

FAST-TRACK PAPER

## A sea-level test for inertial interchange true polar wander events

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### SUMMARY

The possibility of inertial interchange true polar wander (IITPW) events, in which the rotation pole moves 90° with respect to the solid Earth in a matter of ~ 10 Myr, has been discussed in the geophysical literature for more than three decades. Recent evidence for an IITPW event in Early Cambrian time has renewed interest in the issue; however, the veracity of supporting palaeomagnetic evidence remains a matter of significant debate. We propose that sea-level variations driven by polar wander provide an important independent test for the occurrence of IITPW events. Our numerical simulations of the response of a viscoelastic planet to an IITPW-induced forcing predict sea-level changes of up to 200 m, depending on the details of the earth model, the location of the site relative to the rotation path and the elapsed time for the reorientation of the pole. A preliminary comparison of our predictions to Early Middle Cambrian sea-level records for Australia, Laurentia and Baltica shows qualitative agreement. This comparison suggests that a definitive test for the Cambrian IITPW hypothesis is possible given a sufficiently accurate, and globally distributed, database of sea-level histories.

**Key words:** Cambrian, earth model, polar wander, sea level.

### INTRODUCTION

Redistribution of mass, either within the Earth or on its surface, changes the moment of inertia of the planet, and leads to movements of the Earth's rotation pole with respect to the solid Earth. This motion is termed true polar wander (TPW). Sea-level variations associated with an instantaneous motion of the rotation axis are characterized by a 'quadrantal geometry', defined by the spherical harmonic of degree two and order one (e.g. Han & Wahr 1989; Sabadini *et al.* 1990), rather than a globally uniform, eustatic trend. The orientation of the quadrants is determined by both the instantaneous position of the pole and its direction of motion. There is a sea-level rise in a given quadrant if the local rotation pole (e.g. the north rotation pole in the Northern Hemisphere) is moving away from the quadrant, and a sea-level fall if the local rotation pole is moving towards the given quadrant. The maximum sea-level changes occur 45° away from the local poles along the great circle containing the instantaneous polar wander

vector. The sea-level change is zero 90° away from the poles (i.e. on the rotational equator) and also on the great circle passing through the rotation poles that is perpendicular to the instantaneous pole path.

Over time scales of the order of 10<sup>6</sup> years and longer, TPW is linked to the advection of mantle density heterogeneities and tectonic plate motions associated with thermal convection. Sabadini *et al.* (1990) were the first to quantify the effects of these long-term variations on sea level. They considered a constant polar motion of 1° acting over 1 Myr and predicted a net sea-level change of tens of metres. Sabadini *et al.* (1990) argued that a long-term TPW rate of 1° Myr<sup>-1</sup> was probably a lower bound, and concluded that TPW was an important mechanism for generating third-order (period ~ 1-10 Myr) sea-level fluctuations. Recently, Mound & Mitrovica (1998) have extended the Sabadini *et al.* (1990) analysis to second-order (period ~ 10-100 Myr) sea-level cycles. They predicted site-dependent TPW-induced sea-level variations of the order of 50-100 m and concluded that the well-documented second-order Cretaceous Tertiary sea-level cycle should be reinterpreted as some combination of a eustatic signal and a regionally varying TPW signal.

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The present paper investigates sea-level fluctuations associated with so-called inertial interchange true polar wander (IITPW) events (Goldreich & Toomre 1969; Fisher 1974). An IITPW event occurs when the magnitudes of the intermediate and maximum moments of inertia of the Earth evolve to near proximity. During such an event, the orientation of the Earth's rotation pole may undergo a shift of nearly  $90^\circ$  over some tens of millions of years. Since IITPW events consist of rapid polar motion (i.e. several  $^\circ \text{ Myr}^{-1}$ ) persisting over tens of millions of years, they provide a link between the fast but short-duration ( $\sim 1 \text{ Myr}$ ) TPW-induced sea-level effects studied by Sabadini *et al.* (1990) and the slower polar motion of longer duration (tens of millions of years) considered by Mound & Mitrovica (1998).

Episodes of IITPW would have profound consequences for the Earth system, extending from mantle dynamics to climate studies [e.g. Gold's (1955) early discussion of the influence of rapid polar motion on sea level and climate], and evidence for their existence has been sought in the palaeomagnetic record (see below). The primary goal of the present paper is to establish whether sea-level variations induced by polar wander can provide an independent test for the occurrence of IITPW events.

As a case study, our numerical predictions will adopt IITPW geometries recently proposed for the Cambrian (Kirschvink *et al.* 1997). Based on a synthesis of the global Vendian-Cambrian palaeomagnetic database, Kirschvink *et al.* (1997)

argued that an IITPW event may have occurred during  $\sim 15 \text{ Myr}$  of Early Cambrian time (Fig. 1). Because their age estimates are based primarily on the numerical calibration of the fossil record, subsequent revisions to that calibration (e.g. Landing *et al.* 1998; Bowring & Erwin 1998) may alter the precise duration of their IITPW model. In addition, the proposed Cambrian event may be one of several rapid TPW episodes during Vendian and early Palaeozoic time (Evans 1998). For these reasons, we generalize our models to encompass several possible IITPW durations. We use the pre-IITPW configuration of Kirschvink *et al.* (1997) and follow the modelled sea-level histories of several sites as they rotate  $90^\circ$  uniformly with the rest of the palaeogeographic elements (Fig. 1). Our numerical predictions will examine the sensitivity of IITPW-induced sea-level variations to the duration of the event, the geographic location of the observation site, and the details of the viscoelastic earth model.

The IITPW event proposed by Kirschvink *et al.* (1997) remains highly controversial (Torsvik *et al.* 1998; Evans *et al.* 1998). The controversy is centred primarily on the palaeomagnetic data, and thus independent constraints may play a key role in the ongoing debate. The numerical results presented below represent testable predictions for the Early Cambrian event. To complete the article we present a preliminary comparison between our predictions and published inferences of Cambrian sea-level trends.

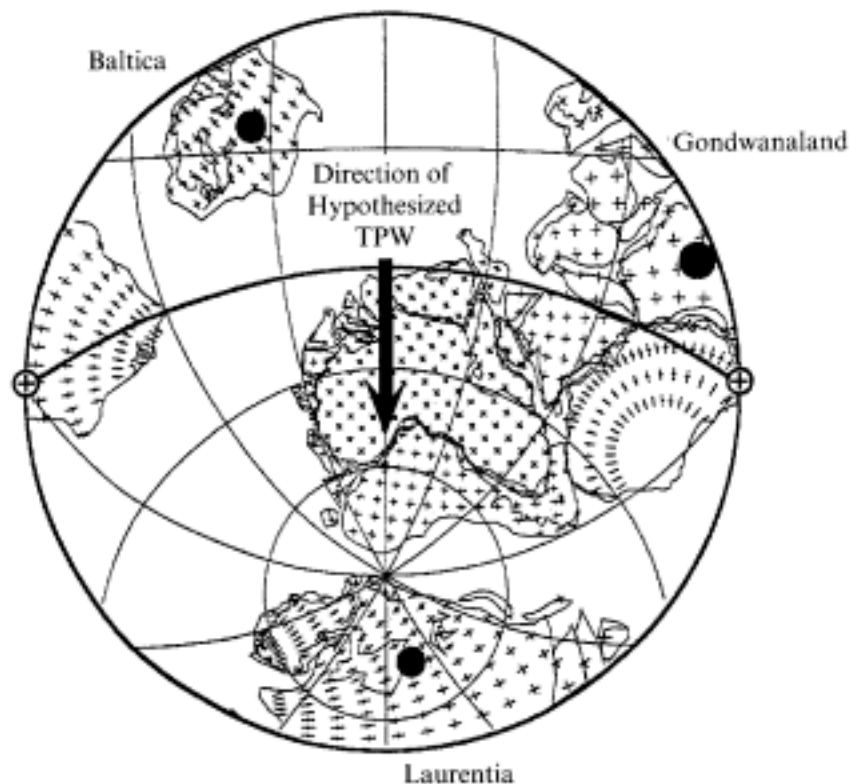


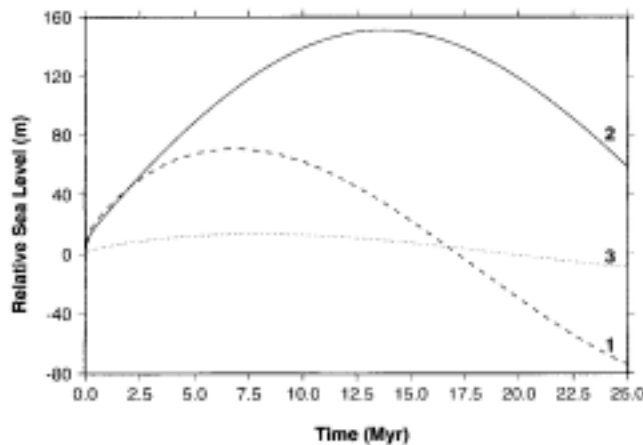
Figure 1. Equal-angle projection of pre-IITPW Early Cambrian palaeogeography, modified after Kirschvink *et al.* (1997), with a  $30^\circ$  palaeolatitude-palaeolongitude grid. For reference, continental blocks contain  $5^\circ$  tick marks of the present geographic grid. The axis of their proposed IITPW event is shown by the antipodal '+' symbols lying along the equator (darker curve). The large arrow denotes the hypothesized uniform motion of continents relative to a reference fixed to the rotation axis. Black dots mark the cratonic locations for which we have modelled local sea-level responses in this study. According to the TPW hypothesis, central Baltica moved through the tropics to mid-southerly latitudes, central Australia rotated anti-clockwise to arrive slightly south of the equator, and central Laurentia translated nearly directly from polar to tropical latitudes on the opposite hemisphere from that depicted here.

## RESULTS

The results presented in this paper were obtained through numerical modelling of the sea-level response to changes in the rotational potential on a spherically symmetric, self-gravitating, Maxwell viscoelastic earth model (see Mound & Mitrovica, 1998). Our numerical predictions are based on a suite of earth models having the elastic and density structure of the seismic model PREM (Dziewonski & Anderson 1981). These models are distinguished on the basis of three parameters: the thickness of the purely elastic lithosphere, which we denote by  $LT$ , and the (assumed uniform) viscosity of the upper and lower-mantle regions, which we denote by  $\nu_{um}$  and  $\nu_{lm}$ , respectively. The boundary between the upper and lower mantle is taken to be at 670 km depth.

In Fig. 2 we show predictions of the sea-level variation at three sites resulting from the hypothesized Cambrian IITPW event shown in Fig. 1. We adopt a duration of 25 Myr for the event. The predictions are based on an earth model characterized by  $LT = 100$  km,  $\nu_{um} = 10^{21}$  Pa s and  $\nu_{lm} = 3 \times 10^{22}$  Pa s. In this case, the site in central Laurentia experiences a sea-level rise of  $\sim 150$  m over the first  $\sim 13.5$  Myr of the IITPW event, followed by a  $\sim 100$  m sea-level fall over the next  $\sim 11.5$  Myr. In contrast, the site in central Australia experiences a sea-level perturbation of less than 15 m from its initial value over the same time period. This difference arises from the distinct positions of the sites relative to the pole during the IITPW event. The change in the rotational co-latitude (which we define as the angular distance between a site and the north rotation pole) is one determinant of the magnitude of the sea-level variations associated with TPW. The Laurentian site lies relatively close to the great circle along which the rotation pole is proposed to have moved during the IITPW event; the event thus produces a large change in the rotational co-latitude and a large-amplitude sea-level signal. The Australian site remains close to the rotational equator throughout the IITPW event, hence almost no sea-level change is predicted for this site.

Geographic position relative to the rotation pole also controls the sign of the sea-level trend. As a site crosses the rotational equator, the sea-level trend at the site reverses. This

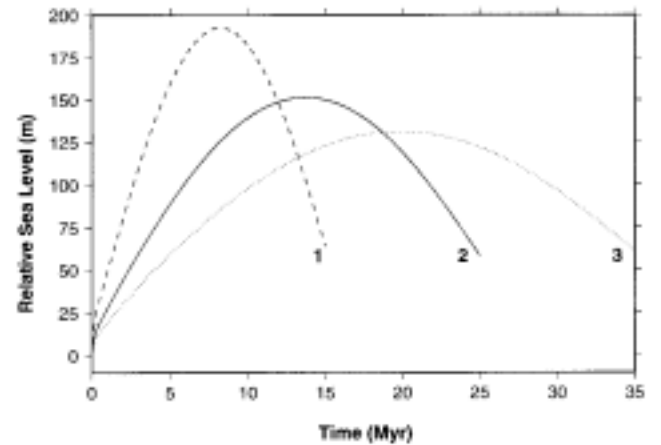


**Figure 2.** Predicted sea-level responses to the 25 Myr IITPW event at the three sites shown in Fig. 1. Calculations are based on an earth model characterized by  $LT = 100$  km,  $\nu_{um} = 10^{21}$  Pa s and  $\nu_{lm} = 30 \times 10^{21}$  Pa s. Lines correspond to sites in central Baltica (dashed; 1), central Laurentia (solid; 2) and central Australia (dotted; 3).

explains the shape of the predicted sea-level curves in Fig. 2. Consider Baltica, where an initial sea-level rise slows and then reverses trend to a rapid sea-level fall. At the onset of the IITPW event, the site is in the Northern Hemisphere at a longitude such that the local (i.e. north) rotation pole is moving away from Baltica. As the IITPW event progresses, the site moves across the rotational equator. Once this occurs ( $\sim 7$  Myr after the onset of IITPW), the local (i.e. south) rotation pole is moving towards the site. This change is reflected by the reversal of the sea-level trend. (As a consequence of viscous effects, the reversal of the sea-level trend in Baltica actually occurs before the site crosses the equator.)

Fig. 3 shows the predicted sea-level trend at the Laurentian site for IITPW durations of 15, 25 (as in Fig. 2) and 35 Myr. These values reflect the uncertainty in the elapsed time for the Early Cambrian event; however, they also provide a measure of the sensitivity of the sea-level response to the duration of a generic IITPW event. The magnitude of the sea-level highstand for the Laurentian site grows monotonically larger as the duration of the IITPW event is shortened. Indeed, the maximum excursion of sea level from the value at the onset of the event increases  $\sim 50$  per cent from  $\sim 130$  to  $\sim 190$  m as the duration is reduced from 35 to 15 Myr. As the elapsed time for the IITPW event increases, the efficiency with which viscous relaxations compensate for the instantaneous (and large) elastic response to TPW also increases. (Sea-level fluctuations induced by TPW are nearly zero on an inviscid earth model.) Thus, sea-level fluctuations will be larger for IITPW events of shorter duration.

The effective elastic thickness and the radial viscosity profile of the Earth are the source of some contention, and they are probably functions of the timescale of the applied forcing. Accordingly, we have considered the sensitivity of our predictions to variations in the physical properties of the earth model. In Fig. 4 we present results for Laurentia for the case where  $LT$ ,  $\nu_{um}$  and  $\nu_{lm}$  are independently varied from the values used to generate Figs 2 and 3. The predictions show the greatest sensitivity to changes in  $LT$ , although the sensitivity to variations in  $\nu_{um}$  is nearly as large. The predicted sea-level fluctuation increases as the departure from a purely inviscid



**Figure 3.** Predictions of the sea-level response at the site in central Laurentia as a function of the duration of the IITPW event. The dashed line (1) corresponds to a duration of 15 Myr, the solid line (2) 25 Myr, and the dotted line (3) 35 Myr. All calculations used an earth model with  $LT = 100$  km,  $\nu_{um} = 10^{21}$  Pa s and  $\nu_{lm} = 30 \times 10^{21}$  Pa s.

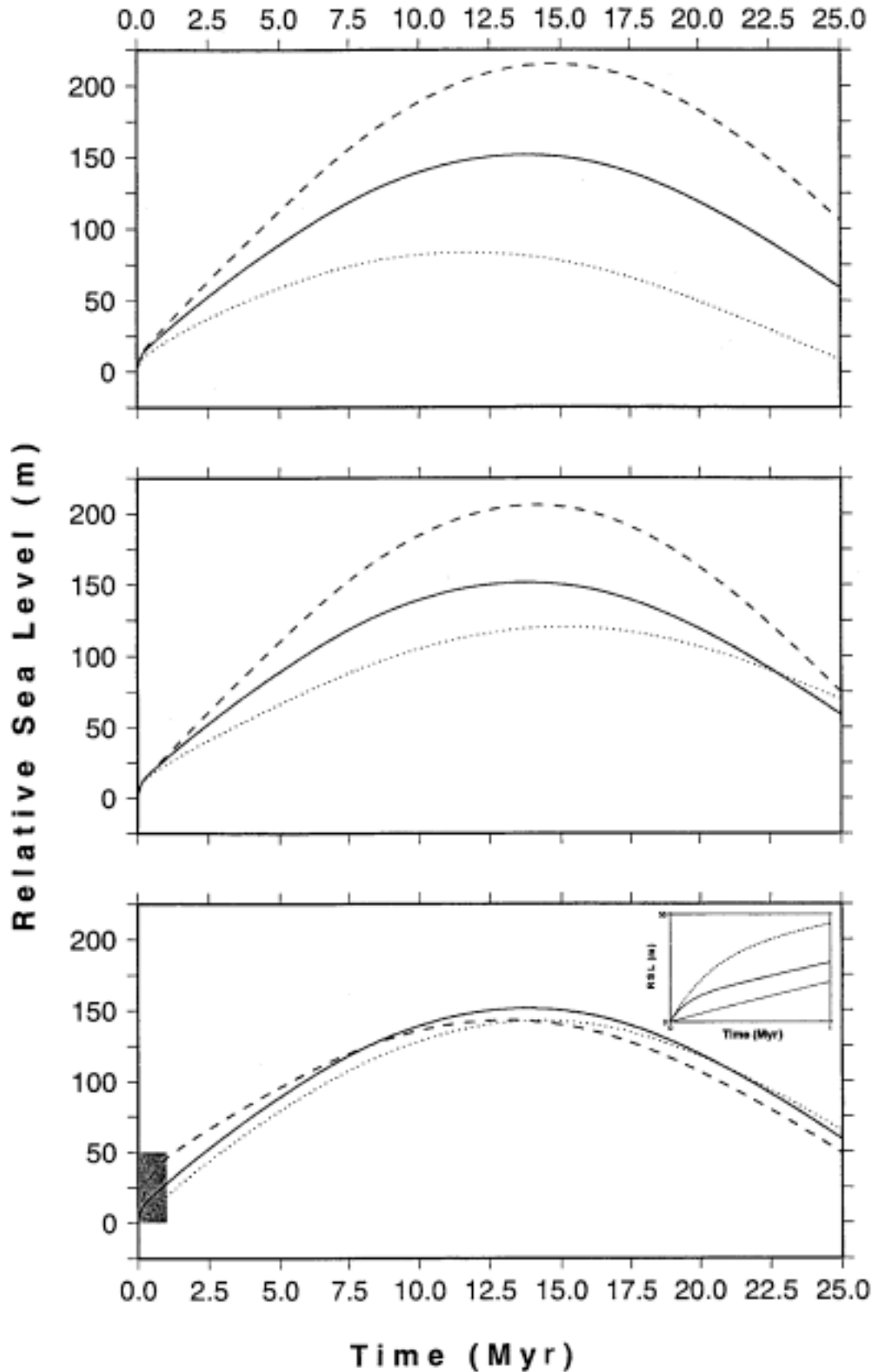


Figure 4. Predictions of IITPW-induced sea-level change for the central Laurentian site in response to a 25 Myr IITPW event for a suite of earth models in which the physical parameters are varied from their 'standard' values of  $LT = 100$  km,  $v_{um} = 10^{21}$  Pa s and  $v_{lm} = 30 \times 10^{21}$  Pa s. (a)  $LT = 50$  km (dotted line), 100 km (solid line) or 150 km (dashed line); (b)  $v_{um} = 5 \times 10^{20}$  Pa s (dotted line),  $10^{21}$  Pa s (solid line) or  $2 \times 10^{21}$  Pa s (dashed line); (c)  $v_{lm} = 10 \times 10^{21}$  Pa s (dotted line),  $30 \times 10^{21}$  Pa s (solid line) or  $100 \times 10^{21}$  Pa s (dashed line). The inset in (c) provides a detailed view of the shaded region.

response grows. This departure increases as either the lithosphere is thickened or the upper mantle is stiffened. The maximum sea-level fluctuation ranges from 75 to over 200 m in Fig. 4.

The magnitude of the sea-level fluctuation over the course of the IITPW event is not a particularly strong function of  $\nu_{lm}$ . Mound & Mitrovica (1998) observed the same insensitivity in their prediction of the second-order sea-level variation over the last 130 Myr. This insensitivity differs from the results for third-order sea-level cycles of Sabadini *et al.* (1990), who considered the sea-level response over 1 Myr to a constant TPW of  $1^\circ \text{ Myr}^{-1}$ . To explore this difference we show, in the inset to Fig. 4(c), an enlargement of the first 1 Myr of our sea-level predictions for various values of  $\nu_{lm}$ . These results show the same sensitivity to variations in lower-mantle viscosity first described by Sabadini *et al.* (1990; Fig. 2). [As discussed by Sabadini & Vermeersen (1997), the amplitudes predicted by Sabadini *et al.* (1990) are also sensitive to the earth model discretization procedure adopted in that study.] Over timescales of  $10^5$ - $10^6$  yr, increasing  $\nu_{lm}$  reduces the level of viscous relaxation that acts to compensate the direct effect of the TPW, and this reduction leads to sea-level predictions of higher amplitude. Over timescales longer than a few million years, these differences represent relatively small transients on total sea-level predictions which exceed 100 m. We conclude that sea-level trends induced by a prescribed IITPW event will not be strong functions of the lower-mantle viscosity (assuming that IITPW events occur over periods in excess of a few million years).

#### DISCUSSION: A PRELIMINARY COMPARISON WITH CAMBRIAN SEA-LEVEL RECORDS

To illustrate the utility of sea-level predictions as a test of any proposed IITPW event, we end this paper with a comparison of our numerical predictions with various constraints on Early Cambrian sea-level trends. The comparison is highly preliminary for two main reasons. First, we have not attempted an exhaustive compilation of available Cambrian sea-level records (which may, in any case, not yet be sufficient for the task). Second, our comparison will not attempt to correct for the effects on sea level of eustasy, long-term subsidence and sediment compaction, and far-field tectonic influences (e.g. Mitrovica *et al.* 1989). Furthermore, regional patterns of flooded continental interiors can only be converted to absolute sea-level variations via assumption of a given continental hypsometry (cf. Algeo & Sessler 1995). Nevertheless, our focus on regional sea-level trends for the three sites in central Australia, Laurentia and Baltica is motivated by their tectonically stable locations near the centre of cratonic regions, and their differences in position relative to the IITPW and rotation axes.

Australia's proximity to the proposed IITPW axis, and the correspondingly insignificant IITPW-induced sea-level variation (Fig. 2), makes it a favourable reference locality for determining Early Cambrian eustasy. Cambrian sedimentary rocks are distributed in several regions of autochthonous Australia, predominantly in the Flinders and Mount Lofty ranges of South Australia (Gravestock 1995) and the disrupted Centralian Superbasin further north (Walter *et al.* 1995). The former region was a rapidly subsiding basin which was affected by

the Delamerian orogeny, perhaps as early as Early Cambrian time (Chen & Liu 1996). For that reason, we opt for more northerly regions (Amadeus and Georgina basins) to constrain cratonic flooding. A detailed Cambrian palaeogeographic atlas of cratonic Australia (Cook 1988) shows a shallow (0-20 m) marine transgression over these areas during Early Cambrian time. The low amplitude of sea-level changes in this area is consistent with our results of little TPW-induced onlap or offlap, and could also suggest that Early Cambrian eustasy was relatively constant.

The Phanerozoic sea-level curves of Vail *et al.* (1977) are based primarily on data from cratonic sequences in North America. These curves show a marked Cambrian onlap, the so-called Sauk transgression (Sloss 1963). Algeo & Sessler (1995) argue that this onlap represents ~75-150m of monotonic sea-level rise, depending on the palaeohypsometry chosen for Laurentia. In contrast, some syntheses of Early Palaeozoic Laurentian flooding records include within this transgression a slight regression near the Early-Middle Cambrian boundary (Wise 1974, after Schuchert 1955).

Our results for Laurentia indicate a transgression leading to highstands of 75-200 m above the pre-TPW baseline, which is consistent with the observational record. Our predictions also suggest a sea-level regression towards the end of the IITPW event, although the magnitude of the regression relative to the earlier transgression is model-dependent. For example, some earth models yield a significant IITPW-induced regression [for example, for the  $LT = 50$  km prediction in Fig. 4(a), the regression is almost equal in amplitude to the transgression], and thus appear to be inconsistent with the geological record. However, the predicted regression associated with the IITPW event is weakened relative to the transgression as the adopted upper-mantle viscosity is reduced or the elastic lithosphere is thickened. For example,  $\nu_{um} = 5 \times 10^{20}$  Pa s yields a regression roughly three times smaller than the earlier transgression, thus providing a reasonable match to the observed Sauk flooding of Laurentia during Early-Middle Cambrian time. We note that a weak upper mantle has been favoured on the basis of near-surface plume deflection (Richards & Griffiths 1988), glacial rebound data (e.g. Nakada & Lambeck 1989) and joint inversions of long-wavelength geoid and rebound data (Mitrovica & Forte 1997).

A relative sea-level curve for the Early Cambrian of Baltica may be estimated from flooding records of the Russian cratonic platform. Unfortunately, those available to us (Ronov *et al.* 1984) are only compiled at epoch resolution, i.e. Early, Middle and Late Cambrian. These maps, as well as a quantified update at the same resolution (Algeo & Sessler 1995), confirm that central Baltica experienced a marked regression of perhaps 100-200 m during Cambrian time. About half of this sea-level fall occurred during the interval of proposed IITPW. The results for Baltica in Fig. 2 indicate a moderate transgression, followed by a substantial regression, with a net regression of about 80 m. As for Laurentia, this value will be dependent upon elastic thickness, mantle viscosity and the rate of TPW. Baltica's hypothesized Cambrian palaeogeographic position is rather poorly known because of its lack of reliable Cambrian palaeomagnetic poles (Kirschvink *et al.* 1997; Evans *et al.* 1998), and this introduces a further uncertainty. Nevertheless, we note that our analysis predicts a net sea-level drop for Baltica, consistent with its observed Cambrian emergence.

## CONCLUSIONS

The Earth system implications of an IITPW event are enormous. The results presented in this article suggest that sea-level variations driven by IITPW are of significant amplitude and distinct spatial geometry. We conclude that sea-level records provide an important independent test for any suggestion that an IITPW event may have occurred in geological history.

A preliminary comparison between our predictions, based on a proposed IITPW event in Early Cambrian time (Kirschvink et al. 1997), and observed Early-Middle Cambrian sea-level records for Australia, Laurentia and Baltica shows some qualitative agreement. However, we caution that any definitive judgement on the proposed event will require a systematic, quantitative comparison with a sufficiently accurate database of Cambrian sea-level histories. The results presented herein provide the required framework for this future test.

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