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EDITED BY
Jackson K. Njau,
Indiana University Bloomington, United States

REVIEWED BY
Sjoerd Kluiving,
VU Amsterdam, Netherlands

*CORRESPONDENCE
Emanuele Lodolo
✉ elodolo@ogs.it

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Did plate tectonic changes lead to the emergence of hominid bipedalism?

Zvi Ben-Avraham[1,2], Joel Rak[3], Gerald Schubert[4], Emanuele Lodolo[5]* and Uri Schattner[6]

[1]Department of Geophysics, Tel Aviv University, Tel Aviv, Israel, [2]Leon H. Charney School of Marine Sciences, University of Haifa, Haifa, Israel, [3]Department of Anatomy and Anthropology, Tel Aviv University, Tel Aviv, Israel, [4]Department of Earth, Planetary, and Space Sciences, University of California, Los Angeles, Los Angeles, CA, United States, [5]Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS), Trieste, Italy, [6]School of Environmental Sciences, University of Haifa, Haifa, Israel

When early hominids began walking upright around 6 Ma, their evolutionary course took a sharp turn. The new posture enabled physical and mental developments that had not been possible before. The factors driving the transition from quadrupedalism to bipedalism remain open. Most studies have linked this fundamental transition to environmental, topographical, geomorphological, and climatic changes that progressively transformed jungle- and forest-dominated areas of southern and eastern Africa into vast savannas, thus partitioning ecological niches. During the same timeframe, major tectonic events occurred worldwide within a relatively short geological period, due to a significant and sudden shift in the motion of the Pacific plate. In our previous work, we coined the term *ripple tectonics* to link a major tectonic impact to the short-term local events it caused worldwide. The ripple tectonic cascade in the Pacific around 6 Ma instigated significant environmental transformations in Africa, which ultimately catalyzed the biological evolution of early hominids towards a bipedal posture.

KEYWORDS

Hominid bipedalism, plate tectonics, East Africa Rift, ripple tectonics, Pacific plate

1 Introduction

1.1 Emergence of hominid bipedalism

During the Miocene-Pliocene transition, about 6 million years ago (Ma), a fundamental change in posture from quadrupedalism to bipedalism took place among hominids in southern and eastern Africa. This new form of upright locomotion enabled key physical and cognitive developments in early hominids that were not previously possible (Harcourt-Smith and Aiello, 2004). Bipedalism triggered a series of anatomical and physiological adaptations that opened new niches for hominids. It facilitated remodeling the trunk, pelvis, knees, feet, and spine to enable efficient upright walking (Latimer and Lovejoy, 1989). These skeletal changes also affected soft tissues, muscles, and the position of organs, enabling endurance running and heat dissipation (Bramble and Lieberman, 2004). Bipedal posture altered the visual field and vocal tract of early hominids (MacLarnon and Hewitt, 1999). In addition, walking upright changed the use of hands and arms, enabling complex tools and gestural communication (Young, 2003).

The earliest evidence for habitual hominid bipedalism dates to around 6–7 Ma based on fossils such as Sahelanthropus and Orrorin from Chad and Kenya (Senut et al., 2001; Brunet et al., 2002). From 4 Ma onward, hominids such as Australopithecus Afarensis and Anamensis were bipedal, as evidenced by remains from sites throughout east Africa like Hadar, Laetoli, and Woranso-Mille (Johanson et al., 1978; Leakey and Hay, 1979; WoldeGabriel et al., 2001). Their new mode of bipedal locomotion allowed these primitive hominids to inhabit diverse environments ranging from forests to grasslands (Coppens, 1994; Reed, 1997). As a result, hominids began spending less time in trees and more time on the ground, traveling and foraging for food.

Bipedalism evolved gradually in response to dynamic environmental pressures and changing hominid lifestyles that altered the availability of food resources and occupational niches (Domínguez-Rodrigo et al., 2008). Several evolutionary hypotheses have been proposed for the origin of bipedalism in hominids related to dietary changes, parental care, and tool use (Lovejoy, 1981; Wheeler, 1984; Jablonski and Chaplin, 1993). However, most evidence suggests a combination of social and ecological factors (Niemitz, 2010).

Fragmentation of forest habitats likely facilitated shifts to more open environments, where upright walking provided an advantage. These modifications are closely related to significant topographic transformations across Africa, as rifting activity produced rugged topography and climatic changes promoted extensive savanna ecosystems that partitioned former ecological niches (Figure 1; King and Bailey, 2006). However, a recent paleoanthropological study conducted on chimpanzees in an east African habitat quite similar to that of early hominids seems to suggest that our early ancestors developed walking in trees and only then adapted it to terrestrial environments (Drummond-Clarke et al., 2022). The question of the driving factors for the transition from quadrupedalism to bipedalism thus remains open.

Here, we propose that *ripple tectonics* served as a driving mechanism that could have rapidly and drastically modified the environment where the hominids lived by altering topography, landscape, vegetation coverage, and localized climatic niches. These radical modifications (e.g., Maslin and Christensen, 2007; Maslin et al., 2014; Ring et al., 2018; Couvreur et al., 2021; Figure 1) created conditions that exceeded the hominids' ability to adapt to. As a result, hominids were forced to adopt a new posture.

1.2 Ripple tectonics

Throughout geological history, tectonic and volcanic processes have built up and reshaped the Earth's interior and surface (Le Pichon, 2019). They have opened oceans, formed mountains and savannas, dictated erosion and sedimentation, and even caused climatic changes (Molnar and England, 1990; Pérez-Díaz and Eagles, 2017). Most studies examining the connectivity between tectonic, seismic, and volcanic events worldwide rely on local and regional structural relationships, spatial proximity, and temporal association. A recent paper proposed a mechanism linking many short-term and synchronous tectonic modifications worldwide to a major event (Ben-Avraham et al., 2020).

A *ripple tectonic* cascade was triggered ∼6 Ma when the largest plate on Earth suddenly changed its course. For millions of years, the Pacific plate, which occupies ∼32% of the Earth's surface, gradually subducted beneath the ∼3,000 km long Melanesian Arc until subduction was choked for a short ∼100 ka (Austermann et al., 2011). The largest oceanic plateau on Earth, Ontong Java Plateau (OJP), located in the southwestern part of the Pacific plate, approached the subduction zone and resisted tectonic downwelling into Earth's mantle (Cox and Engebretson, 1985a,b; Mahoney and Coffin, 1997; Neal et al., 1997). As a result, the Pacific plate rotated 5°-15° clockwise, triggering a swarm of short-lived tectonic, volcanic, and structural events worldwide, such as the separation of the Mediterranean from the Atlantic, the formation of topographic divides, and the formation of ecological niches across continents (Figures 1, 2; citations for the events: Vogt, 1972, 1979; Hsü et al., 1973; Duncan and McDougall, 1974; Ryan and Cita, 1978; Matsubara and Seno, 1980; Leakey, 1981a,b; Hay and Leakey, 1982; Cox and Engebretson, 1985a,b; Sarewitz and Karig, 1986; Bergerat, 1987; Fitton, 1987; Joffe and Garfunkel, 1987; De Ribet and Patriat, 1988; Dewey et al., 1989; Patriat and Parson, 1989; Cloetingh et al., 1990; Pollitz, 1991; Coffin and Eldholm, 1994; Cande et al., 1995; deMenocal, 1995, 2004; Rusby and Searle, 1995; Harrison et al., 1997, 2004; McNutt et al., 1997; Tebbens and Cande, 1997; Csontos and Nagymarosy, 1998; Kempler, 1998; Gutscher et al., 1999; Krijgsman et al., 1999; Ebinger et al., 2000; Krijgsman and Langereis, 2000; Wessel and Kroenke, 2000; Allen et al., 2002; Bruguier et al., 2003; Lodolo et al., 2003, 2013; Bell, 2004; Cande and Stock, 2004; Duggen et al., 2004; Faccenna et al., 2004; Rankenburg et al., 2004; Ben-Avraham et al., 2005; Domínguez-Rodrigo et al., 2005; Eagles et al., 2005; Lu et al., 2005; Tassone et al., 2005; Wang et al., 2007; Croon et al., 2008; Woolley and Kjarsgaard, 2008; White et al., 2009; Cande and Stegman, 2011; Chauvel et al., 2012; Hilgen et al., 2012; Iaffaldano et al., 2012; Baristeas et al., 2013; Colli et al., 2014; Ghiglione et al., 2014, 2016; Ben-Avraham and Katsman, 2015; Maslin et al., 2015; Simon et al., 2015; Balázs et al., 2016; Capella et al., 2017; Macchiavelli et al., 2017; Leroux et al., 2018; Vibe et al., 2018; Rozenbaum et al., 2019). The tectonic and environmental disruption was profound and widespread, but short-lived. It was accepted as a transition between the Miocene and Pliocene. Among the best-known and studied consequences of the ∼6 Ma event is certainly the drying up of the Mediterranean Sea (Hsü, 1983; Garcia-Castellanos and Villaseñor, 2011), as testified by the widespread Messinian salt and gypsum deposits present in many Mediterranean basins.

1.3 Aim of this study

As outlined above, most previous research has linked the emergence of erect posture to climatic changes and the resulting formation of new ecological niches (e.g., Ward et al., 1999). However, the link to global tectonics, particularly the reason for the ∼6 Ma timing, has yet to be determined. We hypothesize that the changes in the geomorphology of Africa - topography and environment - may have developed through continuous, disconnected volcanic and tectonic events as widely described in the literature. In east Africa, plate tectonics forces have progressively transformed a relatively flat, forested region into

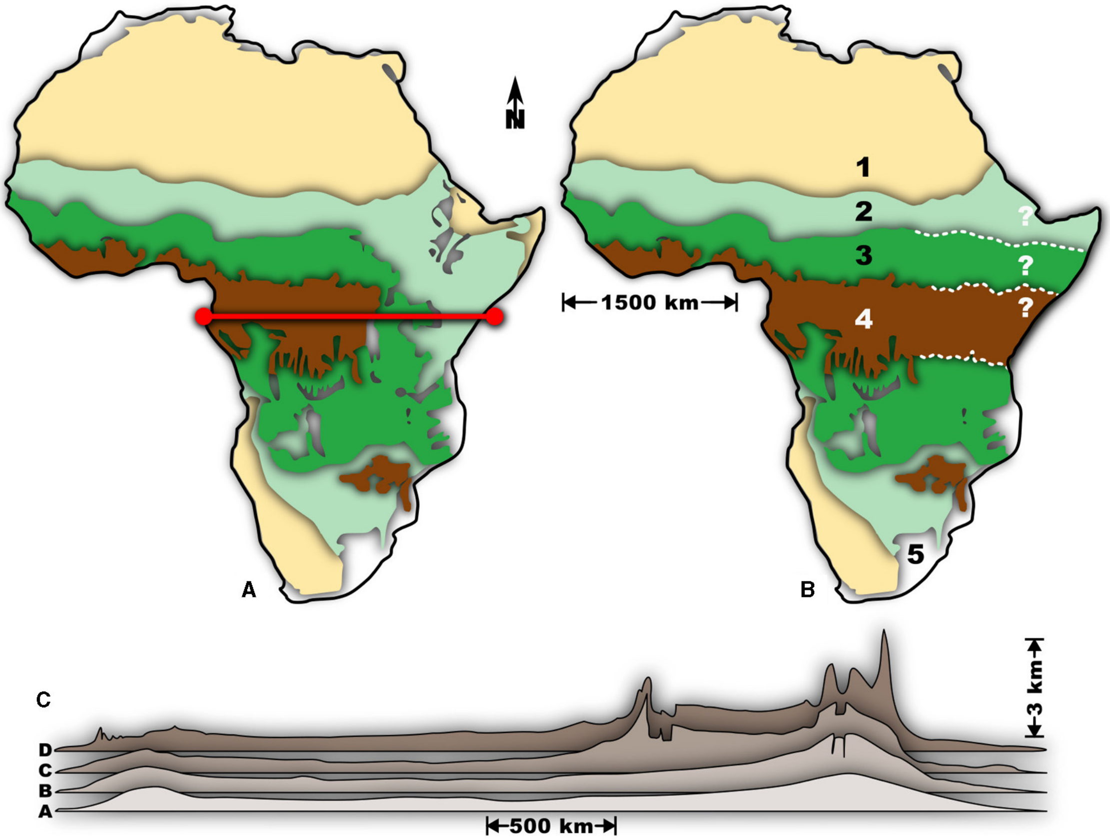

FIGURE 1
(A) Schematic distribution of modern vegetation biomass according to the present topography (after White, 1983; Miller et al., 2016). Red line marks the location of **(C)**. **(B)** Hypothetical distribution of vegetation without the topographic effect, marked by question marks and dashed white lines. 1 - desert/semi-desert, 2 – savanna, 3 – deciduous woodland, 4 - tropical rainforest, 5 – other. **(C)** Topographic profiles, showing the gradual uplift of eastern Africa and its rifts (after Vrba et al., 1995). A - Late Oligocene to mid-Miocene, B – mid-Miocene to Pliocene, C - late Pliocene to recent, D – modern topography.

a mountainous fragmented landscape, dominated by the rapid appearance and disappearance of huge, deep-water lakes and large rift valleys, where vegetation varied from forest to desert scrub. The East Africa Rift bounding mountains prevented moist air from the Indian Ocean from passing over east Africa, causing the region to dry even further.

These geomorphological changes have been triggered by a cascade of transient tectonic and magmatic events worldwide due to a significant Pacific plate rotation (yellow circular arrow in Figure 2). These events altered the topography and landscape throughout Africa, creating an environment suitable for the development in hominids of an erect posture (Figure 1).

If we want to draw a parallel between tectonic events and the consequences for the landscape and climate, we could use the well-known example of the Tibetan Plateau, the highest plateau on Earth with an average altitude of over 4500 m and an area of over 2.5 × 106 km^2. It was formed by the collision between the Indian subcontinent and the Eurasian plate from the early Cenozoic onwards and has played an important role in global atmospheric circulation, from the aridification of inland Asia to the development of the Asian monsoon (Molnar et al., 2010; Wu et al., 2015) and in the evolution of Asian vegetation and fauna (Deng et al., 2019; Spicer et al., 2020).

1.4 Environmental conditions during the emergence of hominid bipedalism

The Miocene-Pliocene transition was accompanied by a sudden global climatic change both in the ocean and on land. The overall uniform warm conditions that prevailed during the Miocene, rapidly cooled to the near-modern climate, with dynamic glaciations in the Northern Hemisphere (deMenocal, 2011; Herbert et al., 2016; Holbourn et al., 2018). This cooling coincided with the widespread reorganization of the terrestrial environments, including the spread of open grassland habitats across broad areas due to declining precipitation and increased aridity (Cerling et al., 1997; Polissar et al., 2019; Wen et al., 2023). One of these environments was the north African Sahara – a Miocene green area that transformed into a hyper-arid desert during the Pliocene, according to palaeobotanical evidence (Micheels et al., 2009; Couvreur et al., 2021). In northern Chad, woodlands fragmented into a mosaic of forested areas and edaphic grasslands (Moussa et al., 2016). Early hominids inhabiting diverse places like Toros-Menalla in Chad adapted to the emerging mosaics of woodland, shrubland, and grassland (Vignaud et al., 2002). Similarly, in the Ethiopian Afar Rift, moisture availability decreased near Australopithecus afarensis fossil sites (Levin et al., 2004).

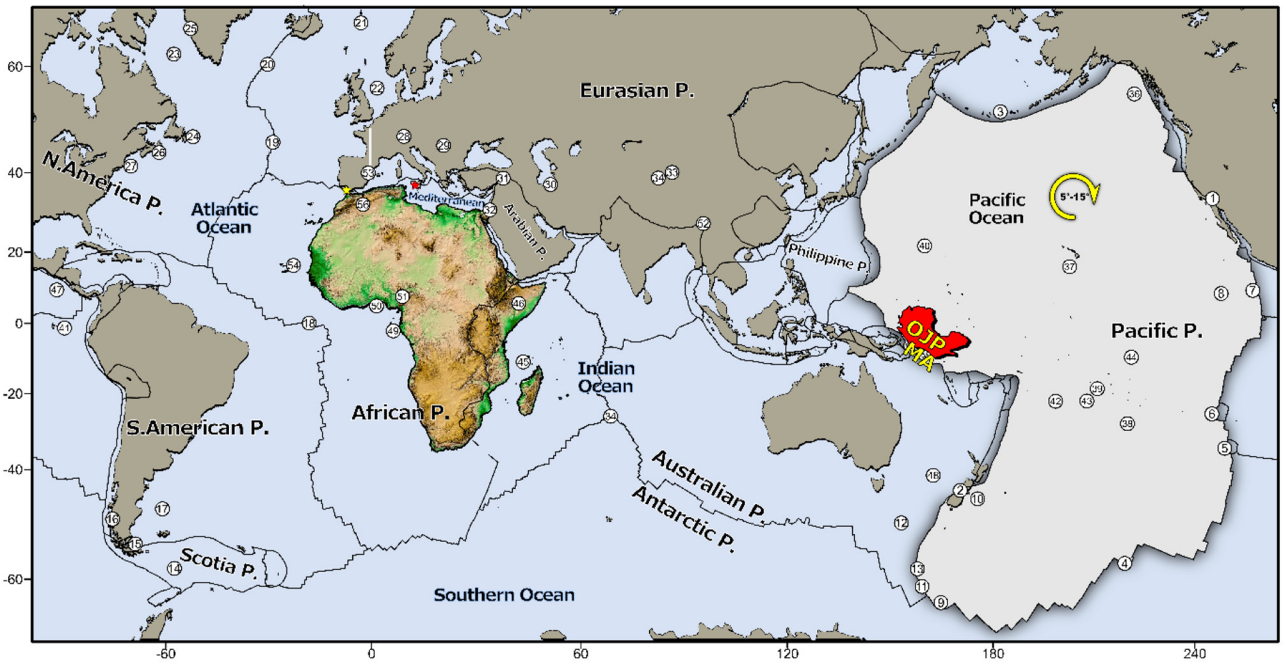

FIGURE 2
Illustration of the *ripple tectonic* concept: collision of the Ontong Java Plateau (OJP) with the Melanesian Arc (MA) choked the ~3,000 km long subduction zone (after Leroux et al., 2018; Ben-Avraham et al., 2020). This resulted in a sudden 5°-15° clockwise rotation of the Pacific plate - largest on Earth. This significant tectonic modification altered stress balance throughout the Earth plate boundaries, triggering 56 short-lived tectonic topographic changes worldwide (numbered). A central modification was the closure of Gibraltar strait (yellow star) that led to the Mediterranean desiccation and the Messinian salinity crisis. The end of the crisis defines the Miocene-Pliocene transition, defined in southern Sicily (red star). Africa's topography was also modified by the same trigger (Africa SRTM topography taken from: www2.jpl.nasa.gov). 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 transform 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.

The co-occurrence of these modifications in the separated niches coincides with the many events listed here.

Some studies linked these climatic changes with declining atmospheric CO_2 levels in the late Miocene (7.5–5 Ma; e.g., Tanner et al., 2020). Other studies have invoked paleogeographic changes (e.g., ocean gateways closure: LaRiviere et al., 2012; Zhang et al., 2014) and regional mountain uplift (Sepulchre et al., 2006) as the main triggers for the overall Miocene-Pliocene cooling.

Coincident with climate changes around 6 Ma, the onset of the East African Rift System led to the uplift of its surroundings, resulting in extensive geological, geomorphological, and habitat changes (Figure 2; Ebinger, 2005). Rifting activity altered drainage and produced rugged terrain in Ethiopia, Kenya, and Tanzania. Freshly formed rift valleys were flanked by fault scarps and active volcanoes, creating habitats for hominids. Sepulchre et al. (2006) and others suggest these changes caused hominids to switch to bipeds as they crossed new savanna areas. For example, at Woranso-Mille in Ethiopia's Afar region, chert deposits indicate that hominids lived near rift lakes and volcanoes (Domínguez-Rodrigo et al., 2008). Early bipeds that roamed these landscapes adapted their postures to traverse the mixed topography of the rifts (Figure 1). Thus, widespread tectonic and volcanic processes reshaped the African landscape and disrupted the dynamic ecological balance as the hominid biped evolved.

2 Tectonic processes working behind the scenes

2.1 Global scale

The collision of the massive OJP with the 3,000 km long Melanesian subduction zone around 6 Ma disrupted the Pacific plate motion and slab pull forces, triggering a ripple cascade of tectonic changes worldwide (Ben-Avraham et al., 2020). The OJP choked the smooth Pacific-Australian subduction, causing slab tearing (Neal et al., 1997; Bercovici et al., 2015). The resulting stress release enabled short-lived geodynamic events at plate boundaries and volcanic centers worldwide (Lodolo et al., 2013; Leroux et al., 2018). A review by Leroux et al. (2018) and later Ben-Avraham et al. (2020) highlighted 56 locations where these events occurred.

Here are some examples of the ~6 Ma tectonic swarm. Spreading rate changes occurred along the Pitman Fracture Zone at the Pacific-Antarctic Rise, while microplate formation was initiated along the East Pacific Rise (Cande et al., 1995; Rusby and Searle, 1995). At the same time, compressional effects propagated along the periphery of the Africa-Eurasia convergent boundary, leading to tectonic inversion along the Mid-Hungarian line, subsidence of the Caspian Sea, and the emergence of Cyprus (Allen et al., 2002; Harrison et al., 2004; Balázs et al., 2016). Further south, the Dead Sea Fault valley experienced enhanced subsidence and evaporite deposition (Joffe and Garfunkel, 1987; Rozenbaum et al., 2019). Rapid exhumation of the Tibetan Plateau and a peak in Himalayan metamorphism also occurred around 6 Ma (Harrison et al., 1997; Wang et al., 2007). These widespread tectonic effects around Africa appear to be linked to the distant reorganization of the Pacific plate through the ripple tectonics mechanism (Ben-Avraham et al., 2020).

A key tectonic response initiated the *Messinian Salinity Crisis* in the Mediterranean region. The Gibraltar subduction zone had been gradually weakening for millions of years, leading to the rollback cessation and opening of the Alboran Sea (Duggen et al., 2004; Faccenna et al., 2004). The rapid release of global stresses from the Pacific enabled the Gibraltar Arc to close completely by 5.97 Ma, interrupting the Atlantic-Mediterranean gateway and lowering the sea level (Hsü et al., 1973; Krijgsman et al., 1999). This triggered the steep 2,000 m sea level drop during the *Messinian Salinity Crisis*, profoundly altering the Mediterranean environment and surrounding niches (Ryan and Cita, 1978).

2.2 Africa scale

Rifting in east Africa, which nucleated in the mid-Eocene and developed throughout the Miocene, intensified ~6 Ma with extensive faulting and volcanism in Ethiopia, Kenya and Tanzania as the continent underwent stretching and thinning (Ebinger et al., 1989; George et al., 1998; MacGregor, 2015; Purcell, 2018; Boone et al., 2019). Rifting produced complex landscapes with rugged valleys, border faults, and active volcanic complexes (Chorowicz, 2005; Maslin et al., 2014). At the same time, the rotation of Africa was accompanied by a lower relative motion between Africa, Europe, India and Arabia (Jolivet and Faccenna, 2000; Cande and Stegman, 2011). The compression propagated along the Alpine and Mediterranean margins, triggering tectonic inversions and orogenic pulses (Carminati et al., 1998; Gelabert et al., 2002). Around the Afar region, the uplift of the Ethiopian and Somali Plateaus occurred, while the main Ethiopian Rift extended southwards (Pik et al., 2003; Bonini et al., 2005; Olaka and Ebinger, 2023). Within the Kenya Rift, strong faulting and subsidence continued, as indicated by sediments in Lake Turkana and the Baringo-Bogoria basins (Morley et al., 1992; Tiercelin and Lezzar, 2002). To the north, increased subsidence and evaporite deposition occurred on the strike-slip Dead Sea Fault (Joffe and Garfunkel, 1987; ten Brink and Ben-Avraham, 1989; Ben-Avraham and Schubert, 2006; Ben-Avraham and Katsman, 2015; Rozenbaum et al., 2019; Segev and Schattner, 2023). By 4 Ma, rifting had progressed through the Main Ethiopian Rift, Kenya Rift, and Afar, creating high relief and lakes (Trauth et al., 2005; Sepulchre et al., 2006). Overall, extensive faulting and volcanic processes resulted in complex rift landscapes across east Africa throughout 6–4 Ma (Africa topography in Figure 2).

3 Concluding remarks

Around 6 Ma, a swarm of major tectonic, climatic, and evolutionary events occurred across the globe. Events such as the closure of the Gibraltar Gateway, enhanced volcanism, extensive faulting, and changing topography reflect reverberations caused by the initial Ontong Java Plateau-Pacific trigger. At the same time, Earth's climate cooled and dried, expanding arid habitats in Africa, while rifting and volcanism persisted in east Africa, generating rugged landscapes. This environmental variability forced new selection pressures on hominid adaptation. Intriguingly, the first evidence of habitual upright walking appears in fossils of Australopithecus and Ardipithecus about ~6 Ma ago, with bipedal posture improving the exploitation of changing mosaic environments. Previous studies linked the emergence of bipedalism to topographic, ecological, and climatic changes in Africa. However, this study links these regional changes for the first time to a global-scale response initiated in the Pacific Ocean with the so-called *ripple tectonic* phenomena. Integrative findings from various disciplines illuminate this critical point in the origin of our ancestors.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

ZB-A: Writing – review & editing, Writing – original draft. JR: Writing – review & editing. GS: Writing – review & editing. EL: Writing – review & editing. US: Visualization, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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