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Sedimentology as a Key to Understanding Earth and Life Processes

1. Introduction

China Association of Sedimentologists (CAS) organized successfully one international Sedimentology Summit Meeting and International Workshop on “Building the Future of Sedimentology” on 22nd to 28th of September, 2016 in Beijing. This workshop invited all bureau members of The International Association of Sedimentology (IAS) and several world-leading experts in various fields of sedimentology discipline as well as almost all senior and active sedimentologists from China to give keynote lectures to summarize recent achievements in sedimentology studies. These presentations focus on nine themes, namely Precambrian sedimentology, biological process and sedimentology, energy sedimentology, basin dynamics and sequence stratigraphy, paleogeography reconstruction, modern sedimentological process, depositional environments and facies, sedimentary geochemistry, and deep-time paleoclimate. Each theme group finished one formal report for development strategy of various disciplines within sedimentology in short future. These comprehensive reviews of all fields of sedimentology therefore will provide strategy advice for the future funds in sedimentology researches, at least, in China and also may re-shape the future development direction of sedimentology worldwide. To better understand sedimentology as the key to unravel Earth and life processes, this special issue assembles 12 papers directly from this workshop or invited from other world-leading experts outside the workshop to address integrated global stratigraphy, biosedimentology, sedimentologic implications in reconstructing paleoclimate and paleogeographic configurations, and implications on P-Tr mass extinction and recovery in ocean and on land, with emphasis on sedimentary records from China.

2. Integrated global stratigraphy: timescales for Earth and life evolutions

Our knowledge of the fascinating history of our planet mainly comes from deciphering the sedimentary record of events and trends of biologic, ecologic, geochemical, climatic, physical, and other systems using a vast array of tools and innovative techniques. Integrated stratigraphy (i.e., lithostratigraphy, biostratigraphy, chronostratigraphy/chronology, chemostratigraphy, magnetostratigraphy, cyclostratigraphy) of sedimentary records provide reliable timescales for reconstructing event sequences and life evolutions in the geological past. As the principal author of serial geochronologic guidebooks ‘*Geologic Time Scale*’ (i.e., Gradstein et al., 2012; Ogg et al., 2016), Ogg (2019) presented his recent summary on global integrated stratigraphy, and addressed the following six aspects: (1) selection and documentation of major global research reference sections to standardize the divisions of geologic time (e.g., Global Stratotype Section and Point (GSSP) for inter- or intra-stage boundaries, (2) inter-calibration of marine and terrestrial records both within and among different regions to compile a global integrated scale, (3) improving and applying age models to understand cause-effect relationships and rates of processes, (4) public databases and syntheses, (5) international efforts and centers, and (6) Earth-systems geo-education that emphases relationships among fields in addition to training in particular specializations. The precise timescales based on the sedimentary records from China’s basins have been successfully applied to reveal the “lethal” temperature changes of seawater in Early Triassic (Sun et al., 2012), Cretaceous evolution of birds (Zhou et al., 2003, 2010), and catastrophic impacts of large igneous eruptions (Burgess et al., 2014, 2017; Burgess and Bowring, 2015).

3. Biosedimentology: tracing biotic activities involved in sedimentological processes through the Earth history

Growing evidence shows that biotic activities are involved in almost all sedimentation processes throughout the evolutionary history of life on our planet (Chen et al., 2017, 2019). A new subdiscipline of sedimentology—Biosedimentology— that studies biotic processes involved in the sedimentation has attracted increasing interests from sedimentologists and paleontologists worldwide. This special issue assembles several papers reviewing microbe-involved sedimentological processes and biomarkers as well as their implications on reconstructing ancient and modern environments, revealing deep-time extreme biotic and environmental events, and unconventional oil and gas exploration and development.

Chen et al. (2019) documented biosedimentary features of major transitions that are characterized by depositional system switch from microbe-dominated to metazoan-dominated ecosystems through Precambrian to Phanerozoic times, with emphasis on sedimentary records from China. Five major microbe-metazoan transitions (MMTs) were recognized in the late Ediacaran, the Cambrian, and the aftermaths of the mass extinctions of the end-Ordovician, Late Devonian, and end-Permian, respectively. Of these, the first MMT began with microbe-dominated oceans with occasional occurrences of metazoans during the middle-late Ediacaran, and ended with the occurrence of tubular metazoan-dominated reefs in the latest Ediacaran (Penny et al., 2014). The Cambrian MMT was the longest microbial-metazoan alternation period and is marked by the switches of stratigraphic abundance from microbial reef-dominated to metazoan-dominated reefs through the entire Period. The occurrences of the early Silurian, latest Devonian, and Early-Middle Triassic MMTs are closely linked with the first three Phanerozoic mass extinctions: end-Ordovician, Frasnian-Famennian (F-F) and end-Permian extinctions. Most MMTs seem to have undergone four developmental stages: initial microbe-dominated successions (Stage A), alternations of microbe- and metazoan-bearing or

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bioturbated successions (Stage B), co-occurrence of both microbial and metazoan reefs (Stage C); and a dominance of metazoan reefs (Stage D). Ediacaran and Cambrian MMTs seem to have undergone the first three development stages, whereas the three post-extinction MMTs experienced the full set of Stages A − D, corresponding to metazoan survival, initial recovery and full recovery.

Almost all microbe-mediated sediments/structures observed in the Cambrian MMT reoccurred in the aftermath of the end-Permian mass extinction during the Early–Middle Triassic MMT, suggesting high similarities between those two MMTs. These two MMTs also share comparable carbon and sulfur isotopic perturbations, warming regimes, and generally oxygen-deficient seawaters. In addition, the majority of volatile-rich Large Igneous Provinces (LIPs), coupled with intensive acidification events, anoxia and global warming regimes, took place during the Mesozoic–Cenozoic. However, microbe-dominated sediments were only widely deposited during the Early Triassic, and greatly declined after that time. Therefore, microbial abundance in MMTs may not be directly related to these extreme LIP events. This is probably because a primary source of food for the metazoans might have shifted to phytoplankton (e.g., coccoliths, dinoflagellates, and radiolarians) in the marine waters since the Triassic. Certainly, the pre-Mesozoic oceans were not dominated by phytoplankton (Chen et al., 2019).

Another biosedimentary study integrating geomicrobiology, sedimentology, hydrology, and biogeochemistry focusing on modern sedimentary system and process is the paper by Wang et al. (2019) who analyzed hydrobiogeochemical process and accumulation models of high arsenic (As) groundwater in major Chinese basins. Geogenic enrichment of arsenic content in groundwater has attracted an increasing number of researches, and becomes a globally concerned problem due to the severe health threat to an estimated over one hundred million people. This review article found that the most common geogenic As-enriched groundwater occurs in flat, low-lying river floodplains and fluvial-lacustrine plains. In China, tectonic movement, sedimentological processes, and paleoclimatic optima after the Last Glacial Maximum have created favorable conditions for the formation of high-As aquifer systems mainly within the Late Pleistocene-Holocene deposits due to the formation of river systems draining the Himalaya. The indigenous geomicrobes thriving to adapt to specific aquifer environments may mediate Fe-S-As biogeochemical cycling responsible for As speciation transformation, dissolution/desorption, and hence mobilization.

Organic-matter-rich shales (OMRS) are not only important proxies indicating biological and sedimentologic processes during their deposition, but also the main target rocks for unconventional oil and gas exploration and development across the world. The paper by Zou et al. (2019) provides a comprehensive review of the state-of-the-art for OMRS in China's basins—highlighting successes, caveats, best practices, and future opportunities. In China, a total 35 important OMRS units have been recognized from Mesoproterozoic to Cenozoic strata. These shales are categorized to the marine, marine–nonmarine transitional and lacustrine types. Currently, the most favorable marine shales for oil and gas exploration are found in the Sichuan Basin within the lower Cambrian Qiongzhusi Formation and in the Ordovician-Silurian Wufeng-Longmaxi formations. A fortuitous combination of sea-level variations, of paleoproductivity, of tectonic activity causing development and migration of partially closed deep basin depocenters, and of sediment accumulation rates is proposed as the major control of the extensive deposition and distribution of OMRSs in these Wufeng and Longmaxi formations. The marine-nonmarine transitional facies OMRSs are usually associated with coal measures within the Carboniferous and Permian, and are important source rocks for the gas fields in the Ordos and Sichuan Basins. Lacustrine OMRSs were deposited during the Permian through Neogene in various freshwater to saline lake settings. Lacustrine algae contributed to the rain of organic matter; and the preservation of organic matter and distribution of OMRSs was controlled by lake currents, water depth and oxygen-poor conditions, with enhanced preservation when buried by turbidity currents. Algal blooms were partly induced by trace nutrients from volcanic ash falls in all of these lacustrine basins. Some saline lacustrine basins contain organic-rich dolomite mudstone that mainly formed during hot climate conditions when the lakes had high salinity and stratified water columns that deprived the bottom waters of oxygen, thereby preserving massive amounts of organic matter.

Another most important biogeochemical proxy tracing life's activities and environmental evolution in early Earth is microbial lipid biomarker (Xie et al., 2005; Grice et al., 2005; Cao et al., 2009; Yin et al., 2012). This is because lipids can survive long geological intervals within sediments and provide a unique tool that allows the reconstruction of past organismic diversity and environmental conditions. Luo et al. (2019) present their review studies on the biogeochemical signals in the geological past, including the earliest fossil record of biomarker in Paleoproterozoic, and their evolution as critical sedimentary fingerprints of the changes in the atmosphere and oceans and on lands. These authors critically assessed the utility of various biomarkers for better understanding biotic and environmental changes in the Precambrian and some critical periods of the Phanerozoic. In spite of diagenetic and catagenetic alteration, lipid biomarkers commonly preserve the hydrocarbon structure of their biotic counterparts and have been found in rocks up to 1.6 billion years in age. These features have promoted the use of lipid biomarkers in many fields, including petroleum geology, paleoclimatology, oceanography, meteorology, geobiology and environmental science. The ratio of dibenzothiophene to phenanthrene (DBT/P) in marine carbonates is suggested to be a robust proxy for seawater sulfate concentrations in deep time.

4. Sedimentological implications in reconstructing paleoclimate changes and paleogeographic configurations

Sedimentology is one of important approaches reconstructing paleoclimate regimes in geological past (Montañez et al., 2011). Some important climate-sensitive sediments and minerals: tillite, evaporite, calcrete, dropstone, glendonite, coal, palm, mangrove, crocodilians, bauxite, laterite, kaolinite, oolitic ironstone have been treated as important indicators of paleoclimate conditions (Boucot et al., 2013). Paleotemperature analysis from plant fossils based on CLAMP (Climate-Leaf Analysis Multivariate Program) methodology has also been considered as a reliable approach reconstructing paleoclimate (Spicer et al., 2004; Spicer, 2012). Besides, geochemical proxies such as oxygen isotopes of (bio)apatite, universal carbonate clumped isotope of carbonate-apatites (Guo et al., 2009; Passey and Henkes, 2012; Henkes et al., 2013; Kluge et al., 2015; Bonifacie et al., 2017; Kelson et al., 2017; Zhang et al., 2018), and glycerol dialkyl glycerol tetraether (GDGT; Schouten et al., 2013) as well as climatic modelling (DeCoo et al., 2008; Kidder and Worsley, 2010, 2012) are also important approches indicating paleoclimate regimes. Moreover, cyclostratigraphy with paces of astronomical climate cycles (i.e., Milankovitch cycles) from sedimentary records also become important approaches indicating deep-time climate regimes (Li et al., 2016a, 2016b).

To provide better understanding of multiple proxies for paleoclimatic and paleoenvironmental change within sedimentary sequences, Li et al. (2019) evaluated 16 high-resolution paleoclimate proxies recorded in the marine Lower Triassic succession in South China for their applications in paleoclimatology using (1) hierarchical cluster analysis (HCA) and (2) power decomposition analysis (PDA). These 16 proxies are spectral gamma ray (gamma-ray intensity, potassium, uranium, thorium, thorium/uranium and thorium/potassium), rock color lightness (L*), redness (a*) and yellowness (b*), magnetic susceptibility (measured in both laboratory and outcrop), anhysteretic remanent magnetization (ARM), lithologic rank, simplified lithologic rank, and non-carbonate fraction, carbonate thickness and couplet thickness. The analytical results find that these proxies are likely affected by the same process. The ARM and thorium/uranium proxies seem to reflect the hinterland-weathering process during the Early Triassic. Gamma-ray, potassium, uranium, thorium, magnetic susceptibility and non-carbonate fraction proxies refer to terrestrial input. The L*, a* and lithologic rank proxies indicate the productivity, the redox state and the relative sea level, respectively at the studied section. This comprehensive evaluation contributes to the understanding of the sensitivity of these types of proxies for deep-time paleoclimate and astronomical-tuned time scales.

Zhang et al. (2019) documented marine and terrestrial temperature gradients for the latest Cretaceous, Late Paleocene-Early Eocene, Early Oligocene, Pliocene, and Holocene based on various thermometric indicators, including $\delta^{18}O$, plant and animal fossils, glycerol dialkyl glycerol tetraether (GDGT) proxies, and clumped isotope estimates. Except for the Paleocene-Eocene transition, the marine records show distinct inflection points at ~30° and ~50° latitude indicating the existence of frontal systems in the ocean, and also an increasingly steeper trend from latest Cretaceous through Holocene. This trend reflects the increasing intensity of high-latitude and polar cooling as the icehouse state developed. The Paleocene-Eocene transition saw slightly warmer tropic oceans and much warmer higher latitudes than at present. Higher latitude continental temperatures cooled in the end-Cretaceous, became much warmer during the Paleocene-Eocene transition, then cooled during the Early Oligocene and have become increasingly colder since then.

Yu et al. (2019) critically reviewed distribution areas, stratigraphic unit and age of bauxite deposits in China during the Carboniferous and Permian when bauxites were very rare in the rest of the world in conjunction with global cooling. Abundant bauxite deposits occurred in the lower-middle Visèan (Lower Carboniferous), upper Pennsylvanian to Lower Permian, and Middle–Upper Permian in South China, while they were yielded in the upper Mississippian–Middle Pennsylvanian strata in North China. The contrasting trends in bauxite metallogenesis between China and the rest of the world imply different climatic patterns in the eastern Paleo-Tethys (high annual humidity with seasonal dryness) and Pangea (aridification). This hypothesis is reinforced by the differences in the chemical index of alteration and in paleotemperatures determined from Permo-Carboniferous siliciclastic deposits. The new results show that, during interglacial stages, lateritization resulted from high pCO2, high sea-level and groundwater-table elevations, low precipitation, and limited vegetation cover, whereas during glacial stages, bauxitization of these ferralitic weathering products was promoted by low pCO2, low sea-level and groundwater-table elevations, high precipitation, and more extensive vegetation cover.

Except for the above paleoclimate implications, Hou et al. (2019) documented high-resolution paleogeographic change history of the South China block, in which some critical environmental and biotic events have also been discussed. The background controlling factors facilitating paleogeographic variations are also discussed in a broad context. The precise time-framework allows the reconstruction of paleogeographic configuration changes of South China and the recognition of event sequences during the Ordovician. A major challenge is to place these facies maps of the numerous individual blocks compiled three decades ago into the larger contexts of moving plates and of their relationships to adjoining regions, especially for the diverse opinions on pre-Triassic plate tectonic models of Southeast Asia. A multi-institutional coordinated paleogeography program with user-friendly shared databases and visualization outputs from the basin- to inter-national scale is a major goal in China and Southeast Asia stratigraphy and geophysical research.

5. Sedimentological implications on major biotic crisis: the Permian-Triassic ecologic crisis and subsequent recovery in ocean and on land

Sedimentology offers essential analysis methods for the studies on major extreme biotic, environmental and climatic events in the geological past. Sedimentary facies and paleoenvironmental analyses are crucial in minimizing preservtional and environmental biases for quantifying biodiversity variations and biotic extinction, survival and recovery during the critical intervals of mass extinctions (Hallam and Wignall, 1997), enabling biotic variations in the same environmental settings. Sedimentary microfacies analysis also offer fossil fragment changes across the biotic event horizons, which reveal biodiversity variations of microorganisms and ecosystem changes before, during and after the major extinction events (i.e. Chen et al., 2015). Pyrite framboid analysis is also an ideal approach revealing redox conditions of water columns during major biotic events (i.e., Huang et al., 2017, 2019b). Sea-level changes reconstructed based on sound facies analysis can also reveal the potential killing mechanisms for major biotic extinctions. For instance, the greatest global sea-level fall (or regression) of the Phanerozoic history is likely involved in killing benthos, at least, in destroying metazoan reef ecosystems during the Guadalupingian-Lopingian (Middle-Late Permian) mass extinction (Jin, 1994; Hallam and Wignall, 1997, 1999; Haq and Schutter, 2008; Chen et al., 2009; Wignall et al., 2009; Huang et al., 2019a). Similarly, a global regression may also have linked with the end-Permian mass extinction (Hallam and Wignall,1997, 1999; Yin et al., 2014). In addition, biosedimentologic and geobiologic analyses on microbialites immediately after the end-Permian mass extinction are essential in evaluating microbial bloom and their link with devastated environments of biotic extinction (Kershaw et al., 2012; Fang et al., 2017). Detailed sedimentologic analysis is also crucial in reconstructing microorganism ecosystems in the Early Triassic (Chen et al., 2014; more details see Chen et al., 2019). This thematic issue assembles three papers to address the importance of integrated analyses of sedimentology, biosedimentology and paleoecology in revealing biotic and environmental changes across the Permian-Triassic (P-Tr) boundary in marine and terrestrial ecosystems.

The P-Tr mass extinction is the largest biotic perturbation during the Phanerozoic. This crisis was followed by multiple secondary episodes of faunal mortality and recovery during the ~5-Myr-long Early Triassic (Bottjer et al., 2008; Chen and Benton, 2012) that were probably linked to episodic global environmental perturbations (Algeo et al., 2011; Retallack et al., 2011; Chen et al., 2018). Owing to the environmental stresses, marine organisms and their behavioral traces are usually very rare immediately after the end-Permian ecologic crisis (Erwin, 2006). However, Feng et al. (2019) reported two shallow marine, ichnofauna-bivalve-microbial mat biofacies from the basal Triassic successions in northwestern China, which was located at moderate high paleolatitudes on the northern margin of the Paleo-Tethys Ocean (Xu et al., 2017). Detailed sedimentologic analyses show that Biofacies 1 represents a shoreface environment and Biofacies 2 a lower shoreface to offshore transition setting. The former is characterized by a diverse ichnofauna (including deep-tiers of *Rosselia* and *Diplocraterion*), *Claraia*-dominated bivalves, and microbially induced sedimentary structures (MISSs), while the latter biofacies is dominated by a diverse ichnofauna, epifaunal and shallow infaunal bivalves, and wrinkle structures. All biotic and sedimentologic components within the biofacies indicate that microbial mats, bivalves, and trace-makers actively interacted with one another during deposition. Microbial mats are interpreted to have grown under well-oxygenated conditions after storm deposition due to the association of deep-tiering infauna and diverse epifauna as well as well-developed cross-stratification, and the top layer of microbial mats could serve as an oasis for metazoans. Microbial mats not only proliferated in harsh environments, but also coexist with epifauna and deep-tiering infauna in well-oxygenated settings following the end-Permian crisis. Their occurrences in the Early Triassic are unrelated to environmental stresses, which are coincident with their sedimentologic record from other geological time intervals. Such unique biofacies therefore indicate that some organisms survived the end-Permian crisis in a tough time when most biotas suffered biotic depletion and environmental stress.

As the greatest extinction event that Earth life suffered ever, the P-Tr crisis not only devastated seriously the marine ecosystems, but also degraded significantly the terrestrial ecosystems (Benton et al., 2004). The P-Tr vertebrate paradise in the Karoo basin has attracted increasing interests from geologists from around the world (Smith and Ward, 2001). However, the placement of the P-Tr boundary and recognition of biotic extinction have long been disputed in the Karoo Basin. Gastaldo et al. (2019) provided an updated review on the environmental and biotic changes across the P-Tr boundary at the classic Bethulie area of the Karoo basin, South Africa. Their study is based mainly on vertical and lateral facies correlations and integrated studies of stratigraphy, sedimentology, and geochemistry (Gastaldo et al., 2015). In Karoo, the model of vertebrate turnover, from the *Daptocephalus* to *Lystrosaurus* Assemblage Zones, tightly constrains the boundary sequence to a short stratigraphic interval where siltstone color begins to change from greenish gray to grayish red, the latter color interpreted to be a consequence of aridification. The biological response to this facies change has been termed “the Great Dying”, and the sedimentary rocks that are preserved are ascribed to a playa lake depositional setting. The new results by Gastaldo et al. (2019) based on a multidisciplinary analysis do not support the previous interpretation that this inferred P–Tr boundary interval represents the onset of playa lake deposits under conditions of aridification. Rather, the new evidence supports the existence of a “wet” landscape at what is considered the *Daptocephalus/Lystrosaurus* assemblage zone boundary.

The geological persistence of biotic assemblages and their reorganization or destruction by mass extinctions are key features of long-term macroevolutionary and macroecological patterns in the fossil record (Roopnarine and Angielczyk, 2015). Roopnarine et al. (2019) assess ecologic persistence, incumbency and reorganization during the P-Tr transition in the Karoo Basin based on numerically modeling paleocommunity stability over this critical interval. These authors hypothesize that the geological persistence and incumbency of paleocommunities and taxa are maintained by patterns of biotic interactions that favor the ecologic persistence and stable coexistence of interacting species. Numerically modeled food webs for seven tetrapod-dominated paleocommunities spanning the P-Tr boundary show that incumbency before the biotic extinction was maintained by a dynamically stable, community-level system of biotic interactions. The system's structure was lost in extinction interval, and replaced instable paleocommunities during the Early Triassic, which were followed by a novel Middle Triassic community with renewed incumbency. Accordingly, the dying zone defined by the boundary between the *Daptocephalus* and *Lystrosaurus* Assemblage Zones (Smith and Ward, 2001) may not decline biodiversity of vertebrate animals but have destroyed paleocommunity structures, pointing to an ecologic crisis.

6. Concluding remarks

These contributions provide comprehensive reviews of the state-of-the-art for Sedimentology—highlighting successes, caveats, best practices, and future opportunities, and, more importantly, enhance our knowledge on its implication as a key to understand Earth and life development processes. We believe that these updated reviews and research results offer new insights into all major aspects of sedimentology, and provide some stimulating suggestions for future studies on these topics, ultimately promoting the development of sedimentology in China.

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