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Ripple Tectonics—When Subduction Is Interrupted

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Abstract

Subduction plays a fundamental role in plate tectonics and is a significant factor in modifying the structure and topography of the Earth. It is driven by convection forces that change over a >100 Myr time scale. However, when an oceanic plateau approaches, it plugs the subduction, and causes slab necking and tearing. This abrupt change may trigger a series of geodynamic (tectonic, volcanic) and sedimentary responses recorded across the convergence boundary and its surrounding regions by synchronous structural modifications. We suggest that a large enough triggering event may lead to a ripple tectonic effect that propagates outwards while speeding up the yielding of localized stress states that otherwise would not reach their threshold. The ripple effect facilitates tectonic, volcanic, and structural events worldwide that are seemingly unrelated. When the world's largest oceanic plateau, Ontong Java Plateau (OJP), choked the Pacific-Australian convergence zone at ~6 Myr ago, it induced kinematic modifications throughout the Pacific region and along its plate margins. Other, seemingly unrelated, short-lived modifications were recorded worldwide during that time window. These modifications changed the rotation of the entire Pacific plate, which occupies ~20% of the Earth's surface. In addition, the Scotia Sea spreading stopped, global volcanism increased, the Strait of Gibraltar closed, and the Mediterranean Sea dried up and induced the Messinian salinity crisis. In this paper, we attribute these and many other synchronous events to a new "ripple tectonics" mechanism. We suggest that the OJPincipient collision triggered the Miocene-Pliocene transition. Similarly, we suggest that innovative GPS-based studies conducted today may seek the connectivity between tectonic, seismic, and volcanic events worldwide.

Keywords

Plate Tectonics, Subduction-Collision Transition, Miocene-Pliocene Transition

1. Introduction

The evolution of the Earth system is dictated mostly by tectonic and volcanic processes that occur throughout the geological history. These processes take place through events that reshape the Earth lithosphere both at shallow and deep levels and facilitate the occurrence of subsequent tectonic and volcanic events such as ocean opening and closing, periods and regions with extensive seismicity, erosion and sedimentation variations and, in a global perspective, drive the climatic changes. The linkage between the tectonic events and their causative tectonic processes is not straightforward. This linkage usually relies on structural relations, and temporal association, between processes that have spatial affinity. However, to date, an inclusive mechanism linking such processes on a global scale has not been suggested.

The study presented here proposes that the most powerful force in plate tectonics, slab pull, is capable of triggering a chain of tectono-magmatic events that are advanced around the world. The paper discusses the major role of subduction in plate tectonics and asks what happens when subduction (and hence slab pull) is interrupted. To illustrate the chain reaction effect, we first focus on the interruption in the subduction of the largest plate on earth, the pacific plate. We then show how the chocking of the ~3000 km long Melanesian subduction Arc at the southern Pacific Ocean six million years ago, by the arrival of the Ontong Java Plateau, provoked an abrupt global stress change that activated numerous short-lived events. Our new concept links together numerous tectonic and volcanic events with global distribution to a single cause—the disruption of subduction—is presented as a "ripple tectonics" concept in order to inspire a better understanding of the causality between tectonic and volcanic events worldwide and throughout the Earth's geologic history. We hope that the new concept will inspire innovative GPS-based studies that will seek the connectivity between tectonic, seismic, and volcanic events worldwide.

2. Ontong Java Plateau and the Melanesian Arc

Subduction is one of the essential processes in plate tectonics. Slab pull is widely regarded as one of the most powerful forces on Earth [1]. The subduction is closely linked with mantle convection that changes over time scales of >100 Myr [2] [3]. This long-lasting process is accompanied by seismicity, volcanism, and modifications in the stress distribution in the subducting and overriding plates and their surrounding margins. The main question is what happens when the subduction is stalled and even stops. Bercovici *et al.* [3] show that when an oceanic plateau approaches a subduction zone it causes slab necking, which leads to its possible tear along with abrupt continental rebound and rapid changes in plate motion. The larger the plateau/continental crust approaching, the faster and larger is the change and the greater is the global impact.

One of the most interesting case studies to examine this effect is the long-lasting ~120 Myr Pacific-Australian convergence. This convergence along the 4000 km long Melanesian Arc was choked by the arrival of the Ontong Java Plateau (OJP) during the Miocene-Pliocene transition at ~6 Ma (**Figure 1**). The OJP is the world's largest oceanic plateau [4]. Its seafloor expression extends across 2×10^6 km^2, ~2.5 km above the surrounding ocean floor, and its entire 4.27×10^6 km^2 extent covers ~0.8% of the Earth surface [5] [6] [7]. The plateau consists of an exceptionally thick crust associated with volcanism, that drifts along with the Pacific Plate towards the south-west [8] [9]. The arrival of the OJP at the Melanesian Arc severely choked the smooth subduction process [10]. The subduction transformed into a collision of the plateau, while the Pacific slab was torn from underneath. This short-timed disruption occurred during the

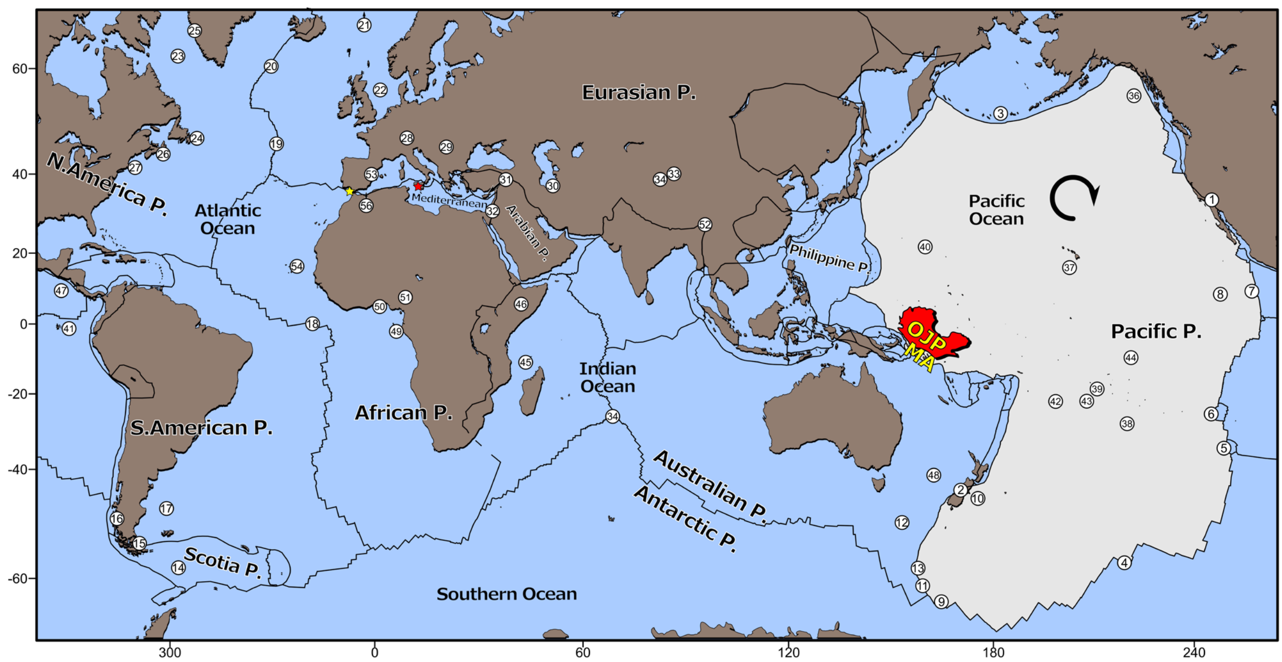

Figure 1. Location of the sites mentioned in the text (numbers surrounding the figure specify geographic coordinates). OJP: Ontong Java Plateau; MA: Melanesian Arc. Numbered locations: 1: San Andreas fault, 2: Alpine fault, 3: Aleutian Arc, 4: Pitman Fracture Zone, 5: Juan Fernandez microplate, 6: Easter microplate, 7: East Pacific Rise, 8: Menard Fracture Zone, 9: Emerald Fracture Zone, 10: Canterbury Basin, 11: Hjort Trench, 12: South Tasman Sea, 13: Macquarie Plate, 14: West Scotia Sea, 15: Magallanes-Fagnano fault, 16: Andean mountains, 17: Argentinian and Malvinas basins, 18: Southern Atlantic spreading, 19: Central Atlantic spreading, 20: North Atlantic spreading, 21: Arctic Ocean, 22: Central North Sea, 23: Labrador Sea, 24: Grand Banks, 25: Western Greenland, 26: Nova Scotia continental shelf, 27: United States Atlantic margin, 28: Alpine arc, 29: Mid: Hungarian line, 30: South Caspian Sea, 31: Cyprus, 32: Dead Sea Fault, 33: Tibetan Plateau, 34: Tengchong volcanic field, 35: Indian Ocean Triple Junction, 36: Bowie seamount, 37: Hawaii hotspot, 38: Macdonald seamount, 39: Tahiti volcano, 40: Caroline chain, 41: Galapagos hotspot, 42: Cook islands, 43: Austral islands, 44: Marquesas islands, 45: Mayotte and Comores Islands, 46: Somali Basin, 47: Bowland and Rosencrans, 48: Tasmantid Seamounts, 49: Annobon Island, 50: Cameroon and Guinea, 51: Biu Plateau and Cameroon Volcanic line, 52: Namjagbarwa and Yuli, 53: Calatrava, 54: Sao Vicente, 56: Alboran Sea.

Miocene-Pliocene transition, at ~6 Myr. It rotated the direction of the Pacific plate motion by 5˚ - 15˚ clockwise relative to hotspots [10] [11], and triggered several short-lived changes across the Pacific plate and its margins. These included a shift in volcanism of the five long-lived, plume-fed hotspots; triggering of "crack spots" that developed as extensional volcanism at preexisting zones of weakness reactivated by Pacific plate stresses transition; tectonic modifications along the Pacific-North American, Pacific-Antarctic and Pacific-Australian plate boundaries such as trench migration and back-arc rifting, transpression at the San Andreas (California) and Alpine (New Zealand) strike-slip faults and Aleutian Arc [12]. While some of these modifications were short-lived, others initiated a cascade of events that persisted through time.

Our hypothesis suggests that the short-lived choking of the Melanesian Arc extended beyond the Pacific plate. It triggered a series of synchronous tectonics events worldwide, which occurred mainly, yet not exclusively, along plate boundaries, during the Miocene-Pliocene transition. Each of these events was on the verge of stress-threshold when the rapid catalyst enabled it to cross-over and yield. Once occurred, these events may have resulted in additional processes such as initiation or cessation of volcanism, basin closure, extensive erosion, and sedimentation. The following paragraphs describe the major events that co-occurred worldwide around 6 Ma. Some of them were gathered in the comprehensive review by Leroux *et al.* [13]. The locations of the sites discussed are shown in **Figure 1**.

3. Ripple Tectonics

In the Pacific region, the Pacific-Antarctic relative motion was disrupted at the end of Chron C3a (6.033 Ma [14]) as recorded by the short-lived 8˚ clockwise rotation of the abyssal hill fabric along the Pitman Fracture Zone [15] [16]; formation of the Juan Fernandez and Easter microplates along the East Pacific Rise (5.25 Ma [17] [18]); trend change in the lineation azimuths of the Menard Fracture Zone, attesting to an increase in the Pacific-Antarctic half-spreading rate [19], and initiation of a propagating ridge system along the Emerald Fracture Zone [20]; and an increase in convergence at the Alpine fault in New Zealand between 8 - 6 Myr, that was accompanied by an increased subsidence of the Canterbury Basin offshore and reversal in its decreasing sedimentation rate [21]. Meanwhile, the subduction across the Hjort Trench, and the ocean crust deformation of the South Tasman Sea are associated with the initiation of the Macquarie Plate as an independent rigid plate around 6 Ma [22]. Further north, a major change in the Philippine plate motion occurred during the Miocene-Pliocene transition [23] [24].

Meanwhile, in the southeast, the opening of the West Scotia Sea ceased at 6 Ma [25]. At the same time (~6 Ma) strike-slip motion along the Magallanes-Fagnano fault system took over the displacement and acted as the western segment of the left-lateral South America-Scotia plate boundary [26] [27]. A phase of drastic increase in the uplift of the southern Andean mountains was recorded at ~6 Ma [28].

In the Atlantic, sedimentation tripled over the Argentinian and Malvinas basins of the southern Atlantic during the Miocene-Pliocene transition [29] [30] and is associated with a decrease in the south Atlantic spreading rate [31]. The drastic decrease around 6 Ma was reported across the southern Atlantic [32] [33], the central Atlantic offshore Iberia [34], and the northern Atlantic [35] [36]. A simultaneous and rapid increase in subsidence occurred across the margins of the North Atlantic and Arctic oceans, in the Central North Sea, the Labrador Sea and Grand Banks, offshore western Greenland, the Nova Scotia continental shelf and the United States Atlantic margin. Cloetingh *et al.* [37] suggest that a regional stress shift causes the simultaneous events.

Further east, the Africa-Eurasia-Anatolia convergence caused compression across the Alpine arc periphery [38]; tectonic inversion along the Mid-Hungarian line [39] [40]; subsidence of the south Caspian Sea [41]; and the uplift and emergence of Cyprus above the Mediterranean Sea Level since the late Miocene [42] [43]. This was accompanied by eastward migration of the Sinai-Arabia rotation pole and an increase in vertical subsidence along the Dead Sea Fault plate boundary [44]. These modifications occurred along with a slight counterclockwise rotation in the absolute motion of the African plate around 6 Ma [45]. This change was accompanied by a decrease in the spreading rate between Africa and its surrounding plates—South and North America as well as India [33].

North of the Indian plate, a rapid exhumation of the southern Tibetan Plateau ~6 - 5 Ma was accompanied by the formation of normal faulting that controlled volcanic eruptions of the Tengchong volcanic field [46]. A major inversion and peak metamorphic recrystallization were recorded across the Himalayan Main Central Thrust [47]. Meanwhile, at the southern margin of the plate, a rapid increase in spreading velocity was recorded around the Indian Ocean Triple Junction with the Antarctic plate around 5 Ma [48] [49].

Evidence for modifications in volcanism was recorded worldwide [50] [51]. Five long-lived hotspot tracks sharply changed their trajectory around approximately at 5 Ma (Bowie Seamount, Hawaii, Macdonald seamount, Tahiti, Caroline Chain [11]). In addition, hotspots rejuvenated in the Galapagos, Cook, Austral and Marquesas islands at 5.9 Ma [52] [53] [54] [55]; Mayotte and Comores Islands, and in the Somali Basin, East Africa at 5.4 Ma; Bowland and Rosencrans, Central Panama at ~5 Ma [56]; Tasmantid Seamounts at ~5 Ma; Annobon Island, Cameroon and Guinea [57]; Biu Plateau and Cameroon Volcanic line [58]. In addition, rare carbonatite rocks emerged between 6 - 5 Ma in Namjagbarwa and Yuli (China), Calatrava (Spain), and Sao Vicente (Cape Verde [59]). Their formation is associated with thermal mantle instabilities [60] and therefore their onset at ~6 Ma indicates a sharp geodynamic transition [13].

One of the most pronounced examples that we ascribe to the ripple tectonic effect is the closure and subsequent opening of the Mediterranean Sea. The tectonic closure of the Mediterranean Sea from the Atlantic Ocean occurred after a long and progressive decline of the roll-back processes in the Gibraltar Arc subduction system, and the opening of the Alboran Sea [61] [62] [63], while the Africa-Eurasia plate convergence vector changed from a N-S direction to a NW-SE one [64]. It was only at 5.97 Ma that the gateway emerged above sea level, closed the Mediterranean, and initiated the Messinian Salinity Crisis (5.97 - 5.33 Ma [65] [66] [67] [68]—one of the most dramatic ecological events in Earth history [13]. The isolation and consequent drop of hundreds of meters in the Mediterranean Sea water level [69] [70] [71] induced massive erosion of the surrounding landmass and reorganization of the marine landscape [13] [65] [72] [73]. The short-lived isolation ended abruptly at 5.33 Ma with the catastrophic Zanclean flooding that incorporated tectonic processes at the Gibraltar area, with the sea-level change, faulting, and gravity-induced slumping [74]. The flooding transgressed inland onto the Mediterranean margins. The abrupt end of the crisis at 5.33 Ma marks the ending of the Messinian age and the beginning of the Zanclean, which defines the Miocene-Pliocene transition [75]-[80].

At the easternmost end of the Mediterranean, the flood progressed into the shallow and elongated Dead Sea Fault valley. Desiccation of these waters yielded a significant thickness of evaporites [81], that in later stages enhances the vertical subsidence of the fault valley [82], facilitated the formation of lakes and formed hospitable environments for waves of hominin dispersal out of Africa [83].

Amongst the tectono-magmatic events linked here with the Melanesian Arc choking, the timing of the Messinian Salinity Crisis is the most accurate. We suggest that the initiation of the Messinian Salinity Crisis at 5.97 Ma marks the timing of Melanesian Arc choking and the initiation of the ripple tectonic mechanism that influenced the Gibraltar area. Hence, the collision of the OJP with the Melanesian arc might have caused the Miocene-Pliocene transition.

4. Conclusion

Although the ongoing tectonic and volcanic activity of the Earth is expected to produce repetitive events, their simultaneous occurrence around 6 Ma could be more than a coincidence. In many localities, worldwide long-lasting stress buildup reached very close to yielding. The chocking of the Melanesian Arc by the arrival of the OJP and the necking and slab tear from underneath induced an abrupt global stress change that activated the short-lived events in these localities. For this reason, these events initiated almost synchronously. The new "ripple tectonics" concept suggested here provides a broad tectonic context for relating seemingly unrelated global events that occurred during other periods. By analyzing the trigger and following events, we can better understand the behavior of the Earth as an intimately interconnected system. The new concept enables GPS-based studies conducted today to seek connectivity between seemingly unrelated tectonic, seismic, and volcanic events worldwide.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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