The late Messinian event: A worldwide tectonic revolution

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The late Messinian event: a worldwide tectonic upheaval

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Abstract :

A review of geological and geophysical observations points towards a worldwide kinematic change at around 6 Ma. The synchronicity of many manifestations (tectonics, magmatism, kinematics, ecological events, among others) at ~6 Ma, similar to those recognized from time to time on the geological timescale, argues for a global geodynamic event that has led to many regional consequences on Earth's surface. In particular, we propose that this global event was the main trigger for the three fold increase in sediment deposits in the world ocean over the last ~5 Ma, but also for the onset of the Messinian Salinity Crisis in the Mediterranean area, one of the most severe ecological crises in the Earth's history. We suggest this Messinian revolution to be the last occurrence of cyclic successions of global events.

1. INTRODUCTION

The evolution of the Earth's surface develops through the erosion of rock and redistribution of eroded masses. This is ultimately driven by energy from two sources: (i) tectonics, which contributes to erosion indirectly through uplift; and (ii) climate, which influences erosion and weathering via temperature and precipitation (**Willenbring and Jerolmack, 2016**). The respective importance of tectonics (**Baran *et al.,* 2014; Schlunegger and Mosar, 2011**) and climate (**e.g. Molnar and England, 1990; Peizhen *et al.,* 2001; Willett, 2010; Herman *et al.,* 2013; Fox *et al*., 2015**) on erosional processes is a long-standing question, which has been addressed by many (sometimes controversial) studies. Exact quantification remains challenging, due to the difficulty in isolating the respective roles of climate and tectonics on erosional processes and their feedback that often enhances or obscures the relation between "signal" and "response" (**Fox *et al.*, 2015**).

Regarding this issue, the Late Cenozoic is particularly interesting as there is an ongoing debate on whether rates of surface processes and vertical crustal motion increased or not during the Late Cenozoic in response to climate change. Many authors argue for a significant worldwide increase in the denudation rate since ~6–5 Ma **(Hay *et al.,* 1988; Herman and Champagnac, 2016)** whereas others (**Willenbring and Jerolmack, 2016**) consider a globally steady rate of erosion, weathering fluxes and shelf sediment accumulation during Late Cenozoic mountain uplift and glaciation. This time-span is also marked by a dramatic crisis in the Mediterranean area, the Mediterranean Salinity Crisis **(Hsü *et al.,* 1973),** whose trigger(s) remain(s) debated as a climate **(van der Laan *et al.,* 2012)** or tectonic **(Krijgsman and Langereis, 2000)** consequence.

Published data sets of the past ~250 Myr show several world-wide events, such as mass extinctions, sea-level lows, continental flood-basalt eruptions, mountain-building events, abrupt changes in sea-floor spreading, ocean-anoxic and black-shale events, or large evaporite deposits

(Rampino and Caldeira, 1993). These events present a cyclicity which may be related to the geodynamic changes as illustrated by the dislocation of Pangea in three main episodes: Triassic (185 Ma), Early Cretaceous (125 Ma) and Tertiary (65 Ma), that can also be recognized in the first order of the time distribution of Earth's Magnetic field**,** which suggests the possibility of a link between biological extinction, magnetic reversal, large body impact (**Raup, 1985**) and global kinematic phases (**Moulin and Aslanian, 2010)**.

In this paper, we present a compilation of geological observations, which are in favour of a worldwide kinematic reorganization at around 6 Ma; this Messinian Revolution is highlighted by the global onset of increased sedimentary yields and the regional Mediterranean Messinian Crisis, due to the closure of Atlantic-Mediterranean Sea connections. This reorganization may be the last occurrence of the worldwide geodynamic cyclicity.

2. RESULTS : A WORLDWIDE TECTONIC EVENT 6 Ma AGO

Many (non-exhaustive) observations are compiled in this paper, both in convergent and divergent areas. Some of them may be still a matter of debate, but we argue that the bundle of these observations favors a major tectonic change all over the world at around 5.9 Ma (**Figure 1).**

2.1. Increased relief all over the world around 6 Ma

The compilation of 18,000 bedrock thermo-chronometric ages from around the world and the use of a formal inversion procedure have allowed **Herman *et al.* (2013)** to estimate temporal and spatial variations in erosion rates. Mountain erosion rates have increased over the last six million years and even more rapidly over the last two million years (**Figure 1**). Even if the increase in erosion rates is most pronounced in glaciated mountain ranges, indicating that glacial processes play an important role, it is nevertheless observed at all latitudes.

2.2. Magmatism pulses and carbonatite occurrences at around 6 Ma

A global magmatic pulse since Late Miocene has been reported by **Vogt (1972, 1979)** characterized by a "dramatic Pliocene and Pleistocene increase in volcanic activity". We emphasize here numerous places where hot-spots are rejuvenated 6 Ma ago **(Figure 1),** such as and non-exhaustively on ***(1)*** the Galapagos and ***(2)*** Cook-Austral & ***(3)*** Marquesas Plateaus Eastern Central Pacific **(Duncan and McDouall, 1974; Canadian Hydrographic Service, 1981; Mc Nutt *et al*., 1997; Gutscher *et al.,* 1999; Chauvel *et al.,* 2012)** at 5.9 Ma, on ***(4)*** Mayotte & Comores Islands, Indian Ocean and in Somali Basin, East Africa at 5.4 Ma **(Canadian Hydrographic Service, 1981)** in ***(5)*** Bowland and Rosencrands, Central Panama at 5 **Ma (Coffin and Eldholm, 1994),** on ***(6)*** Tasmantid Seamounts, South Pacific at 5 Ma **(Canadian Hydrographic Service, 1981),** on ***(7)*** Annobon Island, Central Atlantic and in ***(8)*** Cameroon & Guinea **(Fitton, 1987),** on ***(9)*** Biu Plateau & Cameroon Volcanic line, Central Africa **(Rankenburg *et al.,* 2004).** Volcanism re-started later on ***(10)*** Dickins Island, Pratt-Welker Island (Gulf of Alaska) around 4 Ma and on ***(11)*** Mathematician Seamounts, Pacific Ocean at about 3.6 Ma **(Canadian Hydrographic Service, 1981).**

Note, conversely, at the same time, a decrease in ***(12)*** ridge crustal production in Saint-Paul and Amsterdam hotspot, Indian Ocean **(Maia *et al.,* 2011).**

Note also that four occurrences of carbonatite are dated between 6 and 5 Ma: ***(13)*** Yuli (China), ***(14)*** Calatrava (Spain), ***(15)*** Sao Vicente (Cape Verde) and ***(16)*** Namjagbarwa (China), and one more recently at 4 Ma ***(17)*** Main Sadiman (Tanzania) **(Woolley and Kjarsgaard, 2008).** Carbonatite is an igneous rock composed of at least 50% carbonate minerals. Carbonatites are exotic rocks because of (i) their relative scarcity (carbonatite occurrences are rare, even if they are widely distributed) and (ii) their truly unusual composition relative to the vast majority of igneous rocks (silicicate vs carbonate). Their genesis is still poorly understood but carbonatites seem to result from specific Earth processes and their occurrences are sensitive indicators of thermal instabilities in the mantle **(Bell,**

2004). Because they are rare, their onset in several locations at around 6 Ma shows that this period has something specific and might thus suggest deep geodynamic processes such as mantle plumes, asthenospheric upwellings, or crustal delamination.

2.3. Major kinematic and tectonic events at around 5.9 Ma

The Pacific, Indian and Antarctic areas

A significant change in the Pacific–Antarctic motion is reported at the end of Chron C3A (6.033 Ma) **(Briais *et al.,* 2002):** an abrupt (8°) clockwise rotation ***(18)*** in the abyssal hill fabric is observed along the Pitman flowline near the top of chron C3A **(Cande *et al.,* 1995; Hilgen *et al.,* 2012)**; swath bathymetry and magnetic data show that clockwise rotations of the relative motion between the Pacific and Antarctic plates over the last 6 million years resulted in ***(19)*** rift propagation **(Briais *et al.,* 2002)** or in the linkage of ridge segments, with transitions from transform faults to ***(20)*** giant overlapping spreading centers **(Géli *et al.,* 1997; Ondreas *et al.,* 2001).** This kinematic change also initiated the formation of the ***(21)*** Juan Fernandez and Easter microplates along the East Pacific rise **(Tebbens and Cande, 1997).**

Major changes in ***(22)*** Juan de Fuca spreading center occurred between 5 Ma and 3 Ma with large clockwise rotations of spreading axes and fractures zones as well as an overall decrease in spreading rates **(Wilson *et al.,* 1984; Riddihough, 1984).** Sharp changes in direction along many Pacific Hotspot tracks: ***(23)*** Tahiti, ***(24)*** Mokil atoll in the ***(25)*** Carolin chain, ***(26)*** Macdonald seamount, ***(27)*** Hawaii, ***(28)*** Bowie Seamount were also observed **(Cox and Engebretson, 1985)** and evidenced that the motion of the Pacific plate changed to a more northerly direction at 5 Ma. Note that changes along hotspot tracks within the Pacific plate were dated between 5.2 Ma and 3.2 Ma **(Pollitz, 1986).**

Furthermore, **Cande and Stock (2004)** showed that the **(29)** Macquarie Plate region behaved as an independent rigid plate for roughly the last 6 Myr. The onset of the deformation of the South Tasman Sea and the development of the Macquarie Plate consequently appears to have been triggered by the subduction of young, buoyant oceanic crust near the Hjort Trench and coincided with a **clockwise** change in Pacific–Australia motion around 6 Ma. The revised Pacific–Australia rotations would also have implications for the tectonics of the ***(30)*** Alpine Fault Zone of New Zealand.

A change of motion of ***(31)*** the Philippine Sea plate **(Matsubara and Seno, 1980; Sarewitz, 1986)** is also recorded in the Late Miocene/Early Pliocene. Studies of the ***(32)*** Indian Ocean Triple Junction within the Antarctic Plate also demonstrated a profound change in the geometry **(De Ribet and Patriat, 1988)** and a sharper increase in spreading velocity at chron 3A (~ 5 Ma) **(Patriat and Larson, 1989).**

The North Atlantic and Arctic domains

Data analysis of wells in the **(33)** Central North Sea and **(34)** Labrador-Grand Banks and off **(35)** West Greenland, **(36)** Scotian shelf and **(37)** United States Atlantic margin, showed that the margins and basins in the *circum* North-Atlantic and Artic domains exhibit a simultaneous and rapid change in the subsidence rate since the Late Miocene and Pliocene. Given that this latter cannot be explained by the standard thermal model for basin evolution, **Cloetingh *et al.* (1990)** proposed that this subsidence increase is a consequence of stress changes related to the last Neogene kinematic *reorganization.*

Around the Africa Plate

The absolute motion of **(38)** Africa (relative to the hotspots) modelled for the past 30 My **(Pollitz, 1991)** also indicates a change occurring at 6 Ma **(Figure 1)**: "*the difference between the pre-6 Ma and post-6 Ma absolute plate motions may be represented as a counterclockwise rotation from a pole at 48° S, 84° E with angular velocity 0.085°/Myr*". Whilst it is difficult to distinguish absolute motion changes over such short time-intervals, specifically when the movement of the plate is slow, this change is supported by geological evidences along a large portion of the African plate boundary, including **(39)** the Red Sea and **(40)** the Gulf of Aden spreading systems, **(41)** the Alpine deformation zone, and **(42)** the central and southern mid-Atlantic Ridge. Detailed relative motion analysis for the Neogene Africa - Europe plate kinematic seems to show a motion change to a clear north-west convergence after the Tortonian **(Mazzoli *et al.,* 1994)** and a change in motion is observed at the same time in the Pacific and Atlantic **(Schouten *et al.,* 1987),** as well as a decrease in spreading rate in the South Atlantic **(Nürnberg and Müller, 1991).** Since the end of the Miocene, a fan-shaped distribution of directions of compression has developed at the periphery of the Alpine arc **(Bergerat, 1987).** Since the Late Messinian time, a generally E-W to NW-SE shortening affected more or less extensively the Alpine foreland. The manifestations of this motion can be read in the last Miocene deposits such as in the northern Swiss Jura **(Trümpy, 1980)** or in the Pliocene deposits such as in Bresse **(Rat, 1984).** Events at ~5 Ma, including rapid unroofing of the Alborz Mountains **[Axen *et al.,* 2001],** subsidence of the south Caspian Sea **[Allen *et al.,* 2002],** onset of oceanic spreading in the Red Sea **[Joffe and Garfunkel, 1987]** and possible initiation of tectonic extrusion to the east and west of the collision zone **[Axen *et al.,* 2001; Westaway, 1994],** suggest a widespread change in the mechanism by which shortening of Eurasia was accommodated **[McQuarrie *et al.,* 2003]**.

The Mediterranean Sea and the Messinian Salinity Crisis

The **(43)** Mediterranean area underwent a catastrophic event in the Late Messinian (5.97–5.33 Ma): the Messinian Salinity Crisis (MSC). This event is widely regarded as one of the most dramatic episodes of oceanic change over the last 20 million years. It started 5.97 million years ago, when vast amounts of evaporites began to be deposited in the Mediterranean area, leading to a significant drop in Global Ocean salinity **(Adams *et al.,* 1977).** This event left indelible signs in the present terrestrial and marine landscapes through intense erosion associated with a Mediterranean >1000 m sea-level drop **(Clauzon, 1982; Bache *et al.,* 2009)** and the accumulation of large volumes of detritic **(Lofi *et al.,* 2005; Gorini *et al.,* 2005; Leroux *et al.,* 2017)** and evaporitic rocks, mainly gypsum and halite **(Hsü *et al.,* 1973; CIESM, 2008).**

As introduced by **Pérez-Asensio (2013),** “the general consensus is that the Mediterranean was isolated from the Atlantic due to the closure of the Betic and the Rifian Corridors (Strait of Gibraltar) and that this led to deposition of the Lower and Upper Evaporites. There are still key issues under intense debate. One of these concerns the main mechanisms that led to the isolation of the Mediterranean. Global glacioeustatic sea level lowering, regional tectonic uplift in the Gibraltar area, or a combination of both processes have been invoked as trigger mechanisms **(Weijermars, 1988; Kastens, 1992; Aharon *et al.,* 1993; Butler *et al.,* 1999; Duggen *et al.,* 2003; Hilgen *et al.,* 2007)**. This longstanding debate can be largely attributed to the (i) complex Messinian paleogeography of the Mediterranean area associated with a variety of local tectono-sedimentary regimes, to the (ii) continuing problem of accurate correlation between both deep basin and marginal-basin deposits”, but also to the (iii) discrepancy of accurate chronology between the (high resolution) global climate record **(Pérez-Asensio *et al.,* 2013**; **Ohneiser *et al.*, 2015**; **van der Laan,2012**) and the relatively (rough) global tectonic record. If the link between astronomical forcing **(Van der Laan *et al.,* 2012)** or Antarctic glacio-eustatic contributions **(Ohneiser *et al.,* 2015, Jiménez-Moreno *et al.,* 2013)** to Late Miocene Mediterranean dessication and reflooding have been clearly demonstrated, detailed tectonic processes closing the Rifian Corridor began now to be accurately defined. Several recent data suggest that the last Mediterranean-Atlantic gateway in function, the Rifian Corridor, was closed significantly before the onset of the MSC. **Krijgsman and Langereis (2000)** demonstrated that a shallowing phase, primarily related to active tectonics (although a small glacio-eustatic sea-level lowering also took place), was initiated between 7.2 and 7.1 Ma. Their magnetostratigraphic study indicated that, at least, the Taza-Guercif Basin (Marocco), and perhaps the entire Rifian Corridor, became emerged at an age between 6.7 and 6.0 Ma, while **Ivanovic *et al.* (2013)** refined the age of closure to 6.64–6.44 Ma. **Capella *et al.* (2017**) proposed also that a “thick-skinned tectonics, related to a change in the regional deformation linked to plate convergence, but also possibly coupled with deep lithospheric or dynamic topography processes” would have closed the Rifian Corridor and would have ultimately led to the MSC.

2.4. Other ecological changes

The origin of the ***(44)*** Amazonian rainforest of present-day dimensions (on the passive continental margin of South America and the Amazonian basin) remains enigmatic. It must be set at the Late Miocene, and, as underlined by **Mörner (2016),** "its establishment implied the withdrawal of enormous quantities of water from the global hydrological cycle", that occurred "at the same time as the drastic increase in evaporation leading to the Messinian salinity crisis in the Mediterranean."

The signature of a major ecological change can also be read in the carbonate platform development. Sediment architecture in the ***(45)*** Bahamian platform during the last 6 Ma is "not only a response to sea-level fluctuations, but also a major paleo-oceanographic and climatic change" **(Reijmer *et al.,* 2002).** Among these worldwide ecological changes, **Aranciba *et al* (2006)** also dated the onset of present-day hyper-aridity in the ***(46)*** Atacama Desert (Northern Chile) around 5 Ma, while the process of drying and desertification in the ***(47)*** Taklimakan Desert (one of the largest desert and driest places of the Asia interior) started to accumulate terrestrial sediments in a dry land environment at the latest by ~4.2 Ma **(Sun *et al.,* 2011).**

We showed that rejuvenated volcanism, reorientation of transform fracture zones, carbonatite deposits, significant relief change, and major ecological crisis (such as the MSC) occurred synchronously in different oceans and continents. The temporal match between all these manifestations is evidenced at around 6 Ma within the limits of resolution. Indeed, whereas the global climate record and the beginning of the MSC benefits from an accurate chronology (we refer here to the chronology of **Hilgen *et al.,* 2012**), the global tectonics or magmatism are characterized by a relatively rough chronology. However, the "synchronicity" we are talking about here results from many "rough" observations whose ages unavoidably include uncertainties that are dependent of the nature of the event considered. Whatever they are, the Late Miocene-Pliocene boundary corresponds to a time of enough major global changes to wonder about the causal linkage between all of them. How can we relate these observations together and explain them?

3. DISCUSSION:

The Messinian revolution as one of the major cyclic geodynamic events

Deep Earth and tectonic processes shape ocean structure and material transfer at the largest of scales. Earth's surface features, on land and at the ocean floor, are intimately related to dynamics of the Earth's interior. Large-scale topographic features, such as seafloor spreading ridges, plateaux, mountain ranges, cratonic basins, pediments, and alluvial/fluvial systems are the product of numerous parameters interacting in various ways: tectonic heritage, lithospheric and mantle segmentation, vertical and lateral crustal movements, mantle convection, heat fluxes, lithospheric composition, the presence of fluids, and even the core's dynamo. Despite the profound influence of these parameters on Earth's surface features and the societies that inhabit them, the complex nature of their interaction has left critical gaps in their understanding.

Periodicities in biological and geological events have already been recognized from many geological datasets such as: (i) biological extinctions **(Raup and Sepkoski, 1984; Raup, 1984; Sepkoski, 1989; Lieberman and Melott, 2007; Melott and Bambach, 2010)**, (ii) terrestrial impact cratering **(Matsumoto and Kubotani, 1996),** (iii) flood basalt and onsets of Large Igneous Provinces **(Rampino and Caldeira, 1993),** (iv) climate and (vi) sea-level oscillations **(Zachos, 2001; Miller *et al.,* 2005; Müller *et al.,* 2008)**, (vii) sedimentation **(Myers and Peters, 2011),** (viii) changes in seafloor spreading **(Rampino and Caldeira, 1992; 1993),** global kinematic revolution connected with first order magnetic inversions pattern **(Aslanian and Moulin, 2010),** and, (vii) oceanic anoxic events **(Rampino and Caldeira, 1992; 1993).** Although the exact cyclicity is still a matter of debate, the synchonicity of major geological (and some biological) events is striking **(Raup, 1985).**

Whilst no LIP pulse is observed for the 6–5 Ma period, some authors, as **Vogt (1972, 1979),** have already suggested a global magmatic pulse since the Late Miocene. A magmatic pulse is also recognized at the Late Miocene from the pan-Mediterranean igneous provinces **(Sternai *et al.,* 2017).** As we show, this period is marked by a worldwide peak of magmatic event with reactivation of the activity in a large number of volcanic plateaux, dormant for a long period of time. At the same time, which is marked by a major kinematic event all over the world and a worldwide increase in reliefs, occurrences of very rare events such as carbonatites appear in different parts of the world. Based on these observations, we propose that this period, that we call the Messinian revolution, is the latest occurrence of the cyclic global revolution of the Earth. The occurrences of carbonatite suggest deep geodynamic processes such as mantle plumes, asthenospheric upwellings, crustal delamination, deep mantle convection. The link between major kinematic events and first order cyclicity of the magnetic inversions suggests even deeper connexion and, for instance, **Pal and Creer (1986)** ascribed spurts of geomagnetic reversals to enhanced core turbulence during episodes of meteorite bombardment. Due to the large scale of these processes, as well as the technical challenge of their study, our global understanding of Ocean–Earth Interactions remains in its infancy and this subject is far beyond this paper. But the Messinian revolution occurred 60 Ma after the Tertiary one, which occurred 60 Ma after the Cretaceous one right at the beginning of the Cretaceous Normal (also called Calm) Magnetic Period, and confirms at least a global periodicity of 60Ma and the causal-link between very deep and surface processes at a global scale.

4. CONCLUSION

The bundle of events of different kinds that we have presented, advocates for a global geodynamical event at 6 Ma, that we proposed to call the Messinian Revolution. This global event, that we propose to be the last occurrence of a cyclic global event series, has led to many secondary or regional consequences on Earth's surface that could be revisited with that new point of view, such as the increased sedimentation in basins due to the increased erosion rates in mountain belts, or the onset of the Messinian Salinity Crisis in the Mediterranean area, one of the most severe ecological crises in the Earth history, due to the presence of the Strait of Gibraltar.

FIGURE CAPTION :

Figure 1: Compilation of numerous (and non-exhaustive) observations testifying major tectonic changes throughout the world around 6–5 Ma. Locations of uplift/exhumation rate changes, rejuvenated volcanism (and carbonatite deposits) and kinematic events at that time are superimposed on the map. Red lines represent the present-day ridges surrounded by the 6 Ma isochrons, such that the area between the two outer lines is the ocean floor created since 6 Ma. Dotted red lines correspond to aborted ridges (without any relation with the 6 Ma global event). See text and references for further explanation. Topography and bathymetry from satellite data (Sandwell and Smith, 1997).

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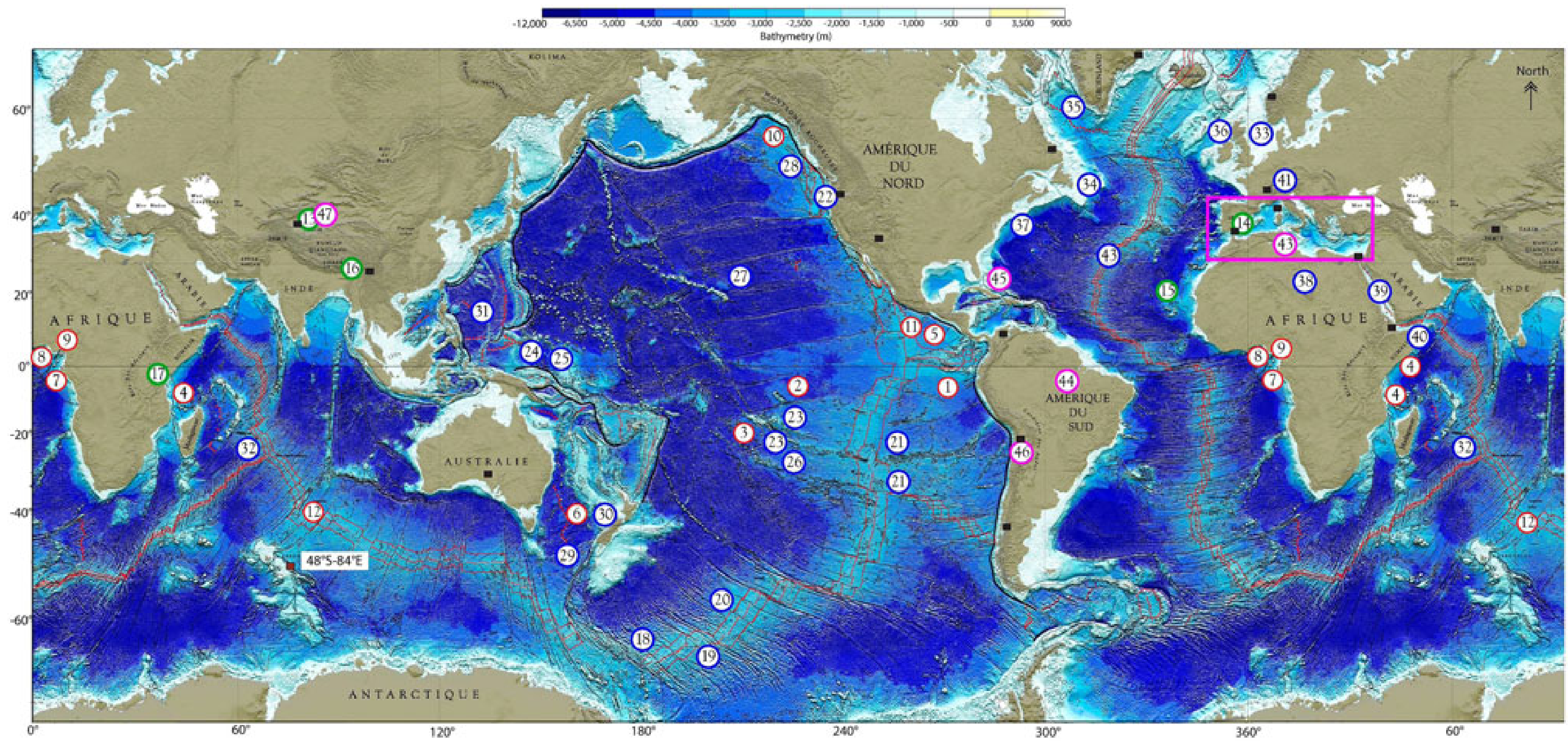

-12,000 -6,500 -5,000 -4,500 -4,000 -3,500 -3,000 -2,500 -2,000 -1,500 -1,000 -500 0 3,500 9000
Bathymetry (m)
North
AMÉRIQUE DU NORD
AMÉRIQUE DU SUD
AFRIQUE
ARABIE
INDE
AUSTRALIE
ANTARCTIQUE
48°S-84°E
60°
40°
20°
0°
-20°
-40°
-60°
0°
60°
120°
180°
240°
300°
360°
60°

INCREASED RELIEF

■ location of increased relief area since 6 Ma[32]

MAGMATISM

Rejuvenated Magmatism (5.9 Ma-5 Ma)

1. Galapagos (Eastern Central Pacific) [12]
2. Cook Austral (Central Pacific) [49]
3. Marquesas plateau (Central Pacific [12,16,24,29])
4. Mayotte & Comores islands & Somali Basin (Indian Ocean) [12]
5. Bowland & Rosencrands (Central Panama)[20]
6. Tasmantid Seamounts (South Pacific)[12]
7. Annobon Island (Central Atlantic)[12]
8. Cameroon & Guinea (Central Africa)[25]
9. Biu Plateau & Cameroon Volcanic line (Central Africa)[65]

Rejuvenated Magmatism (4 -3.6 Ma)

10. Dickins & Pratt-Welker Islands (Gulf of Alaska)[12]
11. Mathematicians Seamounts (Pacific Ocean)[12]

Decrease in the ridge crustal production

12. Saint-Paul and Amsterdam (Indian Ocean)[44]

CARBONATITE

13. Yuli (China), age: 6 Ma-5 Ma[90]
14. Calatrava (Spain), age: 6 Ma-5 Ma[90]
15. Sao Vicente (Cap Verde), age: 6 Ma-5 Ma[90]
16. Namjagbarwa (China), age: 6 Ma-5 Ma[90]
17. Main Sadiman (Tanzania), age: 4 Ma[90]

Some Ecological events

44. Onset of the Amazonian rainforest of present-day dimensions[52]
45. Change in sediment architecture in the Bahamian platform[70]
46. Onset of present-day hyper-aridity in the Atacama desert[4]
47. Onset of present-day hyper-aridity in the Taklimakan desert[79]

KINEMATICS

Major reorganizations in the Pacific-Antarctic & Indian plates around 5.9 Ma

18. Abrupt clockwise rotation along the Pitman fracture zone (South Pacific)[13]
19. Rift propagators or linkage of ridge segments (Pacific plate)[10]
20. Initiation of giant overlapping spreading centers (Pacific)[27,56]
21. Formation of the Juan Fernandez and Easter microplates (East Pacific Rise)[80]
22. Changes (rotation and spreading rate) in Juan de Fuca spreading center (Pacific)[89, 71]
23. Sharp change in the direction along Tahiti hotspot track (Pacific)[21]
24. Sharp change in the direction along Mokil Atoll hotspot track (Pacific)[21]
25. Sharp change in the direction in the Carolin Chain hotspot track (Pacific)[21]
26. Sharp change in the direction in the MacDonald Seamount hotspot track (Pacific)[21]
27. Sharp change in the direction in the Hawaii hotspot track (Pacific)[21]
28. Sharp change in the direction in the Bowie Seamount hotspot track (Pacific)[21]
29. Change in the rheologic behaviour of the Macquarie Plate (South-Western Pacific)[14]
30. Change in tectonics of the Alpine Fault Zone of New Zealand[14]
31. Change of motion of Philippine Sea Plate[45,72]
32. Profound change in the geometry of the Indian Ocean Triple Junction with sharp increase in spreading velocity[22]

Major reorganizations in the Atlantic and Arctic domains around 5.9 Ma

33. Induced subsidence increase along Central North Sea (North Atlantic)[19]
34. Induced subsidence increase along Labrador Grand Banks (North Atlantic)[19]
35. Induced subsidence increase off West Greenland (North Atlantic)[19]
36. Induced subsidence increase along Scotian shelf (North Atlantic)[19]
37. Induced subsidence increase along US Atlantic margin (North Atlantic)[19]

Change in the Absolute motion of Africa relative to North America and Pacific plates

38. Change in the absolute motion of Africa relative to the hotspots[62] ■ Location of the rotation pole[62]
39. Geological evidences in the Red Sea (African plate boundary)[62]
40. Geological evidences in the Gulf of Aden spreading sytems (African plate boundary)[62]
41. Geological evidences in the Alpine deformation zone (African plate boundary)[62]
42. Geological evidence in the Central and Southern Mid-Atlantic Ridge (African plate boundary)[62]

Catastrophic event

43. Messinian Salinity Crisis (whole Mediterranean Area)[1, 6, 17, 18, 28, 35, 41, 43]