True polar wander and marine transgressions

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Among the planets of the solar system, earth is referred to as the 'blue planet' and 'water planet', descriptions befitting its appearance from space created by the vast expanse of water spread over two-thirds of its surface. The origin of this awesome quantity of water can be traced to earth's post-accretionary phase of heating due to decay of radioactive elements and compressive forces from the collapsing accreted bodies, all leading to melting followed by differentiation of the latter melt material. These released the water bound in hydrates and other minerals having H and O bonds such as the micas KAl₂Si₃O₁₀(OH)₂, and the H₂O thus liberated ascended to the surface through volcanic exhalations and lava eruptions, processes that continue even today both on the land and sea (mid-ocean ridges).

Continents and oceans make up the earth's surface, and the coastline or shoreline represents the boundary between these two major units. Shorelines as well as oceans are not fixed entities but have been changing with time as can be seen from some of the palaeogeographic maps tracing the geological evolution of the continents. New oceans had formed and some earlier ones closed (e.g., Iapetus, Panthalassa, Tethys oceans) and among the major impacts of these ever-changing geography were the ones on sea levels, which fluctuated by hundreds of meters. As a result, what were once shorelines or continental slopes (the junction between the continental and oceanic crusts), form interior portions of the continents today. The great Tethyan ocean of the Jurassic period that had separated the supercontinents of Gondwana and Laurasia narrowed progressively and by Cretaceous gave way to the Himalayan mountain chain, and similarly portions that were well inside lands, form a long coastline today (e.g., parting of Arabia and Africa by the Red Sea and the Gulf of Aden are examples of relatively recent geological past (20 m.y. ago)). Rhodes W. Fairbridge has provided an excellent summary of the historical development of various theories to explain some of the major oscillations of sea levels during earth's evolution.

Sea level changes are referred to as marine transgressions and they can be global, also called eustatic, or regional covering only a few geographic regions. These transgressions can be ingestions (rise in the level) resulting in submergence of shore or regressions (fall in the level) whereby accretion of land to the shore takes place. The well-known Cretaceous or Cenomanian transgression was supposed to have submerged nearly 50% of the earth's present land surface and in India, this event had covered a large part of the area on the eastern coast from Pondicherry to the south of Cauvery valley, and also parts of north-eastern regions and Narmada valley and Kutch on the west. Major oceanic transgressions have been recognized during (a) Ordovician when sea level rose by more than 350 m, (b) during early Jurassic when it fell by 165 m and (c) in the past 30 m.y. when the level had fluctuated appreciably - between a fall by 200 m and rise by 135 m. The present day trend, which is a sea level fall, commenced 3 m.y. ago during the Pleistocene period (Table 1). Variations in sea levels can be of short duration with low amplitude of 10 to 20 m, like the tides, caused daily, and the occasional tsunamis and storm tides or of long period duration lasting millions of years producing transgressions of much greater magnitude. Long period variations lasting over 100 m.y. are termed first order cycles, while those between 100 and 10 m.y. are second order cycles and those between 10 and 1 m.y. are third order cycles. Present day ice cover over Greenland and Antarctica, are regions of remnant ice caps of the waning Quaternary ice age and belong to the last category. Apart from their impacts on shores and lands, many of the sea level changes, particularly lowering of the sea level, are also believed to be responsible for major mass extinctions and fluctuations in faunal diversity.

It is well known that the sea is the primary source for the enormous volume of water forming ice-sheets and the large amount of water tied up thus is hardly replenished by run-off from rivers. Hence, continuous accumulation of ice on continents, inevitably, result in lowering of the sea level. Similarly melting of vast areas of ice sheets - about 7000 to 10,000 feet thick, as in the present day polar ice caps, can boost the level of the sea globally producing ingestions. Also, the removal of the load of such vast amount of ice-sheets, initiate isostatic mechanisms to equalize the load by rise of land in certain regions (e.g., present day rise in Scandinavia and parts of eastern Canada by about 500 m) and sinking of ocean floors (Indian, Mediterranean and Caribbean oceans) elsewhere. However, unlike the quicker global increase in the volume of water released from melting ice, the isostatic adjustments are 100-1000 times slower, stretched over geologic time scales. Geological and geophysical causes for long period sea level rise are known, though the mechanism by which this is brought about is not certain. Some of the well-studied causes are, melting of continental ice sheets and isostatic adjustments, thermal expansion of water, filling of ocean basins with sediments and resultant displace-

<table>
<thead>
<tr>
<th>Geological period</th>
<th>Age (10⁶ Y)</th>
<th>Sea level change (m)</th>
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<tbody>
<tr>
<td>Early Ordovician</td>
<td>506-480</td>
<td>+350</td>
</tr>
<tr>
<td>Early Jurassic</td>
<td>190</td>
<td>-165</td>
</tr>
<tr>
<td>Late Cretaceous</td>
<td>90-70</td>
<td>+350</td>
</tr>
<tr>
<td>Late Oligocene</td>
<td>30</td>
<td>-200</td>
</tr>
<tr>
<td>Middle Miocene</td>
<td>13</td>
<td>+135</td>
</tr>
<tr>
<td>Pleistocene Ice ages</td>
<td>3-0</td>
<td>-120</td>
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changes in the salt contents of oceans (palaeosalinity), as deciphered through the adverse impacts on the planktonic foraminifera, have been used on a regional scale. While these are some of the methods to evaluate long period cycles that had already taken place, their recognition within historical times, though difficult, has been achieved by inspection of tide-gauge records spanning several decades. For example, over the past 50 years, these records have revealed rise in the sea-level at a rate of 12 cm/100 years, a rise ascribed to melting of ice sheets and glaciers due to gradual climatic warm-up in the past 150 years. With the advance of space technology, satellite-based techniques (e.g., satellite interferometry) are able to detect even minor changes in the glacial cover and their melting and spot regional sea level trends to enable prediction of their long-term effects.

In spite of a number of causes identified for the sea level oscillations, current ideas tend to emphasize that many of them are possibly inter-linked, one triggering the other, or sometimes acting synchronously and researchers associate geodetic and tectonic causes for many of the past eustatic changes. In a recent study on the sea level fluctuations of about 200 m since the early Cretaceous (130 m.y. ago), a number of short-period secondary transgressions of 100 m or less within this period were identified which, surprisingly, were not supported by any geologic causes (Figure 1b). Now John E. Mound and Jerry X. Mitrovica (University of Toronto, Canada) have re-examined past records and found that 'significant long-term sea level variations may be a consequence of the response of solid earth and oceans to slow changes in the orientation of the earth's orientation vector' or true polar wander (TPW). This wander is caused by imbalances in the mass distribution of the planet which, due to centrifugal forces, is compelled to equalize or correct the imbalances in rapid time scales, unlike the slower movements induced by plate tectonism arising out of mantle current movements. Such rapid TPW-induced movements during earlier geological eras (e.g., 50 m.y. ago during the Cambrian times) had triggered closure of some of the ancient oceans and led to reorganization of continental landmasses.

**Figure 1a.** Global sea level fluctuations since Precambrian; **b** Short duration fluctuations within the Cretaceous second-order cycle.

movement of water and down-faulting of ocean basins, addition of juvenile waters brought up through volcanism, orogenic cycles involving movement of the earth's crust on both land and oceans and consequent volume changes, plate subductions, spreading of the oceanic ridges, tidal deceleration of earth's rotation rate and shift of the pole axis, including global climatic changes.

Sea-level changes of earlier geologic periods can be inferred from fossil records (as judged by the prevalence of deep dwellers or shallow water species), wave cut benches, or terraces (arising due to sea-erosion caused by intermittent tectonic upward or downward movements), nature of sediments (the grain size of the marine sediments are indicators of the ocean depth at the site of deposition - coarse near the shore and increasing fineness farther from shore) and palaeo-temperature studies. Among these, those based on sequences in marine deposits were classic techniques employed earlier to assess many of the past sea level cycles. These methods assumed that sea levels either rose or fell globally simultaneously and consequently the deposition of marine sediments or their non-deposition were also assumed to be synchronous around the world. However, such assumptions ignoring that there could be appreciable variations in the amplitude of the fluctuations geographically, are being increasingly questioned today. Vail et al. had used seismic stratigraphy (recognition of unconformities, and other density heterogeneities in the marine strata through seismic reflections) to generate global cycle-charts for earlier geological periods. Haq et al. applied chronostratigraphic techniques, studies of depositional models of genetically-related sediments, along with fossil records and documented cycles since last 250 million years. Recently,
For example, during the last 130 m.y., the north rotation pole had wandered from middle of Greenland to the present site (Figure 2a) with varying rates of shift (e.g. between 130 and 120 m.y. ago, it had remained stationary and thereafter shifted) and the direction of movement reversed sometime after 50 m.y. ago. On the basis of data obtained through seismic stratigraphy, the authors examined the second-order sea level transgressions (~100 m) during Cretaceous followed by its gradual fall (regression) till present day and correlated them with geologically-inferred polar wander paths over the last 130 m.y. The observed pole-to-equator sea level change, by as much as 100 m over 100 m.y. was earlier ascribed to tidal retardation effect in the earth’s rotation rate (tidal deceleration increases sea level at high latitudes and decreases it at low latitudes), but Mound and Mitrovica feel that the prime cause for this latitudinal control over sea level fluctuations is rotational tilt or true polar wander since 130 m.y. ago which had varied between fraction of a degree (~0.4°/m.y. between 130 and 50 Ma) and 1°/m.y. (refs 13, 17). The relatively rapid ones, according to them, influence or control third order sea level cycles.

Mound and Mitrovica showed mathematically that TPW-induced sea level changes should exhibit zero sea level perturbation along two great circles at right angles to each other, around the globe. The intersection of these circles would define four quadrants globally, and as per their calculations, 'when the local rotation pole (that is the north pole in the northern hemisphere and south pole in the southern hemisphere) is moving towards a quadrant, sea level falls in that quadrant' and the reverse happens (i.e. sea level rises) in the other two quadrants where the local pole moves away from that quadrant (Figure 2b). The authors feel that TPW must have thus brought about second order cycles during the last 130 m.y. and when there was a change in the direction of TPW at about 50 m.y. ago, it caused a reversal in the long-term sea level trend. Thus landmasses located in the opposite quadrants at that time—North America, Europe, N. Africa and Australia should have experienced TPW-induced sea level rise, which they calculated to be about 50 m and sea level fall in Japan, corresponding to local pole movements during this period. They argued that as a consequence, sites in the rotational co-latitudes (e.g. North America) would show larger sea level changes than those places located further away (e.g. Europe). Michael Gurnis (University of Michigan) had shown that the Cretaceous sea level fluctuations were associated with profound changes in the deep thermal structures (internal viscosity and mantle convection) under the oceans and continents. Mound and Mitrovica have recognized that TPW-induced sea level fluctuations do depend on the viscoelasticity of earth’s mantle zones, but felt that lithospheric thickness exerted greater influence. They calculated that doubling the thickness for the North American sites, for example, should increase the predicted sea level by a factor of 2, to ~100 m, but changes in the viscosity of the lower or upper mantle, they argued, wielded little change.

Briefly, according to Mound and Mitrovica, such TPW-induced second-
order sea level variations merely transfers the waters, implying thereby that there is only redistribution of water to adjust to the new orientation of the earth's axis. This shift of the pole axis increases the force and rotational speed towards the equator (centrifugal force) making continents slowly slip over the earth's mantle to produce the bulge at the equator. The glacial melt-induced isostatic adjustment is also linked to the true polar wander; while the impact of the latter on the lands is to slowly shift them, in the case of the oceans the motions alter their shape and size, producing changes in sea levels - ingestion in certain regions and regression in some other regions of the globe. Thus the gradual wander of the north pole from Greenland to the Arctic Ocean region during 130-50 m.y. must have raised the sea level here by 50 m, reversal of this trend must have commenced ever since the pole commenced reversing the course between 30 and 0 m.y. (Figure 1 a).

Mound and Mitrovica caution that TPW effects should not be ignored while attempting correlations of sea level data from different geographic regions and in this connection they strongly believe that the worldwide mid to upper Cretaceous transgression and subsequent regression attributed earlier by Hays and Pitman to the rapid spreading and expansion at mid-ocean ridges and consequent reduction in ocean basin volume, were probably accompanied or triggered by TPW. Sabadini and others have also observed earlier that eustatic sea level transgressions, though co-eval around the globe, were not uniform. They displayed latitudinal dependence and were extremely 'sensitive to viscosity stratification and lithospheric thickness' in the different geographic regions. These perturb or deform sea floors and depending on the direction of polar wander, there can be ingressions in latitudes farther from the equator and no perturbation at the equatorial regions. Therefore, inferences or correlations based on sequences in the deposition or non-deposition of marine sediments around the world are not dependable since a 'high stand in marine package in the northern hemisphere can, in fact, be coeval with a low stand in the southern hemisphere at the same longitude' where sea level fluctuations are induced by true polar wander. Therefore, in his opinion, correlations of sedimentary sequences should introduce appropriate 'temporal resolution of sequence stratigraphy'. The present trend of research undoubtedly suggest, as Mound and Mitrovica observe, that a combination of TPW-induced signals (quadrant-localized) and an eustatic trend, for example, one that depends on changes in ocean basin volume that may arise from variations in spreading rates are responsible for observed second-order sea level cycles. These also have impacts on climate, ocean circulation and faunal diversity. In the light of increasing awareness about various geological and geophysical events bringing about eustatic and regional sea level perturbations, a globally distributed network of sites is suggested to distinguish the relative importance of each contribution whilst assessing the status of marine transgressions studies in the early 1960s, called for intensive quantitative investigation, since 'considerable implications impinge on the fields of meteorology, geodesy tectonophysics, and stratigraphy' were involved in the studies. More than three decades later, during which explosion of data acquisition techniques had come about, his remarks appear to be still relevant.


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