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The challenge of reconstructing the Phanerozoic sea level and the Pacific Basin tectonics

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Abstract

The relationships between the interior dynamics of our planet and global sea level can be unravelled when plate-tectonic reconstructions are available for the entire Earth. A review of global tectonics reveals significant deficiencies in our understanding of the geodynamic evolution of the Pacific (Panthalassa or Proto-Pacific) during the Cambrian-Jurassic time-span. This particular, but major, shortcoming presents a true challenge for modern geoscientists, who are encouraged to produce a detailed plate-tectonic reconstruction of the Pacific for the pre-Cretaceous in order to advance our understanding of Phanerozoic sea-level change. A set of approaches, including geological/geophysical modelling, investigation of accretionary prisms, palaeobiogeographical studies, and careful examination of eustatic sea-level changes, are proposed that will help geoscientists tackle the challenge of understanding how Pacific geodynamics affected global sea level during the Phanerozoic.

Keywords: sea-floor bathymetry, dynamic topography, sea-level changes, plate tectonics, Pacific, Panthalassa, Phanerozoic.

Introduction

A series of global plate-tectonic reconstructions published during the past decade (e.g., Cocks & Torsvik, 2002; Stampfli & Borel, 2002; Scotese, 2004; Torsvik & Cocks, 2004; Torsvik et al., 2010) have pushed our knowledge of Earth's surface tectonics back into 'deep time'. These developments, which were based primarily on palaeomagnetic and palaeobiogeographic data from continents, have certainly increased our insight into the history and tectonic development of our planet. Yet, a careful look at these reconstructions reveals a large 'blank' space on the margins of these global maps, regardless of whether they depict the Cambrian or the Jurassic world. At best, this space is labelled 'Panthalassa' or 'Proto-Pacific', representing a large oceanic region on the planetary face that opposed the Gondwanan and Pangaean assemblies.

Because this large region was presumably nearly entirely covered by oceanic lithosphere that has been lost in the course of time due to subduction, our knowledge of its geological evolution remains restricted to its periphery

(Scotese et al., 2001; Hall, 2002; Schellart et al., 2006; Adams, 2008; Vaughan & Pankhurst, 2008). The tectonic picture of the Pacific world is more or less clear only for the Cenozoic and, already less detailed, for the Cretaceous (Engebretson et al., 1984, 1985; Lithgow-Bertelloni & Richards, 1998; Hall, 2002; Smith, 2003; Schellart et al., 2006; Whittaker et al., 2007; Müller et al., 2008; Torsvik et al., 2010); this time interval constitutes only just over a quarter of the Phanerozoic. Yet, even this picture is far from complete, because the available tectonic reconstructions do not always match, and because the reconstruction of subducted lithosphere presents significant challenges (Xu et al., 2006; Rowley, 2008). Thus, there is a tremendous gap in our knowledge of Panthalassic tectonics prior to the Cretaceous. Since this region covers over half the globe and is integral to our planet's interior dynamics (Collins, 2003; Li & Zhong, 2009; Zhang et al., 2010), it is difficult to determine whether we understand the Earth's mantle and plate-tectonic evolution correctly. Filling this gap, particularly for times before the Cretaceous, is therefore a crucial yet daunting task for those – relatively few – specialists that explore the Pacific geology.

Should a geologist, interpreting regional palaeoenvironments in the middle of a continent, be also aware of Pacific geology? We argue: yes. We will discuss here how both the tectonics of the Pacific Basin and the dynamics of the underlying mantle exert a controlling influence on the global sea level. Because the sea level is a reference level for numerous processes (e.g., erosion and sedimentation), Pacific geology has a controlling global influence. Active subduction around this huge sector of the planet, however, has removed nearly all traces of the ancient, pre-Cretaceous sea floor, so that even a very general reconstruction of the development of this oceanic lithosphere appears to be an outstanding intellectual task. Yet, geological research faces many tasks like this, and several wait already for decades or longer until researchers will become equipped with the correct skills, technology, and data to undertake a fruitful study.

Fortunately, however, this need not be the case for tackling the tectonics of the Pacific. New insights into the question how the eustatic sea-level changes in response to tectonic events in the life of an ocean basin suggest that the sea level itself may provide new constraints on tectonics, especially if combined with other geological constraints and geodynamic models. The development of these new concepts, in combination with the fact that the Pacific Basin is vitally important to the global Earth history, makes the reconstruction of the Pacific's tectonic history an irresistable challenge for modern geoscientists. Based on already published considerations and results of our own research, we argue below that a solution to this problem, which is of prime importance if the history of the Phanerozoic Earth is really to be understood, is possible.

Synopsis of new ideas

Eustatic sea-level changes occur if the volume of sea water changes or if the shape of the ocean basin 'container' changes. Changes in the volume of the sea water can occur via changes in ocean temperature or by sea-water exchange with continental ice or groundwater. Although these climate-dominated affects can change the sea level dramatically (and are currently doing so), such changes predominantly occur at relatively short (a million years or less) time scales (e.g., Miller et al., 2005). Changes in the average climate state can produce changes over longer time intervals (e.g., the net cooling since the early Cenozoic has probably resulted in a sea-level drop of ~50 m (Harrison 1990; Conrad & Husson, 2009); changes in the shape of the ocean-basin 'container' are thought to dominate eustatic sea-level changes over timespans of more than a few million years (Miller et al., 2005). Such long-term changes are linked to the dynamics of the Earth's mantle in the following three ways.

(1) It has long been recognized that isostasy requires the sea-floor depth to correlate with the square root of sea-floor age (Parsons & Sclater, 1977; Stein & Stein, 1992), and thus changes in sea-floor age can directly affect the sea level (Pitman, 1978; Kominz, 1984). Recently, reconstructions of the global seafloor age

have shown that a large part of the observed ~100–200 m drop in sea level since the Cretaceous can be attributed to aging of the seafloor (Cogné et al., 2006; Xu et al., 2006; Müller et al., 2008).

(2) Convection within the Earth's mantle produces up to ~1–2 km of 'dynamic' topography at the Earth's surface, with positive deflections above mantle upwellings and negative deflections above downwellings (e.g., Hager et al., 1985; Mitrovica et al., 1989; Lithgow-Bertelloni & Silver, 1998; Conrad et al., 2004). If the average dynamic topography over the ocean basins is non-zero, the eustatic sea level will be offset proportionally, and this offset can change with time at rates of up to ~1 m per million years as convection patterns in the mantle evolve (Conrad & Husson, 2009). Furthermore, dynamic topography can dramatically influence the records of the relative sea level at any particular location on Earth because it moves the land surface relative to the sea surface (Moucha et al., 2008; Lovell, 2010). For instance, the Cenozoic subsidence of eastern North America is thought to decrease the apparent rate of sea-level drop along North America's Atlantic margin dramatically (Müller et al., 2008; Spasojević & Conrad, 2008; Spasojević et al., 2009).

(3) The emplacement of large igneous provinces (LIPs) in oceanic domains is traditionally regarded as a process that leads to global sea-level rise (Larson, 1991a,b; Müller et al., 2008). Extensive Late Jurassic and Early Cretaceous volcanism in the western Pacific may have produced a significant and long-term sea-level rise (Kalnins & Watts, 2009). The emplacement of LIPs in other settings (e.g., continental) may lead, in contrast, to a more or less spatially limited retreat of shorelines (Hallam, 2001), although preceding surface subsidence (Leng & Zhong, 2010) may initiate a wide, but regional transgression.

Thus, the tectonics of the Pacific's interior ridge system, as well as its interaction with the subduction zones circumscribing the Pacific, will directly influence the global eustatic sea level by affecting the average age of the sea floor. The long-wavelength dynamics of the mantle beneath the Pacific, which are intimately linked to the spreading and subduction systems of the Pacific via mantle convection, also affects the eustatic sea level via dynamic topography. Basin-scale mantle dynamics may also dictate the timing and location of plumes and LIP arrival on the Pacific sea floor (Courtillot et al., 2003; Torsvik et al., 2008).

Modern constraints on eustatic sea-level change have been refined thanks to the development of new sea-level reconstructions for the Phanerozoic (Haq & Al-Qahtani, 2005; Miller et al., 2005; Kominz et al., 2008; Müller et al., 2008), and for the Palaeozoic in particular (Haq & Schutter, 2008). A new stratigraphic correlation of Carboniferous sedimentary successions permitted Ruban (2009) to hypothesize that the Palaeozoic sea level was higher than that of the Mesozoic. This conclusion is consistent with that of an earlier reconstruction by Hallam (1984), who indicated an outstanding eustatic highstand during the Palaeozoic.

In the meantime, the reality of, and the mechanism for, eustatic sea-level fluctuations has recently been questioned (Ruban et al., 2010; Ruban, in press). Dynamic topography should dominate global patterns of sea-level change by affecting land surfaces differently in different regions of the globe, especially during time-spans that are otherwise both tectonically and climatically relatively stable (Ruban et al., 2010; Ruban, in press; see also Lovell, 2010). Such time-spans can be detected if rock successions from widely separated areas show non-correlating patterns of transgressions and regressions. Thus, plate-tectonic mechanisms (in a form of either global-scale processes or regional dynamics) are likely responsible for both long- and short-term sea-level changes if they are not superposed by global glaciation-induced eustatic sea-level fluctuations.

Müller et al. (2008) emphasized the importance of tectonic re-organizations within the Pacific Ocean for global sea-level changes during the Cretaceous-to-Cenozoic time interval. In fact, the large basin bounded by Asia and Australia to the West and the Americas to the East experienced an active and rapid re-shaping during the entire Phanerozoic (Fig. 1). The voluminous production of oceanic crust and the subduction of elevated oceanic ridges must have been important factors that controlled the

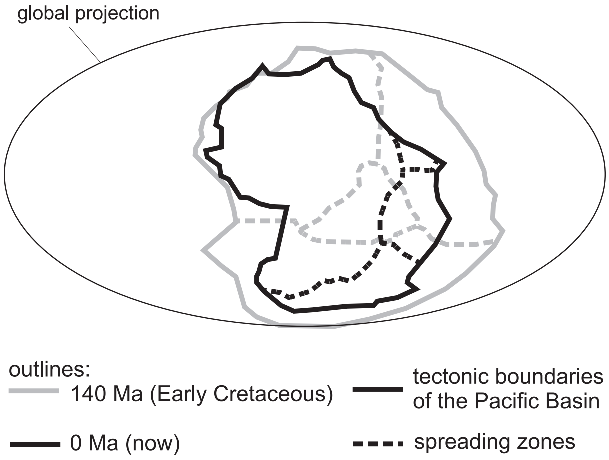

Fig. 1. Changes in the size and plate-tectonic framework of the Pacific between 140 Ma and 0 Ma, demonstrated by overlap of relevant reconstructions (simplified after Müller et al., 2008).

size and average age of the sea floor, and thus must have induced significant tectonically-driven eustatic sea-level changes. Oceanic ridges were likely elevated because of their 'hotter' crust. Their subduction occurred thanks to the rapid growth of new plates in the central Pacific. Such changes are likely to be correlated with both dynamic topography and volcanism within the basin, both of which additionally affect the global sea level.

A new challenge for present-day and future research

Taking into account the ideas detailed above as well as the available global sea-level reconstructions (Fig. 2), the following three important questions can be raised.

(1) What was the mechanism behind the sea-level rise during the Cambrian-Ordovician and the Triassic-Jurassic, and behind the sea-level fall during the Silurian-to-Permian?

(2) What was the influence of both ridge-system tectonics and dynamic topography on the eustatic sea-level changes during the Palaeozoic-Mesozoic?

(3) Did the early Palaeozoic sea-level highstand exceed that of the late Mesozoic?

The available plate-tectonic reconstructions (Cocks & Torsvik, 2002; Stampfli & Borel, 2002; Scotese, 2004; Torsvik & Cocks, 2004) can already provide some answers to the above questions. Analysis of the assembly and subsequent breakup of Pangaea can, for instance, constrain the geometry and sizes of the ridges that must have been positioned between the supercontinental parts. However, as exemplified by analysis of the Cretaceous-to-Cenozoic sea-level changes, information from the Pacific is essential for developing a reliable insight into sea-level trends (Müller et al., 2008; Rowley, 2008); this is also true for the Palaeozoic (Murphy et al., 2009). We need therefore at least a basic understanding of how the size and the mean age of the pre-Cretaceous sea floor of Panthalassa changed with time.

The above-mentioned plate-tectonic reconstructions cannot help with this task because they provide no constraints on the Panthalassic sea floor. Reconstructions proposed by Scotese (2004) indicate that the Palaeozoic Panthalassa was significantly larger than the present-day Pacific, as it was throughout the Cretaceous (Müller et al., 2008). As a result, a large part of Phanerozoic geologic history – encompassing approximately one-half of the Earth's surface – has yet to be revealed. Consequently, pre-Cretaceous plate-tectonic reconstructions of the Pacific Basin provide a major challenge. Although many geoscientists may not yet recognize this challenge, they will soon discover that tackling the problem of reconstructing the entire Phanerozoic history of the Pacific is inevitable because sea-level histories on both global and regional scales (which are crucially important not only for unravelling the Earth history, but even more for meeting society's demand for resources, particularly hydrocarbons) depend on it. Without information from the Pacific, it will likely remain impossible to understand the Phanerozoic eustatic sea-level changes. Even geologists working in the middle of a continent consequently should be aware of the mechanisms that control global sea-level fluctuations in order to correctly interpret the regional (or even local) palaeoenvironmental dynamics of their working areas.

The following recently proposed research approaches may help geoscientists to face this challenge.

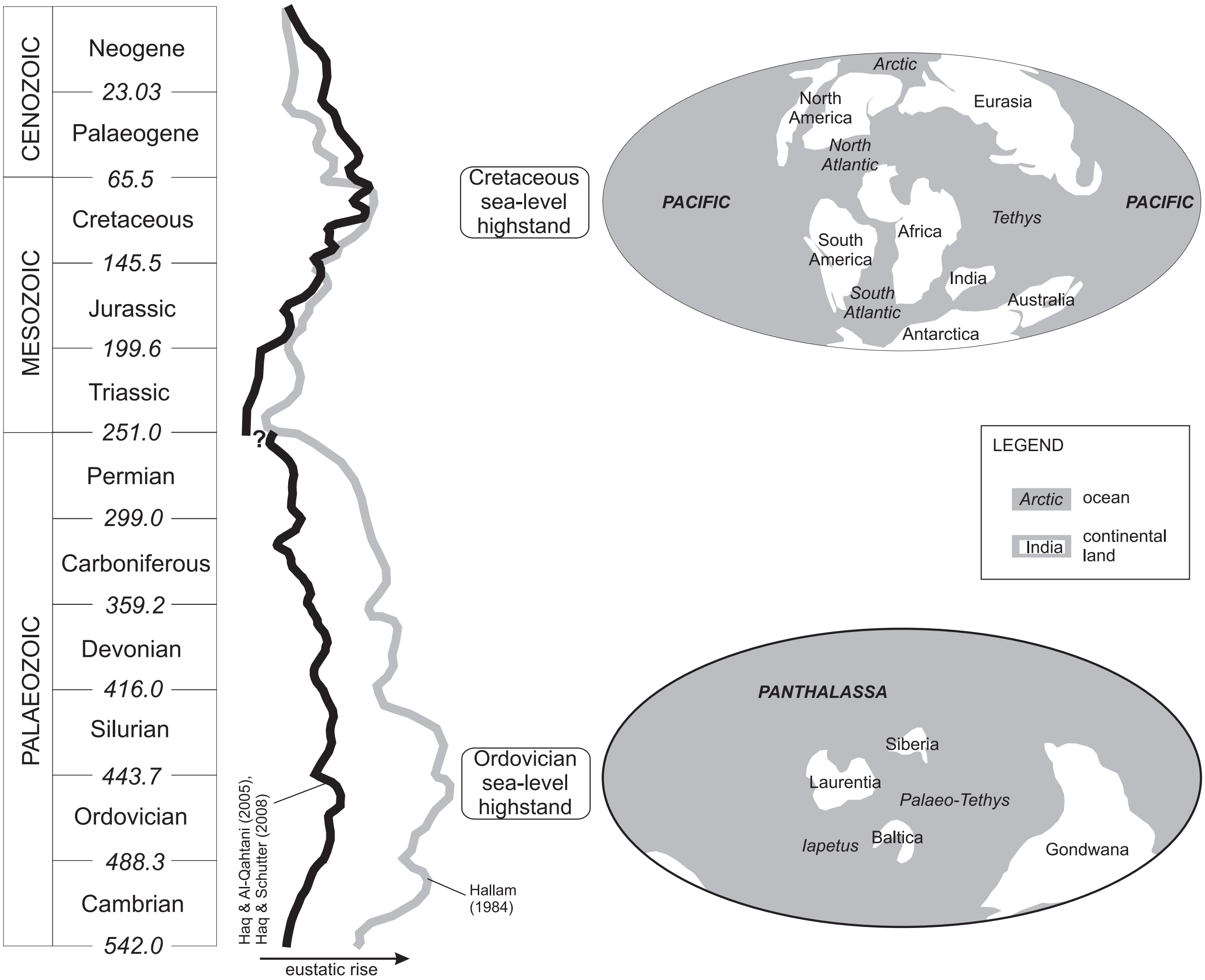

Fig. 2. Phanerozoic eustatic sea-level curves by Hallam (1984), Haq & Al-Qahtani (2005), and Haq & Schutter (2008). The global plate-tectonic reconstructions by Scotese (2004; see also www.scotese.com) suggest a different situation at the time of two remarkable sea-level highstands. Does the fact that the Ordovician Panthalassa was apparently larger than the Cretaceous Pacific argue for a higher sea level during the Ordovician than during the Cretaceous?

(1) Constraints on the geometry and sizes of better-known lithospheric blocks in the Pacific, in combination with the application of the general principles of plate tectonics to these blocks, may result in models for the pre-Cretaceous geodynamic history of the Pacific. Such an approach has already been followed by Müller et al. (2008) to develop Cretaceous-to-Cenozoic reconstructions.

(2) Numerical models of convection in the Earth's mantle may help us understand the basic physical parameters that control the tectonics of ocean basins of Panthalassic proportions. Because spreading ridges are the primary mechanism for dissipating interior heat, they are intimately linked to convection patterns in the Earth's mantle. Recently, numerical convection models have suggested that the mantle may exhibit a cyclic behaviour (Grigne et al., 2005; Labrosse & Jaupart, 2007) that is reflected by tectonic cyclicity at the surface (Silver & Behn, 2008), hemispheric heat buildup in the mantle due to insulation from supercontinents (Lenardic et al., 2005; Zhong et al., 2007; Phillips & Coltice, 2010), and heterogeneity within the mantle interior (Zhang et al., 2010). Indeed, tectonic changes in the Pacific Basin since the Cretaceous are thought to have caused a long-term slowdown in mantle heat flow (Loyd et al., 2007; Becker et al., 2009) that may be part of a longer-term cycle of mantle convection. Moreover, numerical modelling may help us

understand how convective cyclicity within the mantle affects dynamic topography and the associated offset of the sea level (Conrad & Husson, 2009).

(3) Although active subduction along the oceanic margins has removed a significant portion of oceanic crust and thus has erased much information about early Mesozoic and, especially, Palaeozoic tectonic re-organizations in the Pacific, some important constraints can still be discovered. For example, LIPs have a good preservation potential at convergent margins (Stüwe, 2007). This is supported by the recent studies of Kerr & Mahoney (2007) and Safonova (2009), who discovered evidence for intra-oceanic LIPs within accretionary complexes along continental margins. Moreover, seafloor ages for the lost Iapetus ocean can be inferred from geological and palaeomagnetic data from the margins and terranes of the closed basin (Stampfli & Borel, 2002; Heine et al., 2004). Likewise, the Cenozoic and Cretaceous tectonics of the western Pacific lithosphere have been constrained using observations of systematic changes in the fabrics of mélanges along the western Pacific margin (Onishi & Kimura, 1995; Müller et al., 2008).

(4) Palaeontological data can be extremely useful for the evaluation of the Pacific Basin's tectonic history. If common faunas or even floras occurred along the margins of this ocean, one can hypothesize either a smaller size for this water body or the presence of transoceanic migration routes along ridges, hotspot-related seamounts (see the example described by Chatterjee & Scotese, 2010), or island arcs. For example, Iwasaki (see Ruban et al., 2007) drew attention to the similarity of Early Devonian trilobites from Kazakhstan and South America, which were land masses located at opposite sides of Panthalassa. Such observations may have significant plate-tectonic implications.

(5) Accurate reconstructions of eustatic sea-level fluctuations can themselves provide new constraints. For example, Haq & Schutter (2008) highlighted a remarkable sea-level highstand in the Ordovician. Checking the available reconstructions (e.g., Cocks & Torsvik, 2002; Scotese, 2004), it can be concluded that crustal production in the Palaeo-Tethys or Iapetus oceans probably did not produce sufficient sea-level rise. In contrast, significant spreading within Panthalassa along Laurentia and Siberia, which has been depicted tentatively by Scotese (see www.scotese.com), could make the average oceanic crust significantly younger, and thus may explain the observed eustatic sea-level rise. A comparison of plate-tectonic situations for different time slices with eustatic events can be a powerful approach, at least for posing the right questions (Fig. 2).

The above diversity of available approaches, especially if combined, is a strong argument that reconstructions of both Phanerozoic sea-levels and the associated tectonics of the Pacific Basin are potentially achievable. The development of this geological understanding presents a new challenge that should not be ignored by specialists in any major field of the geosciences.

Conclusion

Plate-tectonic reconstructions of the Palaeozoic and Mesozoic Pacific Basin (known variously as 'Panthalassa' or 'Proto-Pacific') are essential for understanding Phanerozoic sea-level changes. Constraining the tectonics and dynamics of this largely unknown ocean basin presents a new and inevitable challenge for geoscientists, and requires a multi-disciplinary approach. Potentially fruitful ways for addressing this challenge include plate-tectonic modelling, simulation of time-dependent mantle convection, study of accretionary complexes, palaeobiogeographical reconstructions, and examination of the eustatic sea-level curves themselves. Such an interdisciplinary combination of all these approaches may significantly transform our current understanding of our planet's eustatic and plate-tectonic history.

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