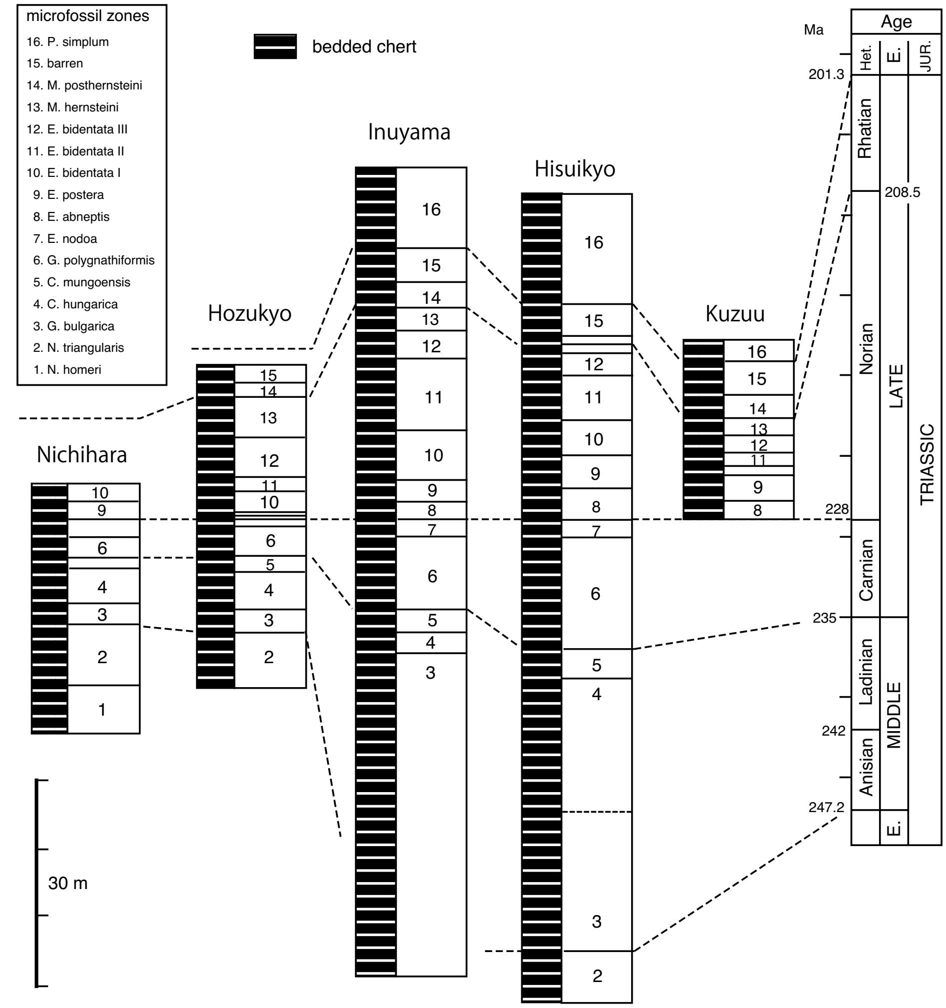


Figure 3. High-resolution microfossil (conodont/radiolaria) zoning in the Triassic–Early Jurassic deep-sea chert in Japan modified from Matsuda and Isozaki (1991) with the latest chronometric ages after Gradstein et al. (2012). All such chert occurs as allochthonous sheets/blocks within the Jurassic accretionary complex (AC) of the Mino-Tanba belt in SW Japan. Note that more than 15 microfossil zones in sequence were commonly recognized in the accreted bedded chert in multiple sections, and that all of them share more or less the same low average rate of sedimentation (ca. 1–4 mm/ka), regardless of their physical separation of more than 1,000 km along the Japanese Islands.

By virtue of high-resolution conodont studies in the late 1970s, multiple Triassic biozones, up to 14 in the sequence, were detected within > 80 m-thick bedded chert at several sections, (Fig. 3; Isozaki and Matsuda 1980; Yao et al. 1980; Matsuda and Isozaki 1982). This microfossil zonation demonstrated for the first time the extremely low average rate of sedimentation for bedded chert, ca. 1–4 mm/ka, and proved conclusively that the bedded chert in orogenic belts corresponds not to continental margin deposits but to modern mid-oceanic deep-sea (sub-carbonate compensation depth [CCD]) pelagic sediment (Matsuda and Isozaki 1991).

In addition to the confirmation of the mid-oceanic deep-sea origin of bedded chert in the Pacific-type orogenic belts, further observations were made on the direct (primary) contacts between pillowed MORB greenstone and deep-sea pelagic chert (Taira et al. 1980), between pelagic chert and a transitional hemipelagic siliceous mudstone above it, and between siliceous mudstone and overlying coarse-grained sandstone and mudstone (Matsuoka 1992). As microfossil ages demonstrated the primary stratigraphic relations among these essential components, the concept of OPS was consequently synthesized (Isozaki et al. 1990; Matsuda and Isozaki 1991). Before applying OPS analysis, these rocks were traditionally labeled 'eugeosynclinal deposits' as a whole, which are characterized by complicated rock assemblage and deformation. Without detailed fossil age for each bed and the criteria of OPS, these multiply repeated sedimentary rocks and associated high-pressure metamorphosed rocks were totally regarded to form an extraordinarily thick *in situ* sedimentary package, as exemplified by the Paleozoic complexes in the Appalachian Mountains and the Franciscan Complex in California. Nowadays, by virtue of high-resolution microfossil dating under the concept, these eugeosynclinal rocks are properly described as AC in terms of OPS (coherent and broken). In each OPS unit identified in outcrop, a systematic age relationship is observed between bedded chert and younger mudstone/sandstone, together with a hemipelagic siliceous mudstone unit sandwiched between them. Even chaotically mixed mélange units can be evaluated in the same standard and context as the non-deformed AC, as will be mentioned later. OPS was originally coined as "oceanic plate stratigraphy" (Isozaki et al. 1990); however, the idiomatic expression of English language recommends "ocean plate stratigraphy" (pers. comm. from B.F. Windley 2007), which has since been adopted.

OPS Studies over Two Decades and More

The utility of OPS in describing and explaining the components of the Pacific-type orogenic belts has been fully exemplified in SW Japan. Despite the similar rock assemblage regardless of AC ages, nearly 10 Phanerozoic AC units were discriminated in terms of OPS in SW Japan (Isozaki 1996; Isozaki et al. 2010). Since the 1980s, the OPS analysis has become a kind of routine procedure in the field work in Japan and the neighbouring countries in East Asia, such as the western Philippines and Primorye, East Russia (Isozaki et al. 1987; Kojima 1989; Wakita and Metcalfe 2005; Kemkin and Taketani 2008).

The application of this scheme was extended into the much deeper past, and some pilot studies have been performed by Japanese geologists in various Precambrian orogenic belts around the world; e.g. the Neoproterozoic–Cambrian orogens in southern Siberia and in Anglesey (Wales), the Archean Isua supracrustal belt, Greenland, and the Pilbara granite-greenstone belt, Western Australia (Komiya et al. 1999; Kitajima et al. 2001; Ota et al. 2007; Kawai et al. 2007). It is noteworthy that these areas were described previously to have belonged not to the typical Pacific-type orogenic belts, but rather to the collision-type ones. Nearly two decades since OPS analysis was formulated, geoscientists in the rest of the world began to realize its utility and significance for analyzing ancient orogenic belts (e.g. Cawood et al. 2009; Kusky et al. 2013).

In the meantime, OPS analysis brought 'spin-off' new findings on some unique phenomena in the ancient mid-ocean; the mass extinction-related global oxygen depletion (superanoxia) and the appearance of a cooling episode (Kamura event) around the Paleozoic-Mesozoic boundary, as will be introduced later.

ANCIENT MID-OCEANIC SEDIMENTS

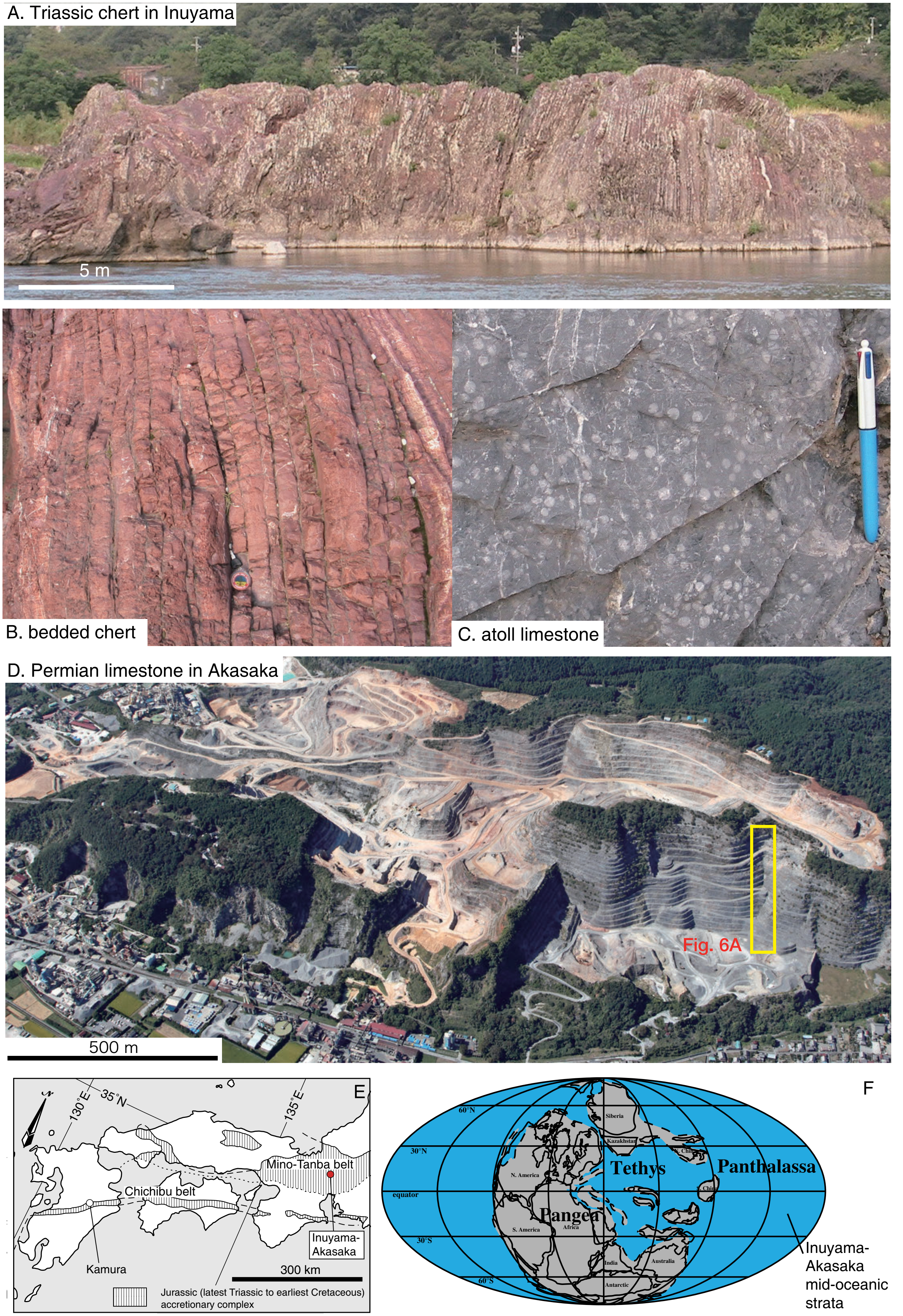
Concerning the pre-Jurassic sedimentary archives, the middle part of an OPS, i.e. mid-oceanic sediments, are of the greatest significance (Fig. 2A). They are two-fold: deep-sea sediment deposited below the CCD and shallow marine sediment formed on the top of topographic highs, e.g. seamounts (Fig. 2C). The former is bedded chert composed mostly of biogenic silica without calcareous bioclasts, whereas the latter comprises mostly shallow marine reef or carbonate mound limestone deposited on top of seamounts. Rarely associated are the supra-CCD but deep-water carbonates formed in the vicinity of mid-oceanic ridges but they are extremely small in amount thus negligible.

Deep-sea bedded cherts are stratigraphically sandwiched between the underlying pillow basalt of MORB affinity and the overlying coarse-grained terrigenous sandstone or mudstone (Fig. 2A, B). Likewise, atoll limestone and its pedestal seamount basalt occur between the same rock types above and below, forming the lateral equivalents of contemporary deep-sea chert (Fig. 2C). Occupying the middle part of an OPS, therefore, both mid-oceanic sedimentary rocks potentially record the main part of the long-term travel log of an oceanic plate from a mid-oceanic ridge to a trench. As these two sets of OPS represent different sedimentary facies in the mid-ocean environment, the former with deep-sea chert is referred to as $\mathrm{OPS}_{\mathrm{deep}}$, and the latter with atoll limestone as $\mathrm{OPS}_{\mathrm{shallow}}$.

Deep-Sea Chert

Phanerozoic deep-sea chert (Fig. 4A, B) generally has the following characteristics: 1) Milankovitch-tuned, rhythmically bedded alternation of vitric and argillaceous layers on a centimetre scale; 2) a vitric layer composed of ca.

Figure 4. *(on following page)* Phanerozoic example of the pre-Jurassic mid-oceanic sedimentary archives in Japan, i.e. deep-sea pelagic chert and atoll limestone. A: Field photographs of the Triassic bedded chert exposed along the Kiso River in Inuyama, central Japan. B: Enlarged view of the Triassic red bedded chert (key fob for scale). C: Enlarged view of bioclastic limestone (fusuline wackestone) at Akasaka, central Japan. D. Aerial photo of the Permian atoll limestone of the Akasaka quarry (courtesy of the Mitsuboshi Lime Co.). E: Index map of the Akasaka-Inuyama area in central Japan. The Triassic deep-sea chert and Permian limestone occur within the Jurassic accretionary complex of the Mino-Tanba (Chichibu) belt in Southwest Japan. F: The primary depositional site of the Permian–Triassic deep-sea chert and atoll limestone of Japan. Note their location in a low latitude area in the southern hemisphere in the mid-Panthalassa Ocean.


A. Triassic chert in Inuyama
5 m
B. bedded chert
C. atoll limestone
D. Permian limestone in Akasaka
Fig. 6A
500 m
E
N
130°E
35°N
135°E
Mino-Tanba belt
Chichibu belt
Kamura
Inuyama-
Akasaka
300 km
Jurassic (latest Triassic to earliest Cretaceous)
accretionary complex
F
60°N
30°N
equator
30°S
60°S
Siberia
Kazakhstan
N. China
S. China
N. America
S. America
Africa
India
Australia
Antarctic
Pangea
Tethys
Panthalassa
Inuyama-
Akasaka
mid-oceanic
strata

95 wt.% silica derived from siliceous microfossil tests (radiolaria, sponge spicules); 3) an argillaceous layer composed of fine-grained clay minerals (mostly illite-derived, likely from eolian dust) with a high concentration of cosmic spherules; 4) a brick red colour reflecting the inclusion of hematite (iron oxide); 5) extremely low average sedimentation rate (less than 5 mm/ka); and 6) the top portion changing gradually into hemipelagic siliceous mudstone (Matsuda and Isozaki 1991; Hori et al. 1993; Matsuo et al. 2003; Ikeda et al. 2010; Sato et al. 2011).

Atoll Carbonate

Phanerozoic atoll carbonate units (Fig. 4C, D) generally have the following characteristics: 1) shallow marine limestone with lateral facies changes from internal lagoon (packstone/wackestone, lime mudstone) to outer slope (allodapic limestone, turbidite; Fig. 2C) occasionally with wave-resistant reef structure (framestone/bafflestone, grainstone); 2) composed mostly of calcareous bioclasts of shallow marine skeletal organisms (protists, plants, and animals; e.g. foraminifers, calcareous algae, corals, crinoids, bryozoans, mollusks, brachiopods, etc.) and lime mud, but no terrigenous clastic material; 3) usually light grey in colour reflecting the pure carbonate composition with a minor amount of organic material; 4) deposited directly on pillow basalt with OIB composition; and 5) gravity flow deposits in the outer slope facies laterally changing into deep-water chert (Kanmera and Nishi 1983; Uchiyama et al. 1986; Isozaki 1987; Sano and Kanmera 1988; Fig. 2C).

Reconstruction of Dismembered OPS

In an AC unit with primary coherency, an OPS package as a fault-bounded sheet, some 100 m thick but several km long (wide), is tectonically repeated multiple times and has undergone layer-parallel shortening to form an asymmetrical duplex structure (Matsuda and Isozaki 1991; Kimura and Hori 1993). AC are formed primarily as imbricate OPS slices beneath the trench inner wall, which can be preserved even in blueschist units (Sedlock and Isozaki 1990; Isozaki and Blake 1994; Kimura et al. 1996). Secondary processes, such as large-scale submarine landslides and/or tectonic erosion, however, commonly destroy the primary duplex structures, and chaotically mix the OPS material into mélange (Okamura 1991). Exotic blocks and lenses of various size and form are often called olistoliths in an olistostrome or blocks in mélange.

The components of OPS are typically further dismembered and/or broken into smaller fragments during the subduction-related tectonics and metamorphism in the deeper part of the subduction zone. Thus, stratigraphic continuity of accreted mid-oceanic sedimentary rocks is rare and limited, even within apparently continuous bedded chert units in older AC exposed on-land (Yao et al. 1980). In particular, when studying deformed AC, the practical identification of primary OPS becomes extremely difficult in the field because contact surfaces between pillow basalt and chert, or between chert and clastic rocks, are modified and tectonized. Nonetheless, the reconstruction of OPS is possible in many Phanerozoic cases even for mélange, by virtue of high-resolution microfossil dating coupled with keen field observations, as performed in Japan and in California (Isozaki 1987; Wakita 1988; Isozaki and Blake 1994).

Microfossils typically occur in large numbers and continuously throughout the section, and are thus more advantageous in fossil zoning than megafossils, in particular in open ocean settings far from land margins where various microplankton thrived. For OPS$_{deep}$, conodont zonation is the most powerful tool in dating Cambrian to Triassic bedded chert with extremely low rates of sedimentation. An alternative versatile microfossil is radiolaria, however, the radiolarian zonation is still not as high in resolution as that for the post-Permian. For pre-Jurassic atoll limestone of OPS$_{shallow}$, conodonts are likewise the most reliable index fossils; nonetheless, their occurrence is strongly controlled by facies which often eliminates the possibility of high-resolution dating. For the Carboniferous and Permian, fusuline biostratigraphy is practical but its cross-correlation with high-resolution conodont zonation is not yet fully established. For much older Paleozoic strata, chitinozoans and acritarchs are good candidates instead of conodonts. For fossil-poor Precambrian cases, other dating techniques are required, as will be discussed later.

SIGNIFICANT EPISODE AROUND THE MAJOR DIVIDE OF THE PHANEROZOIC

This section reviews some exceptionally well preserved examples of the pre-Jurassic sedimentary records from subducted mid-ocean floors, which demonstrate several unique environmental episodes in Earth's history; e.g. the Permian–Triassic boundary superanoxia and the late Middle Permian Kamura cooling event.

Permo–Triassic Boundary Superanoxia and Extinction

The Paleozoic–Mesozoic boundary or Permo–Triassic boundary (P–TB) represents the timing of the largest mass extinction in the Phanerozoic biosphere (Erwin 2006), which marks the main divide of the Phanerozoic. Numerous studies have been performed for the fossiliferous strata around the P–TB horizon both in marine and non-marine sections, in particular, the shallow marine continental shelf deposits accumulated around the warm water Tethys that formed a large embayment on the east of the supercontinent Pangea (Fig. 4B-6). The extinction rate of the Paleozoic marine invertebrate genera at the P–TB allegedly reached ca. 70%, and more or less the same change occurred in land animals (Benton and Newell 2014; Smith and Botha-Brink 2014). The extraordinarily large loss in biodiversity suggests the occurrence of global scale environmental changes. Some possibly relevant but probably circumstantial phenomena have been documented, such as the activation of a large igneous province (the Siberian Traps), total disappearance of reef systems and coal deposition, unusual seawater redox changes, C-isotope fluctuation, etc. In order to explain these, various explanations for the cause have been proposed, such as global cooling and sea level drop, severe volcanism, methane burp, etc.; however, practical killing mechanisms for diverse animals and the ultimate cause of this event still remain enigmatic.

For assessing the global environmental changes relevant to the biggest extinction, a vital piece of information was absent before the 1990s; that is the sedimentary record from the mid-superocean Panthalassa, which occupied nearly 70% of the Earth at that time. The Panthalassan ocean floor comprised mostly Paleozoic oceanic crust; however, owing to the continuous subduction along the circum-superocean trenches, the Paleozoic seafloor totally disappeared afterwards (Fig. 1). Within the Jurassic AC in SW Japan, bedded chert commonly occurs in the middle portion of an OPS_{deep} or in dismembered isolated blocks within mélange deposits, and range in age from the Carboniferous to the Early Jurassic. Regardless of their depositional age, most of them display the primary brick-red colour (except for the parts later altered or metamorphosed), which reflects the ubiquitous occurrence of hematite (iron oxide) within almost transparent silica (Fig. 4A, B), as confirmed by X-ray diffraction, rare earth element abundances, and Mössbauer spectroscopy (Isozaki 1994; Kato et al. 2002; Matsuo et al. 2003; Sato et al. 2011. The 160 m.y.-long deposition of mid-oceanic deep-sea chert implies a considerably long residence time for the relevant oceanic floor in mid-oceanic realms before arrival at the Jurassic continental margin of Japan. Therefore, the deep-sea floor of the mid-Panthalassa Ocean was constantly kept under oxygenated conditions at a level high enough for stabilizing iron oxide in the Late Paleozoic and Early Mesozoic, just like the post-Triassic conditions of ocean floors observed in modern deep-sea red clay.

In contrast, strata deposited near the P–TB horizon are composed of black carbonaceous or pyritiferous claystone (Yamakita 1987; Kajiwara et al. 1994; Isozaki 1994; Kakuwa 1996; Fig. 5A, B) and occur between Permian and Triassic chert beds. The ubiquitous occurrence of pyrite (iron sulphide) and the complete absence of hematite indicate that this interval was deposited under oxygen-depleted conditions. The latest Permian and Early Triassic chert beds above and below likewise show similar features with pyrite but without hematite (Isozaki 1994; Fig. 5A-1). Although similar in iron content, hematite and pyrite never occur together in one chert bed, indicating a difference in chemical state of iron in chert that is related to the paleo-redox of deep-sea water; i.e. red for oxygenated and dark grey/black for oxygen-depleted conditions, as supported by REE patterns, Mössbauer spectroscopy, and molybdenum signature (Kato et al. 2002; Matsuo et al. 2003; Takahashi et al. 2014).

It is noteworthy that the oxygen-depleted interval is not restricted to the P–TB, but has a much longer duration from the late Middle Permian to early Middle Triassic (i.e. about 20 million years). In order to describe this unique long-term oceanographic phenomenon in mid-oceanic deep-sea strata, Isozaki (1994, 1997) coined the term “superanoxia” (Fig. 5B). The temporal length of the Late Permian anoxia is still under debate (Kakuwa 2008; Kato and Isozaki 2009); however, the total duration of this unique oxygen-depleted episode was likely up to 10 million years until its recover in the Anisian, early Middle Triassic (Fig. 5A-1). These observations indicate that the supply of oxygen into the deep sea of mid-Panthalassa stopped for a significant duration across the P–T boundary resulting in the development of the P–TB superanoxia. Across the P–TB, a significant turnover of radiolarians occurred in the mid-ocean from the Paleozoic-type to the Mesozoic–Cenozoic-type. This remarkable change of the representative Paleozoic plankton proves that the P–TB extinction occurred not only in marine organisms of shallow marine Pangean shelves but also in the vast mid-Panthalassan domains, and thus indeed had a global context. A possible link between this mid-oceanic plankton extinction and the superanoxia has been debated (Isozaki 2009a).

The documentation of such a global episode for the first time from the pre-Jurassic sedimentary archive from the lost ocean has promoted further research. Spin-off results from the studies on accreted deep-sea chert in Japan include the documentation of the Toarcian (late Early Jurassic) anoxic chert (Hori 1997), the detection of Milankovitch cyclicity (Hori et al. 1993; Ikeda et al. 2010), and the identification of concentrated PGEs (platinum group elements) in the Manicouagan-related mid-Norian (Triassic) horizon (Sato et al. 2013), which suggests an episode of extraterrestrial impacts and relevant events.

End-Guadalupian Kamura Cooling Event

Beside deep-sea chert, the late Paleozoic to Jurassic AC in SW Japan contain numerous blocks of Carboniferous, Permian, and Triassic shallow marine limestone which primarily formed as paleo-atoll complexes on the top of hotspot-type seamounts (Kanmera and Nishi 1983; $OPS_{shallow}$). As various fossils of shallow-water biota (rugose corals, fusulines, crinoids, bryozoans, mollusks, brachiopods, conodonts, etc.) are abundant in such limestone, the overall biostratigraphic framework within these limestone blocks in Japan was already clarified in the 1950–1960s. Nonetheless, in the mid-1990s, the extinction-related P–TB horizon was discovered for the first time in these mid-Panthalassan paleo-atoll complexes (Koike 1996). The boundary interval is distinct from the rest of the limestone strata, and is characterized by the anachronistic microbial limestone and the sharp shift in carbon isotopic values (Sano and Nakashima 1997; Musashi et al. 2001), almost identical to those described from the Pangean shelf carbonates in South China and in Turkey (Baud et al. 1996; Kershaw et al. 1999). These findings confirmed that the surface seawaters and biota behaved almost in the same way around the globe across the P–TB. Following this first discovery of a geologically significant horizon from the pre-Jurassic mid-oceanic paleo-atoll carbonates exposed on land, another significant interval was identified within the Jurassic AC in SW Japan, the Middle–Late Permian boundary (Guadalupian–Lopingian boundary: G–LB; ca. 260 Ma) interval (Isozaki and Ota 2001; Ota and Isozaki 2006).

The end-Paleozoic mass extinction has been shown to have involved two distinct pulses; i.e., first at the G–LB and second at the P–TB (ca. 252 Ma) (Jin et al. 1994; Stanley and Yang 1994). As the G–LB event marked the first major decline of the

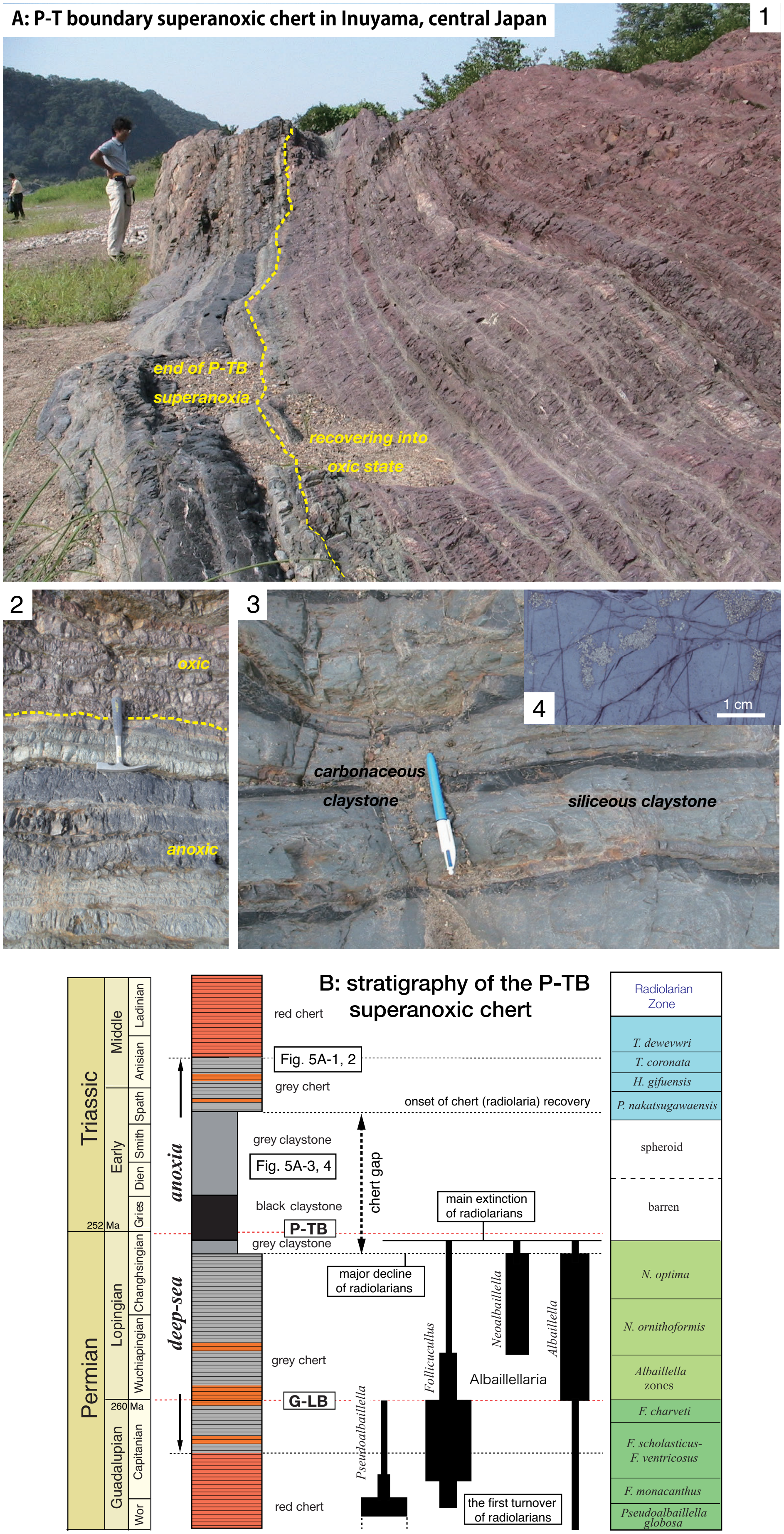


Figure 5. The Permo–Triassic (P–T) boundary superanoxia recorded in the deep-sea pelagic chert in the Jurassic accretionary complex (AC) in central Japan (Isozaki 1994, 1997).
A: Photographs of the Permo–Triassic boundary superanoxic chert in Inuyama, central Japan. 1. Lower Middle Triassic bedded chert showing a remarkable redox change in deep-sea sediment; recovery from the dark grey anoxic chert to reddish oxic chert; 2, 3. Lower Triassic siliceous claystone with black carbonaceous layers and pyrite nodules; 4. Lowermost Triassic black carbonaceous claystone. All these features suggest that an oxygen-depleted condition dominated in the mid-oceanic deep sea. B: Composite stratigraphic column of the P–T boundary superanoxic chert in Japan, which corresponds to the middle part of an ocean plate stratigraphy-deep (OPS$_{deep}$). This set of data documented that the Panthalassa Ocean was involved in long-term oxygen depletion (superanoxia) across the P–T boundary.

Permian fauna after the long-term stable biodiversity throughout the period, it appears more significant than the apparently final P–TB event. Again, the major obstacle in the G–LB study was the absence of information from the mid-superocean.

The G–LB boundary horizon in the Permian limestone blocks at Kamura in Kyushu and at Akasaka in central Japan was identified by fusuline stratigraphy (Sakagami 1980; Ozawa and Nishiwaki 1992; Zaw Win 1999; Isozaki and Ota 2001; Ota and Isozaki 2006; Fig. 6A). A recent detailed lithofacies analysis on the Akasaka limestone reveals that the G–LB horizon is characterized by a sea level low stand that caused an erosional hiatus (Kofukuda et al. 2014). This analysis records a significant sea-level drop in the mid-superocean, in accordance with the results of sequence stratigraphy on the contemporary peri-Pangean shelf strata (Haq and Schutter 2008). These phenomena confirm that the global sea level ubiquitously dropped to the lowest level of the Phanerozoic

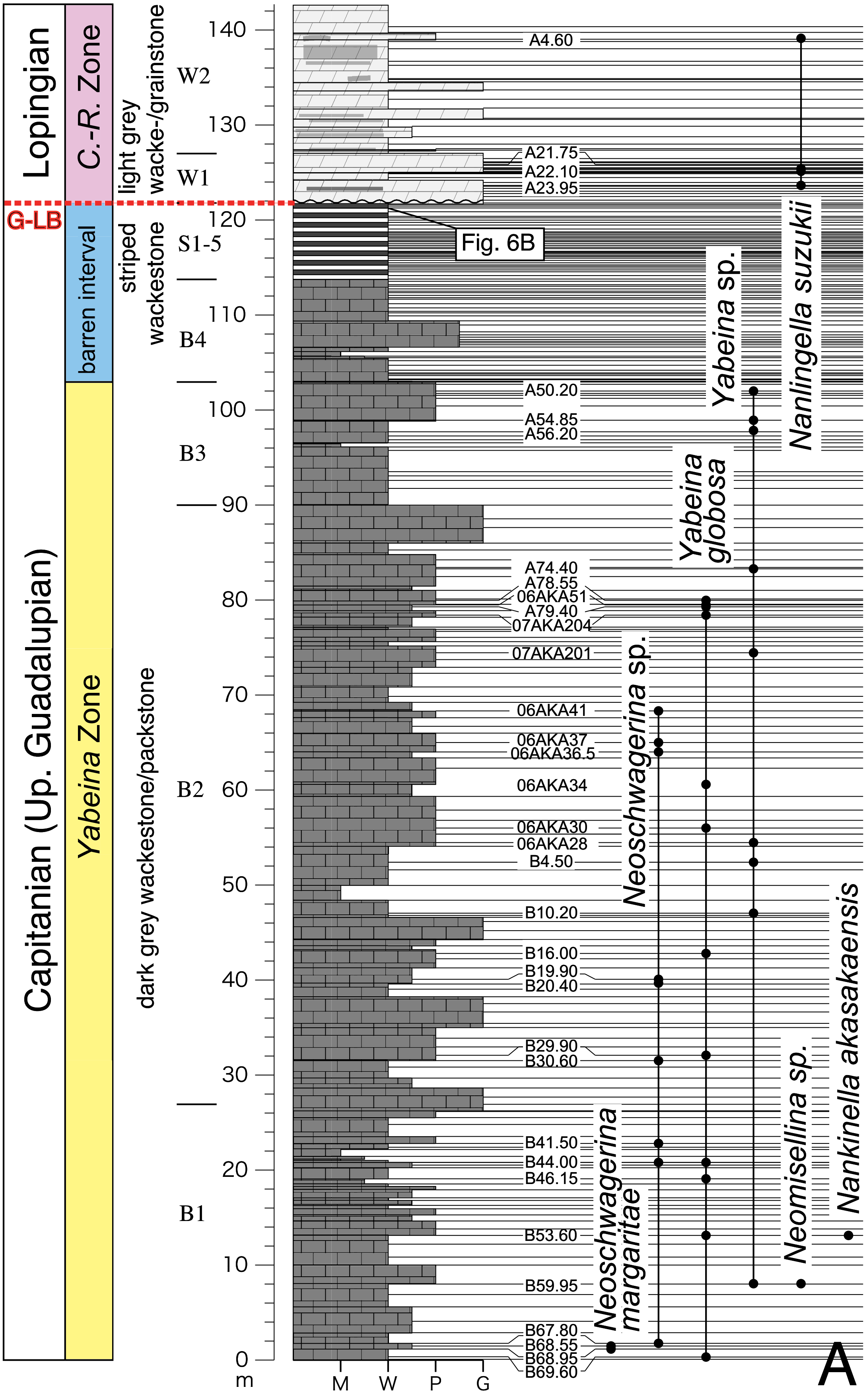


Figure 6. *(on this and following two pages)* The Middle Permian Kamura cooling event recorded in the paleo-atoll limestone in the Jurassic accretionary complex (AC) in SW Japan. A: Stratigraphic column of the Guadalupian (Middle Permian)–Lopingian (Upper Permian) atoll limestone at Akasaka in central Japan (Fig. 4D; Kofukuda et al. 2014), which corresponds to the middle part of an ocean plate stratigraphy-shallow ($\mathrm{OPS}_{\mathrm{shallow}}$). B: Enlarged column and outcrop photo of the G–L boundary identified in the Permian Akasaka limestone in central Japan (Fig. 4D). Note the erosional surface between the Guadalupian striped limestone and the overlying Lopingian massive limestone. C: Composite stratigraphic column of the Middle Permian–Triassic paleo-atoll limestone in Japan, which corresponds to an $\mathrm{OPS}_{\mathrm{shallow}}$. This set of data documented that mid-Panthalassa had experienced a two-phased extinction event across the P–T boundary, as well as the coeval circum-Pangean continental shelf, in other words, the greatest biotic crisis occurred in the global context (Isozaki 2009a). D: The Permian to Jurassic migration trail of the Akasaka paleo-seamount with atoll complex. Note that this Permian seamount migrated from a low latitude area in the southern hemisphere to a mid-latitude domain in the northern hemisphere across the equator in ca. 100 million years, and that it crossed a boundary of a fusuline biogeographical province between the Yabeina territory and Lepidolina territory (Kasuya et al. 2012).

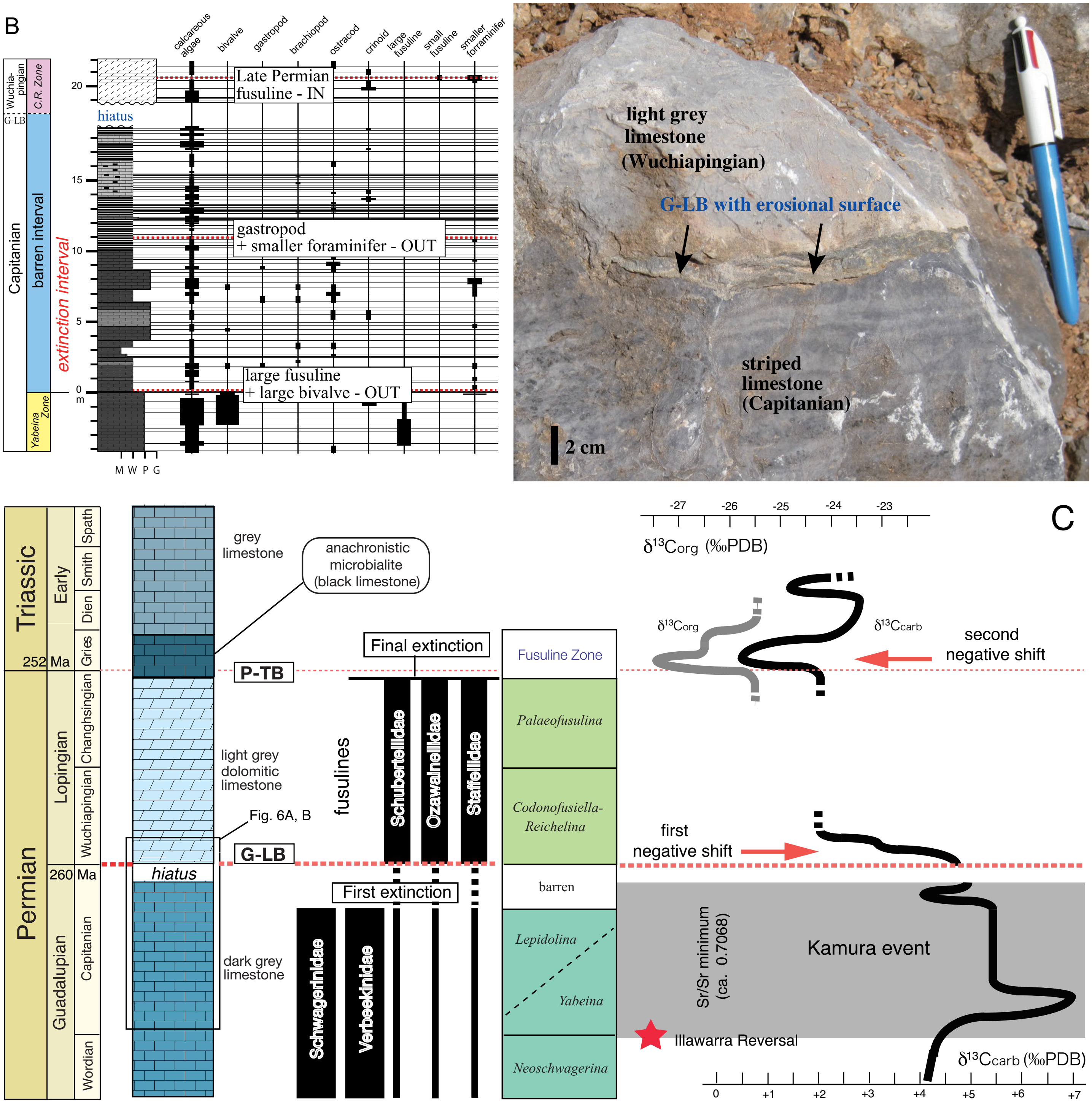
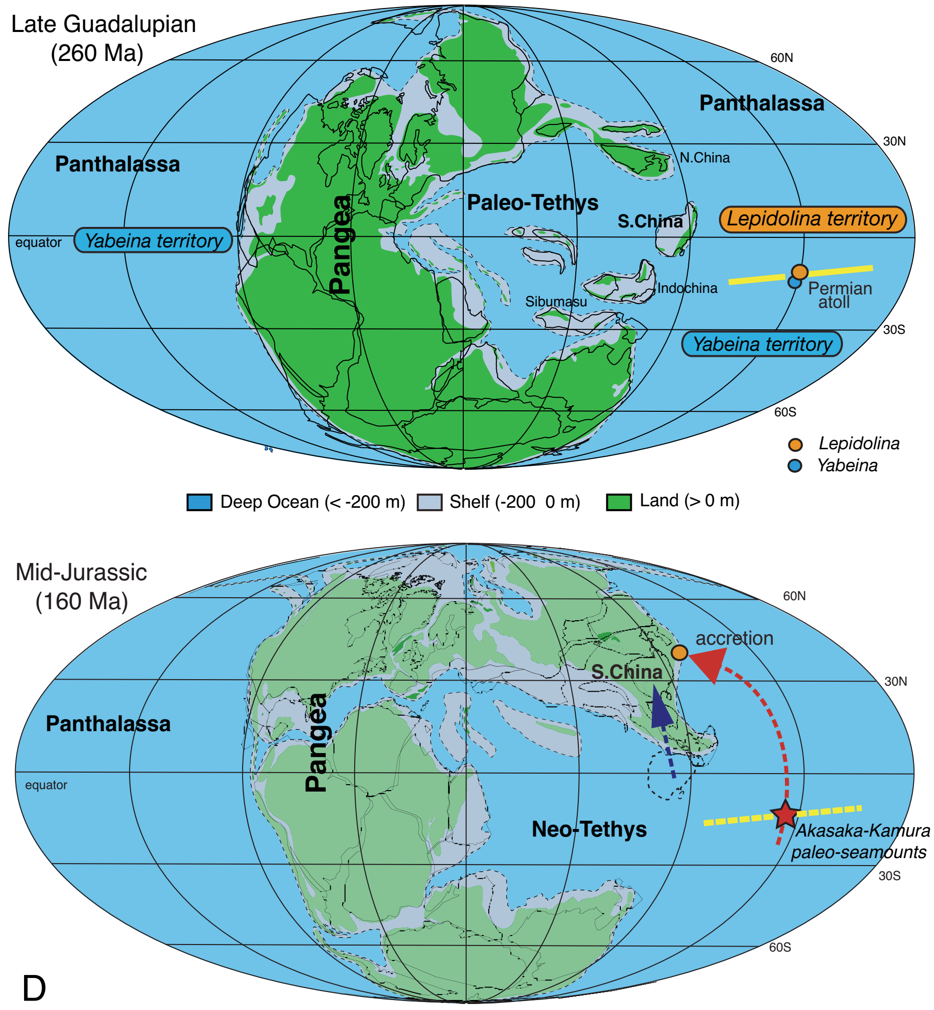


Figure 6. *(continued).*

at the end of the Guadalupian, and suggest the appearance of a significant global cooling event (Isozaki 2009a).

The cold climate at the end of the Guadalupian (Kamura event) was already speculated independently on the basis of stable carbon isotope analysis from the paleo-atoll limestone at Kamura (Isozaki et al. 2007), which was later reproduced in the shelf carbonates in the European Tethys (Isozaki et al. 2011). Supporting lines of evidence include the disappearance pattern of the unique photosymbiosis-dependent shallow marine fossil assemblage in the Permian low-latitude areas in the world (Isozaki and Aljinović 2009), and the discovery of significant glaciogenic deposits at the end of the Guadalupian (Fielding et al. 2008). The isotope stratigraphy deduced from ^{87}Sr/^{86}Sr ratios from paleo-atoll limestone (Fig. 6C) records Phanerozoic minimum values in the Late Guadalupian around 0.7068 (Kani et al. 2008), in accordance with similar data from continental shelves (Korte et al. 2006; McArthur et al. 2012). This unique isotopic signal is explicable in terms of the extensive development of



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continental glaciation during the Late Guadalupian (Kani et al. 2013). As for the isotopic episodes in the Late Guadalupian mentioned above, it should be emphasized that their global nature was virtually confirmed by the studies on mid-oceanic records that were retrieved through OPS analysis. These G–LB and P–TB cases would suggest that similar Sr-isotope signatures at the end-Ordovician, mid-Carboniferous, and Oligocene should be examined with respect to the short-term waxing and waning of glaciation.

Kirschvink and Isozaki (2007) first detected a very faint but reliable paleomagnetic signature from these Permian paleo-atoll carbonates, and confirmed that these limestone units were deposited at ca. 12° in the Permian southern hemisphere. Thus the Middle Permian (ca. 265 Ma) paleo-seamounts migrated through the super-ocean Panthalassa for ca. 40° in latitude (i.e. at least 4,000 km) during its ca. 100 million year-long journey to the mid-Jurassic (ca. 160 Ma) Asian (Japan) margin (Fig. 6D). By documenting faunal provinciality of the Guadalupian fusulines, Kasuya et al. (2012) demonstrated for the first time the existence of a paleobiogeographic provincial boundary within the lost superocean Panthalassa at the paleolatitude of 12°S. This single case study cannot display the regional provincial boundary as a 'line' within the superocean, with respect to the corresponding boundaries on continental margins; however, it definitely provides a new constraint. Previous paleobiogeographic studies solely discussed aspects of shelf sediments deposited on continental blocks, where motions are relatively slow. As in the case of the northward migration history of the Kamura-Akasaka limestone units, seamounts moved much quicker, thus, their records were more latitude-sensitive for identifying the exact location of mid-oceanic provincial boundaries.

New Windows to Observe Much Older Lost Oceans

The lines of evidence obtained from the deep and shallow regimes of the lost mid-Panthalassa Ocean presented here add completely new and pristine datasets to the conventional studies on the Permian extinction-related global environmental changes. In particular, unique events like the superanoxia have been identified for the first time solely in mid-oceanic regimes, outside the sedimentary archive of continental shelves. No doubt, we can use these approaches to study much older and more mysterious pre-Permian worlds. The same methodology and interpretations can be applied to similar accreted oceanic material of the Early Middle Paleozoic ages that occur in Paleozoic AC in the orogenic belts in the rest of the world. Although not as fully analyzed as the Permian cases mentioned above, analogous case studies have been attempted in Neoproterozoic mid-oceanic sedimentary rocks. Under the advantage in concept formulation and refinement of field procedures, pioneer application of OPS analysis to older analogues were performed by Japanese geologists, in particular, Shige Maruyama and his colleagues (including the author) in the Tokyo Institute of Technology, in close co-operation with geologists in other countries, as discussed next.

PROTEROZOIC PORTFOLIO

Just like studies on human history, the older the period of interest, the more difficult it becomes to get reliable information. Simply because the assembly and break-up of supercontinents have been repeated multiple times in several hundred million year intervals in the past (Hoffman 1991; Murphy and Nance 1991), there is no example of a currently active Pacific-type or Cordilleran-type orogenic belt that has survived continuously for more than 500 million years. In other words, Proterozoic AC that may potentially preserve older mid-oceanic archives cannot be found in modern active continental margins, such as the circum-Pacific domain. Nonetheless, within the continent-continent collision-type orogens, there are some possibilities so long as the secondary overprints of deformation and metamorphism are not severe. No continental collision would occur without preceding oceanic subduction to consume intervening oceanic lithosphere; thus even in mid-continent collision-type orogenic belts, we may find fragments of Precambrian AC and their OPS.

Two case studies of Neoproterozoic mid-oceanic sedimentary rocks have identified OPS within well-known collision-type orogens: deep-sea chert in Wales, UK, and paleo-atoll limestone in southern Siberia, Russia. Against all odds, these examples prove that the retrieval of ancient mid-oceanic sediment information from lost oceans is possible through conventional on-land geological fieldwork provided special focus and perception are applied.

Neoproterozoic Snowball Dropstone and Paleo-Redox in Mid-Ocean

In Anglesey and the Lleyn Peninsula of northwestern Wales, UK (Fig. 1), the extensive development of a Neoproterozoic–Cambrian AC was recently identified (Kawai et al. 2007; Maruyama et al. 2010; Fig. 7). This belt is associated with well-known blueschist and granite (Blake 1888; Greenly 1919; Gibbons and Mann 1983; Kawai et al. 2006) and has been traditionally assigned to elements of the Early Pale-

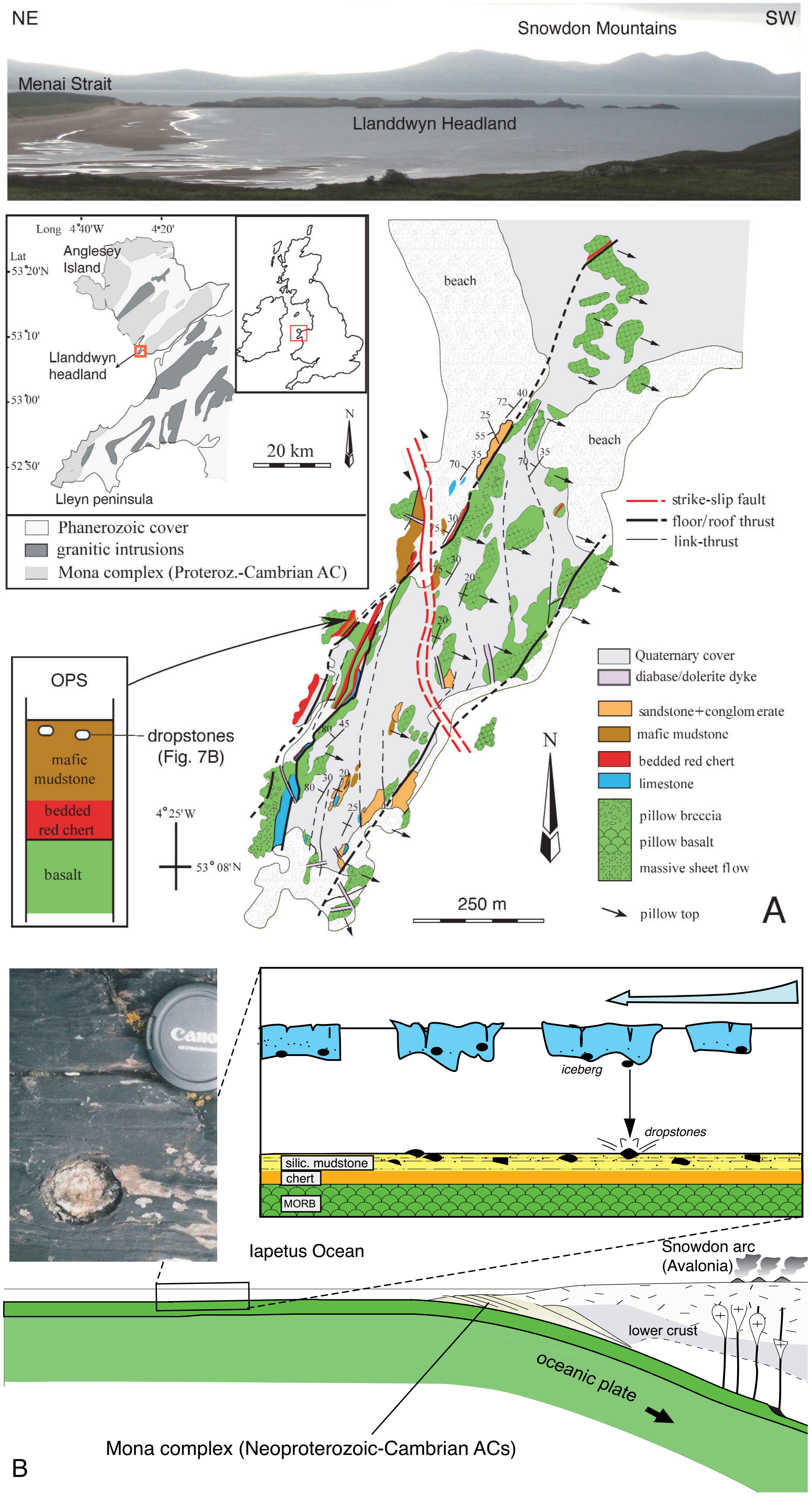


Figure 7. The Neoproterozoic snowball dropstones in deep-sea siliceous mudstone in the Cambrian accretionary complex (AC) on the Llanddwyn headland in NW Wales, UK. A: Distant view and lithologic map of Llanddwyn headland in southwestern Anglesey, Wales, showing duplex structures of ocean plate stratigraphy-deep (OPS_{deep}) in the Cambrian AC (modified from Kawai et al. 2008). This AC unit was developed along the northern margin of Avalonia (southern part of UK) by the southward subduction of the seafloor of the Iapetus (or Moravia) Ocean; B: Schematic cartoon showing the deep-sea siliceous mudstone received dropstones delivered by icebergs likely under the Neoproterozoic snowball Earth condition.

ozoic Caledonian orogen that formed by the collision between Avalonia (a detached piece of northern Gondwana) and Laurentia (North America), owing to the closure of the Iapetus-Rheic (or Mirovia) oceans. During the last two decades, however, it became apparent that a more complex tectonic history is recorded in the Caledonian orogen, particularly with respect to the interactions with multiple intra-oceanic arcs prior to the final collision between the major continental blocks (van Staal et al. 1998; McKerrow et al. 2000; Murphy et al. 2006; van Staal and Barr 2012). This resulted in the pre-collision tectonic evolution, i.e. the part related to oceanic subduction and thus accretion along active arc systems, to be studied in more detail.

The Japanese-British joint research team (led by S. Maruyama, B.F. Windley and their colleagues in the Tokyo Institute of Technology) conducted detailed mapping of the weakly metamorphosed Neoproterozoic–Cambrian rocks (called the Mona Complex) in Anglesey and the Lleyn Peninsula. In particular at the Llanddwyn headland in SW Anglesey (Fig. 7A), they demonstrated well-preserved examples of $\mathrm{OPS_{deep}}$ in an AC within a duplex structure (Kawai et al. 2008; Maruyama et al. 2010). Although the age constraints are still poor, some thin slivers of deep-sea bedded chert occur stratigraphically between pillowed basaltic greenstone and overlying coarse-grained terrigenous clastic rocks. These rocks in NW Wales represent the latest Neoproterozoic to Cambrian AC formed along the northern margin of Avalonia before the final closure of the Iapetus Ocean. Two significant observations were made about the Neoproterozoic mid-oceanic sedimentary rocks and their paleo-environmental implications. One is the finding of iceberg-derived dropstones within deep-sea mudstone, and the other is the confirmation of deep-sea oxygenation already in the late Neoproterozoic.

At Llanddwyn headland, a unique outcrop of pebbly mudstone was observed. This bed contains randomly scattered, rounded to subangular clasts up to 20 cm in diameter within the matrix of fine-grained siliceous mudstone (Kawai et al. 2008; Fig. 7B-inset photo). As the surrounding rocks of ocean plate origin totally lack coarse terrigenous clastic grains, this unique bed is best explained as deep-sea sediments heavily bombed by numerous dropstones from icebergs in the middle of the ocean (Fig. 7B). Previously known occurrences of tillite and dropstones relevant to the Neoproterozoic snowball Earth event (Hoffman et al. 1998; Hoffman and Schrag 2002) were restricted solely to the continental shelf/slope deposits. In contrast, those at Llanddwyn prove that significant amounts of ice reached the lost low-middle latitude Iapetus (or Mirovia) Ocean, and thus represent the first direct evidence from the mid-ocean, which positively supports the global nature of the Neoproterozoic freezing event. As loose age constraints for the dropstone-bearing unit hampered the reliable correlation with either of the Neoproterozoic snowball Earth events, radiometric ages are needed for this non-fossiliferous unit.

As to the Neoproterozoic mid-oceanic glacial record, another previous example to be noted is dropstones in Neoproterozoic greenschist (the Dernburg Formation) in the Chameis subterrane in coastal Namibia (Frimmel and Jiang 2001). Although detailed OPS has not yet been documented from that unit, the rock assemblage and its geochemical characteristics suggest that these rocks occur within an OPS of a Neoproterozoic AC likely formed along the Kalahari margin through the closure of the putative Adamastor Ocean between the Rio de la Plata and Kalahari cratons.

The second issue to note is the occurrence of red bedded chert at Llanddwyn that ubiquitously bears fine-grained hematite (Sato et al. 2009). According to the Fe-mineral identification by Mössbauer spectroscopy (Matsuo et al. 2003; Sato et al. 2011), most of the Phanerozoic deep-sea chert beds share the primary brick-red colour, except for the cases of secondary alteration and peculiar anoxic horizons. Their red colour reflects the dominance of hematite that suggests oxic conditions at the depositional site. The occurrence of red hematitic chert deposits records that the deep-sea of the Iapetus Ocean was oxygenated by the late Neoproterozoic at the latest. The history and processes of deep-sea oxygenation through the Precambrian time have been discussed indirectly in various ways (Anbar and Knoll 2002; Canfield 2005; Kump 2008; Komiya 2008); however, the hematitic chert in Anglesey is the oldest direct geological record hitherto known that proved the development of an oxic condition in *bona fide* deep-sea prior to the beginning of the Phanerozoic.

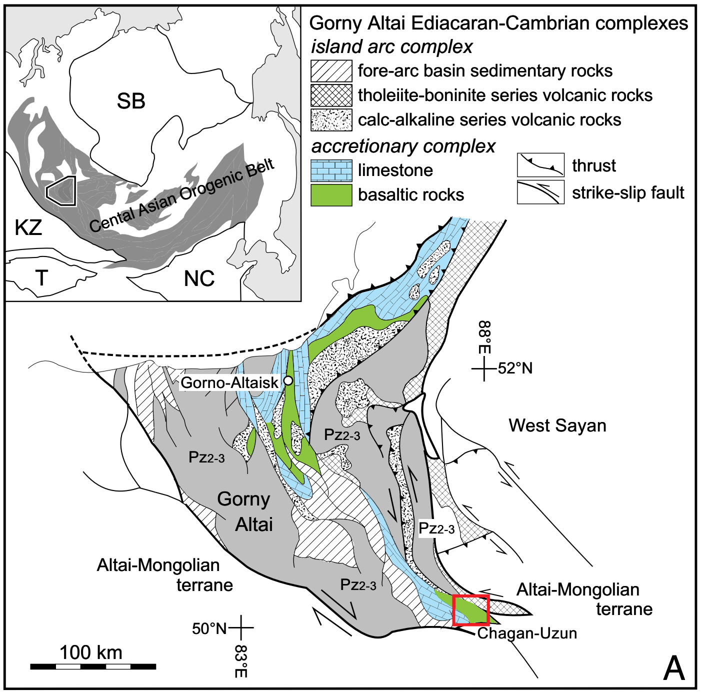
Neoproterozoic Mid-Oceanic Atoll Complex and its Biota

The Central Asia Orogenic Belt (CAOB) represents a major tectonic suture among many continental blocks that form the core of modern Asia (Maruyama et al. 1989; Şengör et al. 1993; Khain et al. 2003; Windley et al. 2007; Fig. 1). Some parts of this large orogen also retain less deformed/metamorphosed units that were formed prior to the final collision stage. The Gorny Altai Mountains in southern Siberia, Russia (Fig. 8A), expose various orogenic products that belong to the western segment of the CAOB (Buslov et al. 1993).

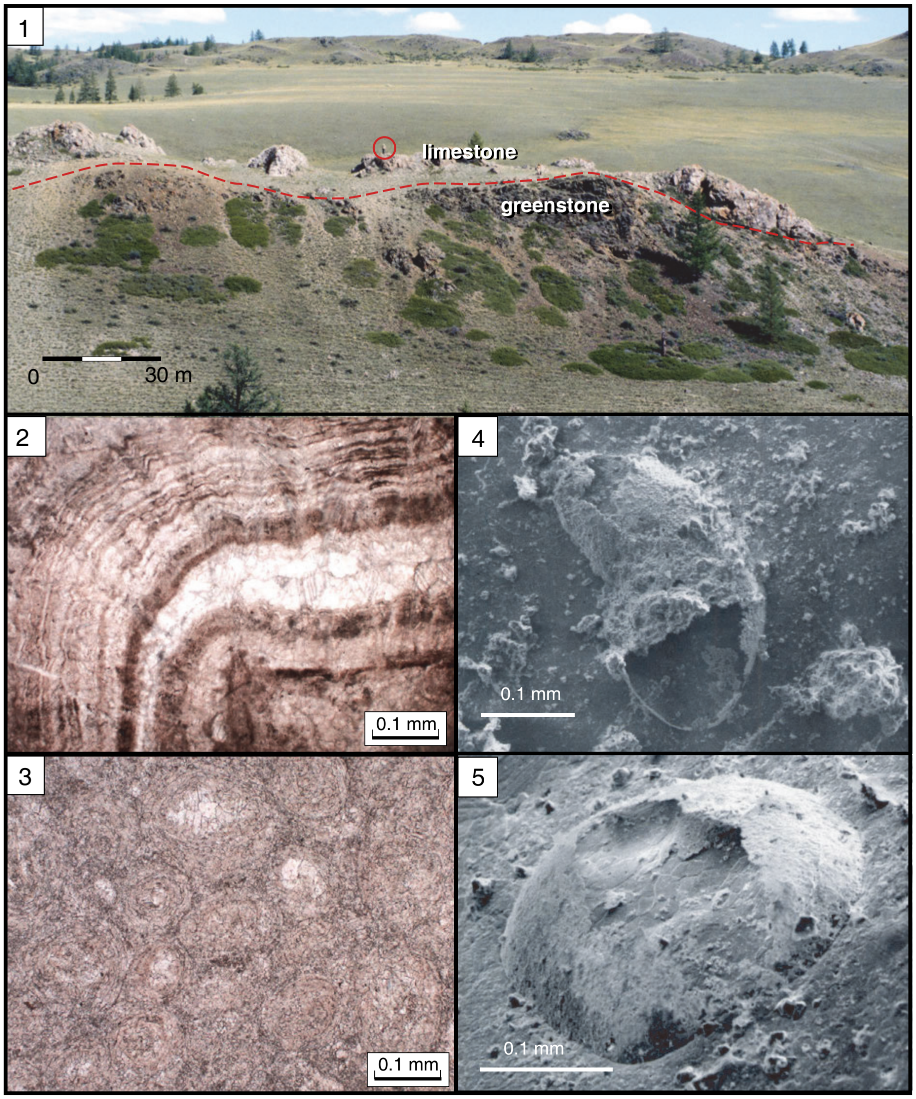
In the Kurai area in the southern part of the Gorny Altai Mtn., the Japanese-Russian joint research team (Hokkaido University, Tokyo Institute of Technology, and Russian Academy of Sciences) revealed that Neoproterozoic to Early Paleozoic subduction-related orogenic components occur extensively in the eastern part of the Gorny Altai Mtns., e.g. the Cambrian AC, Early Ediacaran (627–636 Ma) high-P/T metamorphosed AC, and serpentinite mélange, that were likely formed along the Kuznetsk–Altai island-arc system (Buslov et al. 2002; Ota et al. 2007; Safonova et al. 2008; Fig. 8A).

Within the Cambrian AC, a non-fossiliferous massive limestone, over 200 m-thick, called the Baratal limestone occurs (Fig. 8B-1, 8C), of which the basal part rests directly on the underlying pillow basaltic greenstone in which the geochemistry is similar to modern OIB rather than MORB (Safonova et al. 2008; Utsunomiya et al. 2009). This limestone partly possesses stromatolite or oolite-bearing horizons that suggest a shallow-marine origin (Fig. 8B-2, -3), and it is characterized by the complete

Figure 8. *(on this and next page)* The Ediacaran (Neoproterozoic) paleo-atoll limestone in the Cambrian accretionary (AC) in the Gorny Altai Mountains, southern Siberia. A: Index and geotectonic sketch map of the Gorny Altai Mtns., southern Siberia in the western segment of the Central Asian Orogenic Belt (CAOB). The Kurai area in the southern part of the mountains exposes the Cambrian AC with the Ediacaran–Cambrian atoll limestone (Ota et al. 2007). B: Field and microscopic photographs of the Ediacaran atoll limestone deposited on a seamount in Kurai; 1. far view of the outcrop of pillowed basaltic (OIB) greenstone capped by the Early Ediacaran paleo-atoll limestone (a man on the outcrop for scale) with shallow marine indicators, such as stromatolite (2) and ooids (3) from the basal parts (Uchio et al. 2004). Unidentified microfossils with phosphatic test (4, 5) occur in this limestone (Uchio et al. 2008). C: Facies diversity on seamount and tectono-sedimentary setting of the Ediacaran atoll limestone, which represents the middle part of an ocean plate stratigraphy-shallow (OPS$_{shallow}$).



B: Ediacaran atoll limestone in Kurai and microstructures



absence in coarse-grained terrigenous clastic material. These features suggest a mid-oceanic origin (Uchio et al. 2004; Fig. 8C). Although no reliable index fossil for dating is available, Nohda et al. (2013) detected a secular change in Sr isotope ratio of the limestone that, on the basis of similar chemostratigraphy, correlates with lowermost Ediacaran (ca. 635–630 Ma) or much older late Cryogenian strata. By analogy to the Permian examples of paleo-atoll complexes accreted to SW Japan, the Baratal limestone and the underlying pillow basaltic greenstone are regarded as an ancient mid-oceanic seamount complex capped by atoll-type carbonates (OPS$_{shallow}$) that were accreted in the Cambrian (Uchio et al. 2004; Ota et al. 2007). To date, this likely represents the oldest example of a massive paleo-atoll complex on a paleo-seamount in Earth's history, as will be mentioned later. Another possible candidate for Neoproterozoic OPS$_{shallow}$

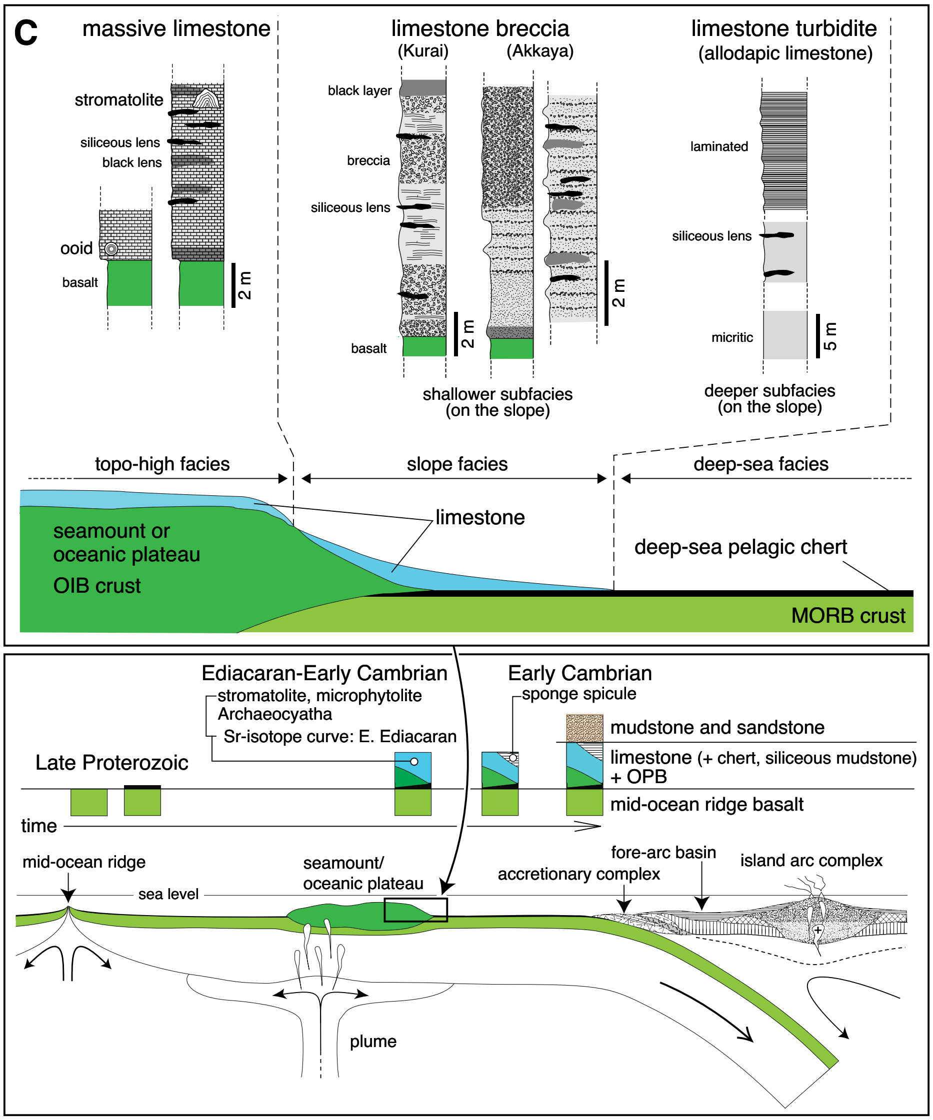


Figure 8. *(continued).*

is the dolomite of the Dernburg Formation in the Chameis subterrane in coastal Namibia (Frimmel and Jiang 2001). Its apparent rock assemblage and geochemical signatures suggest similarity to those of the Baratal paleoatoll limestone in the Gorny Altai Mtns., however, its OPS$_{\text{shallow}}$ should be more fully examined directly in the field for confirmation.

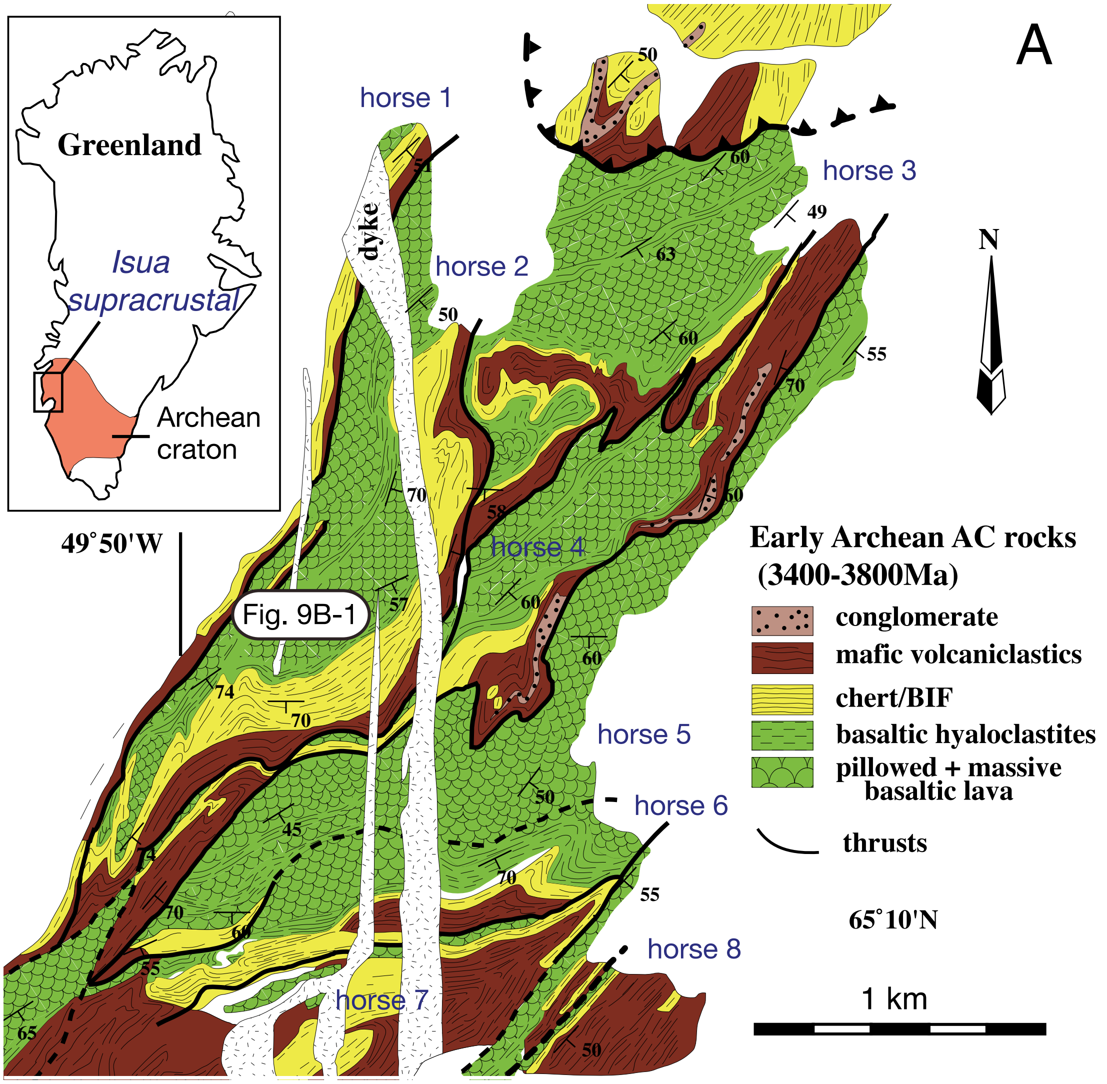
Noteworthy is the occurrence of an enigmatic microfossil composed of phosphatic shells, which was illustrated by Uchio et al. (2008) (Fig. 8B-4, -5). The early Ediacaran time was barren of fossils with mineralized tests or shells, as the earliest one *bona fide* (*Cloudina*) appeared in the latest Ediacaran, ca. 80 million years later. Although the taxonomic assignment of this enigmatic fossil has not yet been determined, this phosphatic microfossil from the Baratal limestone marks one of the oldest skeletonized microfossils of the world; in fact, the second oldest after the ~800 Ma phosphatic shale microfossils from the Yukon Territory (Cohen and Knoll 2012). These findings suggest that the onset of biomineralization likely started as phosphatic tests or shells much earlier than previously thought. Nonetheless, a major remaining enigma includes the origin of the late Neoproterozoic open-ocean setting, significantly before the major outbreak of skeletonization in marine organisms at the beginning of the Cambrian (Porter et al. 2010; Wood and Zuravlev 2012). With radiolarians and foraminifers not yet having appeared, a specific supply system, organic and/or inorganic, is required to explain deposition of chert and carbonates in the Proterozoic mid-oceans. Possible mechanisms may include the biological stabilization of silica and carbonates by microbial activities and inorganic precipitation of these minerals directly from seawater (Grotzinger and James 2000).

MARE INCOGNITUM: ARCHEAN MID-OCEAN

The two case studies on the Neoproterozoic examples mentioned above, one from the deep sea and the other from a near-surface ocean, clearly show the potential utility of accreted oceanic sedimentary rocks in various ways, in particular in paleo-environmental and relevant paleo-biological studies of lost mid-oceans of older Proterozoic and Archean. Some preliminary attempts have been made to investigate the Archean mid-oceans.

The 3.8 Ga Isua Supracrustal Belt

By applying the concept of AC and procedures of OPS analysis recognized in Japan to relatively weakly metamorphosed Archean rocks, the Japanese-Danish joint research team (S. Maruyama and his colleagues in Tokyo Inst. Tech.) conducted intensive field mapping and eventually interpreted that the Archean metasedimentary rocks of the Isua Supracrustal Belt in western Greenland (Figs. 1, 9A) represent the Eoarchean (thus the oldest) AC formed by oceanic subduction (Komiya et al. 1999). The Eoarchean greenstones derived from pillowed basalt and hyaloclastites are directly overlain by chert and then by coarser grained volcaniclastic rocks, representing a typical OPS$_{\text{deep}}$ (Fig. 9B; Maruyama and Komiya 2011). They demonstrated that the metasedimentary rocks of the Isua Supracrustal Belt are composed of repeated OPS sequences incorporated in a duplex framework (Fig. 9A); thus the chert corresponds to mid-oceanic deep-sea sediments of the Eoarchean and possibly Hadean world. In a sharp contrast to the conventional interpretations for *in situ* normal sedimentary sequence on the metamorphosed crust (Nutman et al. 1989), this challenging idea has been largely ignored by the geological com-



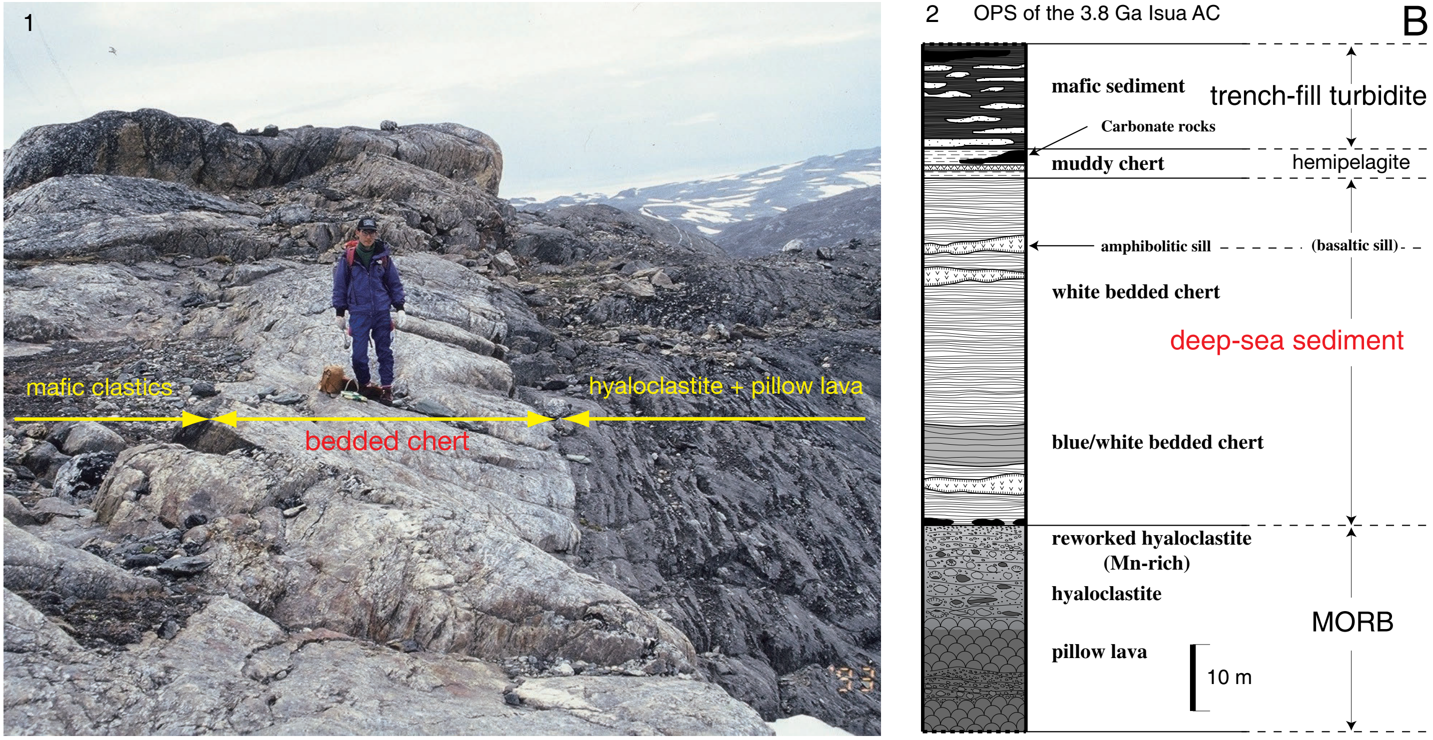


Figure 9. Early Archean (3.8 Ga) deep-sea chert in the Archean accretionary complex (AC) of the Isua Supracrustal Belt in West Greenland (Komiya et al. 1999; Maruyama and Komiya 2011). A: Index and lithologic map of the Early Archean AC recognized within the relatively less metamorphosed part of the belt. Note the duplex structure of ocean plate stratigraphy-deep (OPS_{deep}) composed of pillowed basaltic greenstone (green), chert (yellow), and coarse-grained volcaniclastic rocks (brown). B: Field photo and the Archean OPS_{deep} recognized within the mapped area. From right to left, pillow lava and hyaloclastite, chert, and volcaniclastic turbidite, in ascending order. A man is standing on the middle of an OPS, a 3 m-thick chert.

munity for more than a decade; however, some positive evaluation is slowly emerging (Furnes et al. 2007).

Owing to the high grade of metamorphism, up to the amphibolite facies (Hayashi et al. 2000), decoding the primary environmental signatures is not straight forward. Nevertheless, the relatively low ratios in stable carbon isotopes of the carbonaceous material, giving proof for a biogenic source, was originally reported by Schidlowski et al. (1984), and later reproduced by Rosing (1999) and Ueno et al. (2002). Recently, Ohtomo et al. (2014) analyzed transmission electron microscope images of ^{13}C-depleted graphite and supported the biogenic origin of the carbonaceous material in the Eoarchean strata at Isua. These studies support the hypothesis that primitive life had already appeared by 3.8 Ga in an open ocean environment.

As long as the AC was formed around 3.8 Ga, we may obtain much older sedimentary records within accreted oceanic sediments that possibly date back into pre-4.0 Ga ages (the Hadean), thus we may have a chance to look *bona fide* into the oldest biosphere, even before the putative late bombardment episode around 3.9 Ga.

3.5 Ga Pilbara Greenstone Belt

Another case study of the Archean ocean was carried out in the greenstone belt of the Pilbara craton in northern Western Australia (Fig. 1). This greenstone belt is composed of an extremely thick pile of ca. 3.5–3.2 Ga (Paleoarchean) basaltic greenstone and sedimentary rocks, such as pillowed basaltic (komatiitic in part) lavas, bedded chert, banded iron formation, and sandstone or mudstone. These rocks have been affected mostly by regional metamorphism that ranges up to the amphibolite facies; nonetheless, less metamorphosed parts remain in the prehnite-pumpellyite facies (Terabayashi et al. 2003), much lower than those in the Isua Supracrustal Belt. Thus, primary sedimentary and paleoenvironmental information is much better preserved in them. Huge Archean granite bodies exposed next to these greenstone belts in Pilbara were traditionally regarded to have formed the basement continental crust for the deposition of the basalt and sedimentary strata (Hickman 1983). The Japanese research group (mostly from the Tokyo Inst. Tech. led by S. Maruyama and the author) conducted intense field mapping of the North Pole dome area in central Pilbara in the early 1990s, and documented that the duplex structures are composed of multiple horses of OPS$_{\text{deep}}$ (Fig. 10A, particularly clear in Units I and II), and that igneous zircon ages of intercalated felsic tuff layers systematically become younger toward structurally lower horizons (Kitajima et al. 2008), which is the opposite of the younging direction in the apparently thick sedimentary pile and against the 'law of superposition'. These lines of evidence prove that the ca. 3.5 Ga rocks of the Pilbara greenstone belt indeed represent the Paleoarchean AC.

The most famous rock in the North Pole area is the 3.5 Ga chert with the allegedly Earth's oldest fossils. 'The oldest fossils' from bedded chert of the Dresser Formation in the North Pole area are two-fold; fossil 'bacteria' and domal stromatolite (Awramik et al. 1983; Schopf et al. 1983; Ueno et al. 2001). The biogenic origin of the claimed bacteria (Fig. 10B) was questioned later (Brasier et al. 2002); nonetheless, Ueno et al. (2006) documented the occurrence of methane in hydrothermal fluid suggesting active microbial methanogenesis in the Paleoarchean biosphere. It is particularly noteworthy that fossil-bearing chert belongs to the middle horizon of OPS$_{\text{deep}}$ in a Paleoarchean AC because this automatically suggests that the depositional setting for the fossil-bearing units have been in the deep sea, clearly lower than the photic zone, and far from land (Kitajima et al. 2001). As syn-depositional extensional deformation was observed in the 'bacteria' and stromatolite-bearing chert and in underlying pillow basalt with MORB-like geochemistry (Isozaki et al. 1998; Nijman et al. 1999), the tectono-sedimentary setting for the claimed Paleoarchean life was located most likely in the vicinity of a mid-oceanic ridge, on the deep-sea floor (Isozaki et al. 1998; Kato et al. 1998). This conclusion is totally inconsistent with the conventional interpretation of the shallow marine continental shelf setting for Paleoarchean life on the basis of the belief on that the 'stromatolite formed by photosynthetic bacteria.'

Being considerably older than the hard geological evidence for the active oxygenic photosynthesis confirmed merely after 2.3 Ga in the Earth's biosphere history (Anbar and Knoll 2002; Kump 2008; Johnson et al. 2013), Paleoarchean life was unlikely dependent on oxygenic photosynthesis in shallow seas as once imagined. In this regard, hydrothermal systems around mid-oceanic ridges appear more realistic for a possible energy or nutrient source for Early Archean life, where chemosynthesis dominated in the deep sea by utilizing significant thermal and geochemical gradients adjacent to inorganic heat sources (Ueno et al. 2006). Furthermore, this explanation is consistent with the genome-based phylogenetic tree of extant Eubacteria/Archea, in particular, with the 'root zone' dominated by hyperthermophiles (Woese 1987). These issues on the biogenic origin of Paleoarchean fossils and their possible habitable environments are still hotly debated. The above-mentioned deep-sea microbial community and habitat in the North Pole have not been fully accepted by the conservative research communities during the last two decades, but this new interpretation is slowly opening the tightly shut doors to the mysterious early Earth history.

SECULAR TREND THROUGH TIME

By virtue of the OPS analysis, exploration into older lost oceans in the past has been extended through the Paleozoic into the Precambrian, even to the Eoarchean. Figure 11 displays the age distribution of pre-Jurassic mid-oceanic sedimentary archives hitherto identified. As to the pre-Jurassic Phanerozoic, both OPS$_{\text{deep}}$ (bedded chert) and OPS$_{\text{shallow}}$ (atoll limestone) were identified in the Paleozoic–Mesozoic AC units in Japan, covering at least intervals of the Triassic, Permian, and Carboniferous (Isozaki et al. 1990; Matsuda and Isozaki 1991; Isozaki 1996, 2009a). Although the Lower Paleozoic records are still sporadically documented, mid-oceanic deep-sea chert and atoll limestone range down no doubt into the Ediacaran (Uchio et al. 2004; Ota et al. 2007; Kawai et al. 2008). Furthermore, some examples of

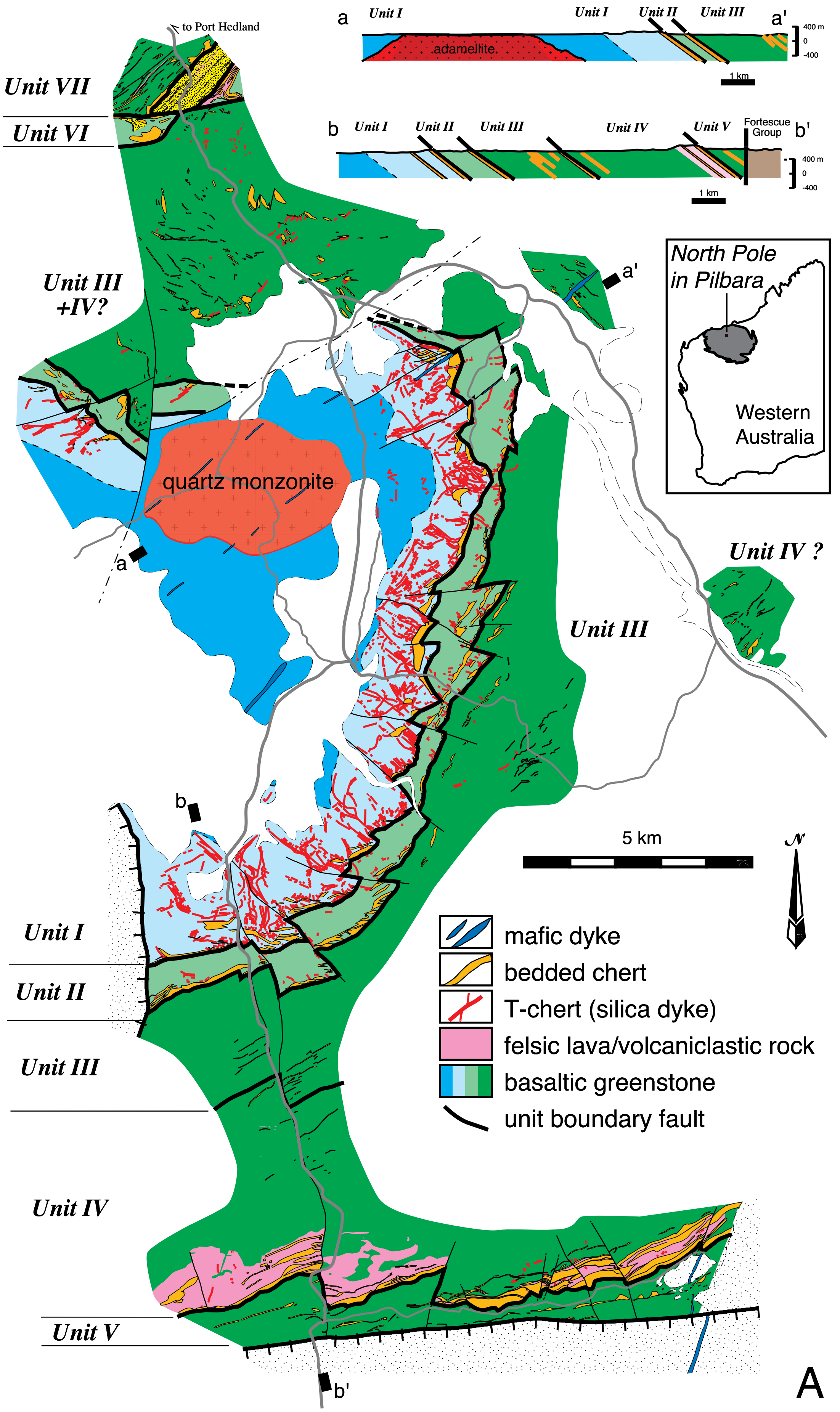


Figure 10. *(on this and next page)* Early Archean accretionary complex (AC) in the North Pole dome area in the Pilbara craton, Western Australia. A: Lithologic map of the Archean greenstone belt in North Pole dome area (after Kitajima et al. 2008). Note that the greenstone units comprise more than 5 units, and that each unit has a duplex structure, as represented by the multiple bifurcations of chert, and that the zircon U–Pb ages become systematically younger towards the structural bottom. B: Field photo of Archean bedded chert in North Pole, columns of reconstructed ocean plate stratigraphy (OPS) for the 5 units (above). Photos of the so-called 'bacteria-bearing' chert immediately above the right-side-up pillowed MORB greenstone; hand specimen (left) and thin section view of the bacteria-like carbonaceous filaments in chert (right). Note that both the 'putative oldest bacterial remains' and the well-known 'stromatolite' occur in the middle of the Archean OPS$_{\text{deep}}$.

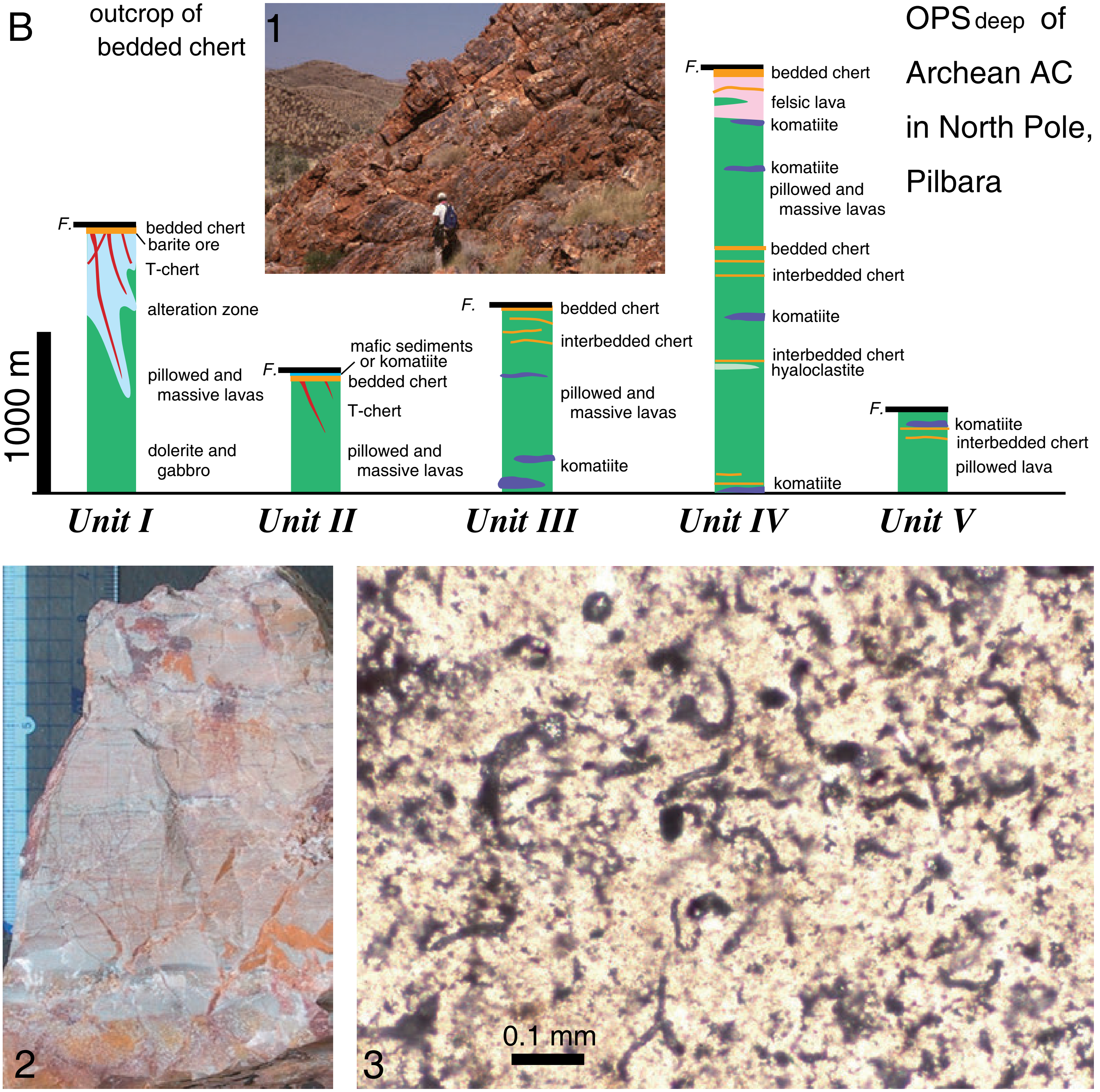


Figure 10. *(continued).*

Eoarchean OPS$_{deep}$ were documented as introduced above (Komiya et al. 1999; Kitajima et al. 2001). These retrieved collections are no more than patchy with respect to the entire 4 billion year-long history of the Earth's oceans; nonetheless, available data and their compilation have already highlighted some trends with profound geological connotations. Here, I briefly mention two aspects of potential interest, the pattern of long-term redox change in the ocean and the onset of mid-oceanic atoll-carbonate deposition.

Deep Ocean Redox History

The overall secular change in ocean oxidation has been discussed for a long time, mostly on the basis of characteristics of sedimentary rocks from shelf facies and their geochemical interpretations, particularly with respect to isotopic aspects. In general, it is regarded that the primarily reduced ocean waters have changed into more oxygenated ones, in accordance with the atmospheric evolution during the Precambrian (Anbar and Knoll 2002; Canfield 2005; Kump 2008). In particular, the two major steps of oxidation in the Paleo- and Neoproterozoic have been much emphasized with respect to the

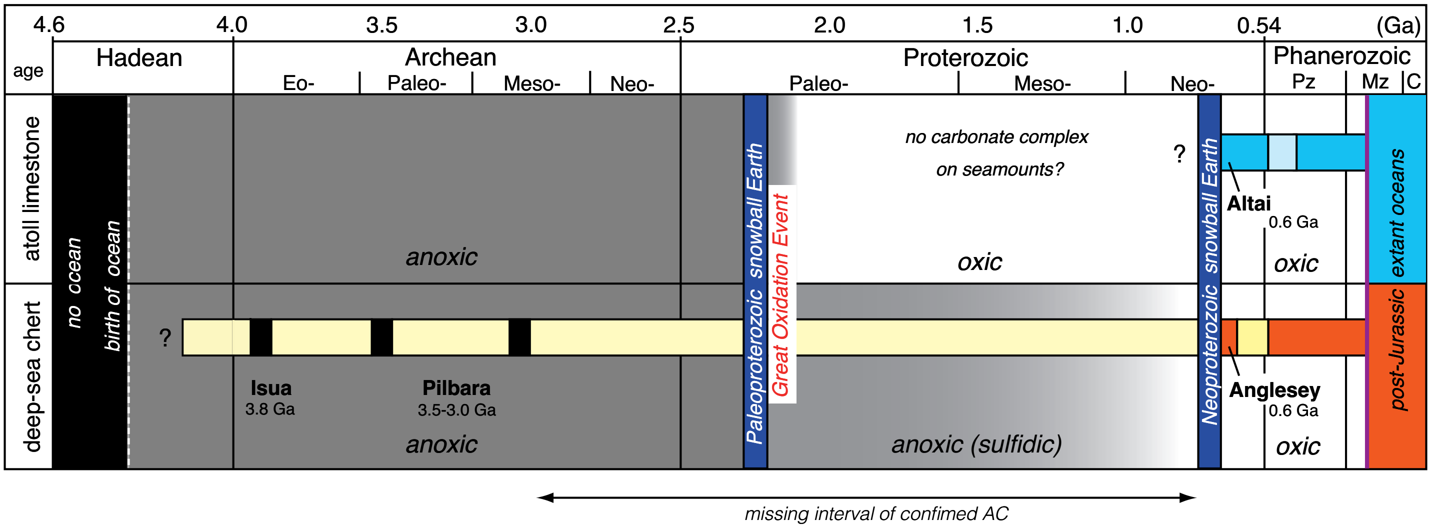


Figure 11. Age distribution of pre-Jurassic mid-oceanic sedimentary archives hitherto analyzed (compiled from Isozaki et al. 1990; Matsuda and Isozaki, 1991; Isozaki, 1996; Komiya et al. 1999; Kitajima et al. 2001; Uchio et al. 2004; Ota et al. 2007; Kawai et al. 2008). The overall secular change in ocean redox can be monitored by direct assessment of mid-oceanic bedded cherts ($\mathrm{OPS}_{\mathrm{deep}}$) and atoll carbonates ($\mathrm{OPS}_{\mathrm{shallow}}$). The primarily anoxic ocean waters likely changed into more oxygenated ones through multiple steps that include the two snowball Earth events in the Paleo- and Neoproterozoic (Hoffman et al. 1998; Kirschvink et al. 2000). The oxygenation naturally started from the ocean surface by the onset of the oxygenic photosynthesis, then diffused into deep-sea (Anbar and Knoll 2002; Canfield 2005). It is noteworthy that atoll carbonates ($\mathrm{OPS}_{\mathrm{shallow}}$) were not identified before the Neoproterozoic snowball Earth event. This may indicate that the carbonate precipitation was not promoted in mid-oceans before the Cryogenian, if at all, possibly due to the immature biogenic skeletonization to form reef carbonates in remote thus nutrient-poor setting, or to the too much high sea-level from seamount tops with respect to relatively shallower carbonate compensation depth (CCD) in the Precambrian.

extreme climate called the snowball Earth (Hoffman et al. 1998; Kirschvink et al. 2000; Fig. 11). A possible causal relationship with the two distinct snowball Earth episodes has been discussed (Hoffman and Schrag 2002; Anbar and Knoll 2002; Canfield 2005; Kump 2008); however, details are still unknown. For example, the Paleoproterozoic Makganayene diamictite deposited at low latitude (Beukes et al. 2013) is significantly younger than the claimed timing of disappearance of mass-independent fractionation of sulphur isotopes that supports the coeval Great Oxidation Event (Holland 2002; Bekker et al. 2004).

It is reasonable to imagine that the oxygenation of ocean water naturally started from the ocean surface by the onset of the oxygenic photosynthesis, then diffused into the deep sea; however, details of such changes, like their pattern and rate, have rarely been confirmed by direct checking of real deep sea sedimentary records from lost oceans. By utilizing rare earth element (REE) composition of accreted deep-sea chert and associated banded iron formation (BIF) in Pilbara, Kato et al. (2006) preliminarily reported that the onset of deep-sea oxygenation, in the limited context of iron oxide formation, took place sometime in the Neoarchean. Sato et al. (2009) detected the occurrence of hematite-bearing non-metamorphosed red bedded chert of Ediacaran age from Anglesey in UK and the Gorny Altai Mtn. in Siberia. This indicates that the Ediacaran deep sea was already ventilated considerably to the level seen through most of the Phanerozoic. In contrast, pre-Ediacaran AC lack primarily red chert beds, e.g. the Archean chert from Isua and Pilbara are dark grey in colour, except for the secondarily altered reddish ones. Komiya et al. (2008) analyzed major, trace, and REE elements of primary carbonates from both shallow- and deep-water Precambrian–Phanerozoic rocks, and concluded that the dissolved oxygen in seawater had increased not in a linear, unidirectional manner but in a considerably fluctuating way with multiple sharp oxygenation spikes during the Proterozoic.

These studies confirm two significant aspects of ocean oxygenation: 1) the overall oxygenation trend throughout the Precambrian is correct but possibly with more multiple fluctuations than previously believed, and 2) the deep sea became ventilated to the level equivalent to most of the Phanerozoic by the Ediacaran. A putative cause and effect link between the first deep-sea ventilation and the snowball Earth episode has not yet been fully explained. For resolving this particularly interesting issue, we definitely need more data from Archean–Proterozoic deep-sea chert.

Mid-Oceanic Carbonate Chronicle

The oldest mid-oceanic paleo-atoll limestone hitherto known is from the Early Ediacaran in the Gorny Altai Mtns. It is noteworthy that such atoll carbonates ($\mathrm{OPS}_{\mathrm{shallow}}$) have not yet been identified from the pre-Ediacaran units (Fig. 11). For example, the Eoarchean AC in Isua and the Paleoarchean AC in Pilbara contain OIB-type basaltic greenstone units but without associated massive carbonate rocks. Some may see this as an artifact of the scarceness of detected AC and OPS from the Neoarchean to Mesoproterozoic interval to date. Even during this 'boring 2 billions' in terms of AC studies, however, the assembly and breakup of supercontinents were repeated multiple times (Windley 1977). Thus, active continental margins no doubt must have formed AC to host OPS, and we need to seek possible OPS$_{\text{shallow}}$ from this missing interval in the future.

Nevertheless, the absence of paleo-atoll limestone possibly indicates a unique condition for mid-oceanic carbonate deposition in the pre-Ediacaran time. In other words, the carbonate precipitation in mid-oceans was not much promoted in the pre-Ediacaran world if at all; in contrast to the thick shallow marine carbonate accumulation on coeval continental shelves throughout the Proterozoic (Hoffman 1974; Grotzinger and James 2000). As long as the contemporary shelves and epeiric seas were draped by thick carbonate strata, the overall seawater chemistry during the Proterozoic allowed massive carbonate precipitation under saturated conditions also at the surface in the mid-ocean, regardless of considerable blocking alkalinity by the anaerobic respiration in deep ocean (Higgins et al. 2009).

A possible explanation for this pre-Ediacaran missing interval of mid-oceanic atoll carbonates (Fig. 11) is a long-term sea-level high-stand during the Archean–Proterozoic followed by a large scale sea-level drop in the late Neoproterozoic. On the basis of the compilation of metamorphic facies series though time, Maruyama and Liou (2005) explained that sea level started to drop sharply around 700 Ma by the onset of water absorption into the mantle, simply because the temperature of the upper mantle lowered across a threshold that allows the subduction of a large quantity of hydrous minerals into the deep mantle without returning to the surface; i.e. the resultant absorption of a large volume of water into the interior of the solid Earth. They estimated that an irreversible sea-level drop of nearly 600 m might have occurred during the late Neoproterozoic. It should be emphasized here that this large-scale sea-level drop was not a consequence of the Cryogenian snowball Earth event. Given that the size (height) of hotspot-type seamounts were more or less the same as modern ones, most of the pre-Ediacaran seamounts were deeply drowned even at their birth under such extremely high-stand conditions. Even above the Precambrian CCD, carbonate precipitation was unlikely enhanced in mid-ocean significantly below the photic zone. Another important constraint to be concerned about may be, of course, the immature establishment of reef-building biomineralization during the Neoproterozoic. In order to prove or disprove this *avant-garde* interpretation, we need more exploration for possible pre-Ediacaran atoll carbonates in the Precambrian AC exposed on land.

CONCLUDING REMARKS AND FUTURE PERSPECTIVE

It is concluded that analyses of OPS in ancient AC are inevitable in reconstructing pre-Jurassic environments and their secular changes, in addition to the conventional studies on normal continental shelf and terrestrial strata. The pre-Jurassic mid-oceanic sedimentary archives directly diagnose and monitor secular changes in various aspects of paleo-oceanography in the lost oceans, e.g. redox and biological activities. They are particularly significant in detecting extremely rare, unique, and irreversible global episodes in the past, as clearly presented by the case studies for the Permo–Triassic deep-sea chert and paleo-atoll limestone in the Phanerozoic. More significantly in near future, records of the Hadean oceans will provide critical data for the origin and cradle of Earth's life, because the oldest AC in Greenland of the Eoarchean (3.8 Ga) likely retains OPS with the Hadean ocean records that were once appeared nearly unreachable.

To hunt for pre-Jurassic oceanic information, the key issue is the identification of ancient AC units not only along the currently active margins but also within older collision-type orogenic belts, in particular, in the recognition of OPS with mid-oceanic sedimentary strata in the interiors of extant land masses. Concerning the paleoenvironmental analyses for the pre-Jurassic time, the author emphasizes that the critical point in this approach is not necessarily geochemical analyses in the laboratory but rather in the detailed field mapping with keen eyes and clear concepts in mind.

The main obstacles in the search for Precambrian mid-oceanic sedimentary rocks are two-fold: severe secondary overprinting that destroys the primary signature, and poor age constraints. In this regard, less weakly metamorphosed and less deformed parts of ancient AC should be the main target for reading the Precambrian mid-oceanic sedimentary archives. Previous case studies have revealed that the high-grade metamorphosed AC, up to the jadeite-glaucophane (blueschist) facies or even to the amphibolite facies, still retain OPS and deep-sea chert, as long as the deformation was not so severe (Sedlock and Isozaki 1990; Isozaki and Blake 1994; Kimura et al., 1996; Komiya et al. 1999; Kitajima et al. 2001). As no reliable index fossil occurs in Precambrian strata, other dating schemes are required. Measuring isotopic ratios of elements, such as C, S or Sr, may help fully or partly with chemostratigraphic correlation and dating. Nonetheless, full records of various isotopic curves throughout the entire Precambrian are not yet available. In this regard, direct radiometric dating, in particular, for U–Pb and Pb–Pb ages of zircon appears promising, as preliminarily performed in some Phanerozoic and Precambrian cases (Kitajima et al. 2008; Isozaki et al. 2010; Aoki et al. 2011; Fujisaki et al. 2014).

By deploying the approach described in this article, i.e. the detailed OPS identification in studies of ancient AC, more fruitful results are guaranteed in the future, not merely for the Precambrian Earth but also even for early Mars and extra-solar planets. As long as physical conditions of a water-hosting planet allow the existence of rigid but mobile lithospheres on its surface, plate tectonics naturally works and generates AC along convergent margins. On the basis of such OPS analyses also on other planets in the future, we may dream about designing a new general model for the evolution of Earth-like planets and possible life on them.

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