Late Cenozoic global pulsations in hotspot magmatism and their possible interplay with plate tectonics, Earth's core and climate

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A study of the Earth's main hotspots indicates an increase in magmatism during the last 1.5 myr, supporting a previous hypothesis on global magmatic co-pulsation on c. 10 myr scale through the Cenozoic. A similar pattern is found for magmatism dominantly related to plate tectonics since 15 Ma. It is suggested that the inferred syncronicity in magmatism is related to two large areas under Africa and the central Pacific expressing anomalously slow *S*-wave velocities in the lower mantle. Heterogeneous heat flux in the fluid outer core related to the lower mantle anomalies may cause spatially related aspherical inner core growth and rotation of the inner core with respect to the lower mantle. It is speculated that the heterogeneous heat flux in the outer core can be modulated by inner core processes of aspherical growth and rotation on 10 myr scale, subsequently leading to syncronized plume pulses from the rim of the hot lower mantle anomalies. Some of the magmatic pulses appear to coincide with abrupt drops in eustatic sea level, and it is suggested that these were caused by glaciations triggered by the volcanism.

Keywords: Climate, hotspot magmatism, hotspot pulsations, mantle plumes, plate tectonics.

TECTONO-magmatic observations on the Earth are generally interpreted within the plate tectonics or mantle plume theories respectively[1,2]. Plate tectonics refers to dominantly upper mantle convection leading to construction and destruction of lithospheric plates, whereas mantle plumes causing hotspots on the Earth's surface may dominantly originate from the deep mantle. Although the basic concepts of both theories are fairly well developed, the interaction between the two remains poorly understood.

Both plate tectonics and mantle plume are strongly related to magmatism, and its variation in space and time may hold the key to reveal the link between the phenomena. Mjelde *et al.*[3] presented evidence on Cenozoic co-pulsation of mantle plumes originating from the deep mantle. Spectral analysis indicated a dominant period at about 10 myr (10, 22, 30 Ma, etc.) and predicted another pulse at present[3]. The main objective of the present study is to test this hypothesis. Furthermore, the Late Cenozoic hotspot magmatism will be compared with plate tectonics magmatism in order to identify any link between the two phenomena. It will be shown how the observations possibly might be linked to processes in the Earth's core. Finally, the interaction between magmatism and climate will be discussed.

Hotspot production rate is obtained using a combination of the following methods: crustal thickness estimates from wide-angle seismic data[4–6], hotspot swell flux[7–9], age of oceanic magnetic anomalies[10,11] and radiometric dating[12]. The article follows the methodology described in detail in Mjelde *et al.*[3].

Results

Magmatic events for the studied hotspots since 5 Ma

Mjelde *et al.*[3] estimated the magmatic variations in hotspots during the period 70–2 Ma (Figure 1). Their results for the late Cenozoic indicated a magmatic peak at 10 Ma, and a weaker peak at 4 Ma (Figure 2). In the following, the same hotspots will be investigated with regard to possible magmatic events during the last 5 myr, for 0.5 myr intervals. In view of the uncertainty of the method (± 0.2 myr), one cannot expect to resolve more than one event per hotspot in this period, in addition to the 4 Ma peak.

The St Helena hotspot reveals a steady increase in magmatic production during the last 5 myr (ref. 9). Cape Verde and the Canaries show an increase in magmatism since about 3 Ma, but it is likely that the peak occurred at 0.5 Ma (refs 13–17). The Madeira Province shows the same trend, with increasing magmatism since 3.5 Ma, probably reaching a peak at about 1 Ma (ref. 18).

One of the Earth's most active hotspots, Hawaii, recorded roughly a doubling of magmatism since 5 Ma (refs 8, 19). The magmatic production at the Hollister Ridge, which most likely represents the present location of the Louisville hotspot, is modest, but appears to have increased from about 3 Ma (ref. 20). The same applies to the more active Easter hotspot, which may have reached a

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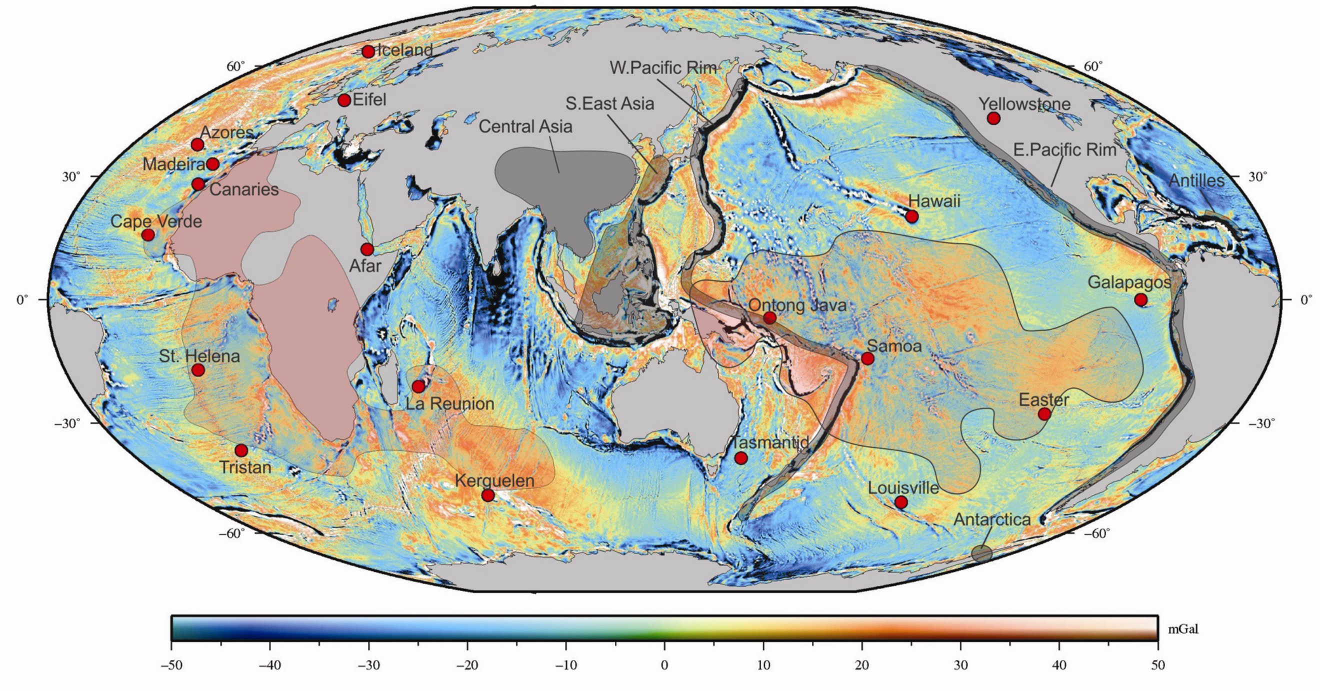

Figure 1. Ocean gravity map with present-day locations of studied hotspots indicated by dots. The Eifel hotspot is shown as example of the widespread European magmatism[134]. See Hillier[135] for location of Pacific seamounts. Shaded areas show locations of the Pacific and African lower mantle shear wave anomalies (2850 km) depth[136]. The studied non-hotspot magmatic areas are also indicated.

peak in magmatism at about 1 Ma (refs 21, 22). Also, the Samoan hotspot has recorded increased magmatic activity during the last few million years (myr)[23–25].

The most active hotspot in the Indian Ocean, the La Réunion hotspot, shows an increase in magmatism since 3 Ma (refs 26, 27). The same applies to the Kerguelen hotspot[28].

Also the Yellowstone hotspot appears to have increased it activity since 3 Ma, but the magmatic peak may have been reached at 1 Ma (ref. 29). The magmatic productivity for the remainder of the studied hotspots appears to have been relatively stable for the last 3 myr. No sign of decrease has been inferred for any of the hotspots studied. The reader is referred to Mjelde *et al.*[3] for a full list of references concerning all hotspots.

Figure 3 provides a summary of the present findings. After the broad magmatic peak at about 4 Ma (ref. 3), the magmatism decreased to a minimum at about 1.5 Ma. Thereafter, a clear increase in magmatism is observed, leading to significantly enhanced hotspot productivity in the last 5 myr.

Non-hotspot related magmatic events since 5 Ma

The study of magmatism dominantly related to plate tectonics is based on the same methods as used for the hotspot-related magmatism. The global study has been divided into the following areas: East Pacific Rim, West Pacific Rim, Central Asia, Southeast Asia and the Antilles (Figure 1). Table 1 lists the references used in this study and the results are summarized in Figure 4 for each area, as well as globally. The global sum (Figure 4 *f*) also includes two studies from Antarctica providing one count at 1, 0.5 and 0 Ma respectively[30,31]. Figure 4 shows that all areas shows a first-order increasing trend since 5 Ma. Harangi *et al.*[32] reviewed the subduction-related magmatism in the Alpine–Mediterranean region, which shows no clear evidence of increase or decrease since 5 Ma. It should also be noted that the seafloor production rate at spreading ridges appears to have decreased steadily by about 10% during the last 20 myr (ref. 33).

Discussion

Co-pulsation of Cenozoic hotspot magmatism

The hotspot-related magmatism during the last 2 myr has been plotted in Figure 2 at 1 myr intervals in order to allow direct comparison with the older part of the time curve. Plotting with this interval removes the apparent, and probably insignificant, local minima at 0.5 Ma (Figure 3). It is likely that the increase in magmatism continues at present. These results appear to confirm the c. 10 myr periodicity in magmatism, as inferred by Mjelde *et al.*[3]. Note that the results of Mjelde *et al.*[3] have been modified slightly, by moving one count from 18 to

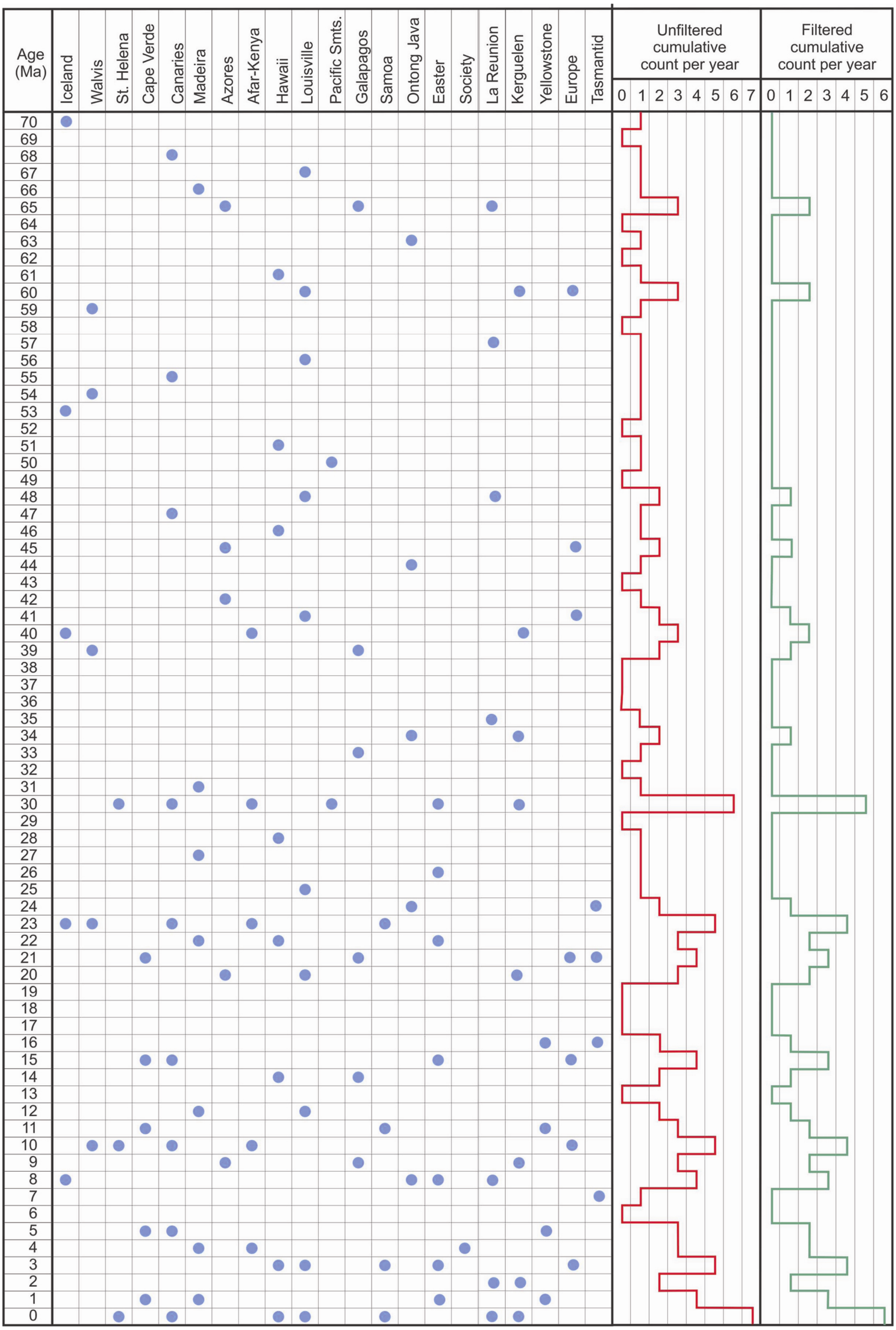

Figure 2. Variation of Cenozoic magmatism related to the hotspots studied. Pulses of magmatism are indicated with blue circles. The red column shows (unfiltered) cumulative count per Ma for all hotspots, whereas green column shows the filtered version where one count has been subtracted for each Ma. The curve from 70 to 2 Ma is from Mjelde *et al.*[3], whereas 1–0 Ma represents the present study.

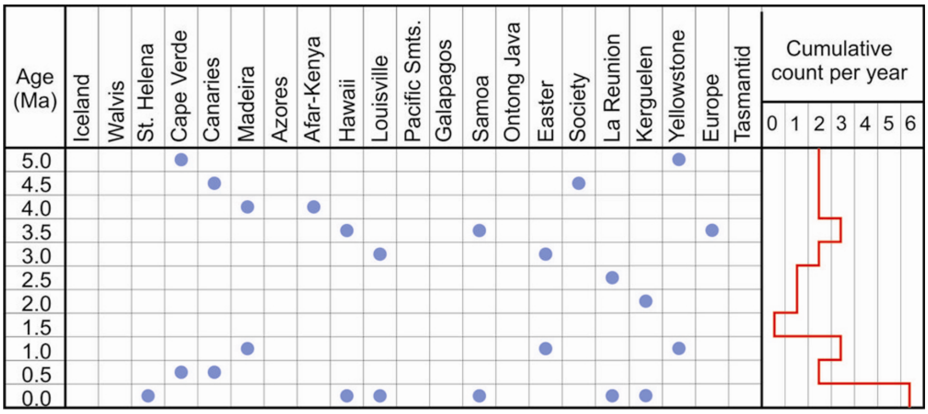

Figure 3. Same as Figure 2 (right column) during the last 5 myr, for 0.5 myr intervals.

Table 1. References related to the non-hotspot magmatic study

East Pacific Rim
California: Refs 66–70
Alaska: Ref. 71
Mexico: Refs 72–80, 137
Andes: Refs 81–100
West Pacific Rim
Fiji: Ref. 101
New Zealand: Refs 102–106
Kamchatka: Ref. 107
Izu-Bonin, Japan: Refs 108–110
Southeast Asia
Philippines: Refs 111–114
Taiwan: Refs 115–117
New Guinea: Ref. 118
S. Korea: Ref. 119
Indonesia: Refs 120–121
Central Asia: Refs 122–129
Antilles: Refs 130–133
Antarctica: Refs 31–32

16 Ma based on new results from Yellowstone[34]. Similarly, new dates from the Hawaiian-Emperor chain have induced the following changes[35]: the dating of Suiko seamount has been moved from 65 to 61 Ma, Koko from 50 to 51 Ma, and Diakakuji from 42 to 46 Ma.

Miocene–present non-hotspot magmatic events

Figure 4 shows that the increasing trend in magmatism since 5 Ma exists for all the studied areas. For the East Pacific Rim and Central Asia, the histograms may suggest a slight secondary increase from about 2.5 Ma. The local peak in magmatism at about 0.5 Ma is not real, as the last column covers only 250 kyr.

These results refine and corroborate the work of Kenneth *et al.*[36], who documented a circum-Pacific volcanic event from 2 Ma to the present. Their conclusions were based on a compilation of the number of radiometric dates reported for terrestrial volcanic sequences and the number of volcanic ash horizons recorded by deep-sea drilling. A correlation was found between activity in the southwestern Pacific, Central America and the Cascade Range of western North America. Furthermore, these authors documented similar volcanic events at 16–14 Ma, 11–8 Ma and 6–3 Ma. The mid-Miocene (18–13 Ma) and the most recent event (5–0 Ma) were elaborated by Cambray and Cadet[37]. These events correspond to the magmatic peaks since 15 Ma shown in Figure 2. The Late Cenozoic event (after 3 Ma) has also been documented from the dating of volcanic ash layers in the Atlantic[38].

Hotspot versus non-hotspot magmatism: interaction and causality

Mjelde *et al.*[3] concluded that it is unlikely that the observed global variations in magmatic productivity for hotspots can be explained by differences in lithospheric thickness, fluctuations in intraplate stress levels following plate tectonic reorganizations and/or interaction with spreading ridges. Instead they related the observations to two large areas under Africa and the central Pacific expressing anomalously slow *S*-wave velocities in the lower mantle[39] (Figure 1). Most of the studied hotspots are located near the edges of these anomalies[40], indicating that the hotspots are sourced predominantly from the deepest mantle. The faster regions in the lower mantle have been suggested to dominantly contain colder subducted material in slab graveyards[40,41]. Numerical experiments have shown that plumes are expected to form near the intersection between the different lower-mantle reservoirs[40,42]. The dynamics in the lowermost mantle may be strongly related to the different properties of perovskite, located within the hot regions and post-perovskite that may exist within the colder regions[43].

Anderson[44] noted the relationship between subduction and the African and Pacific anomalies, and argued that subduction was the main driving force (top-down causality). On the other hand, Potter and Szatmari[45] argued that

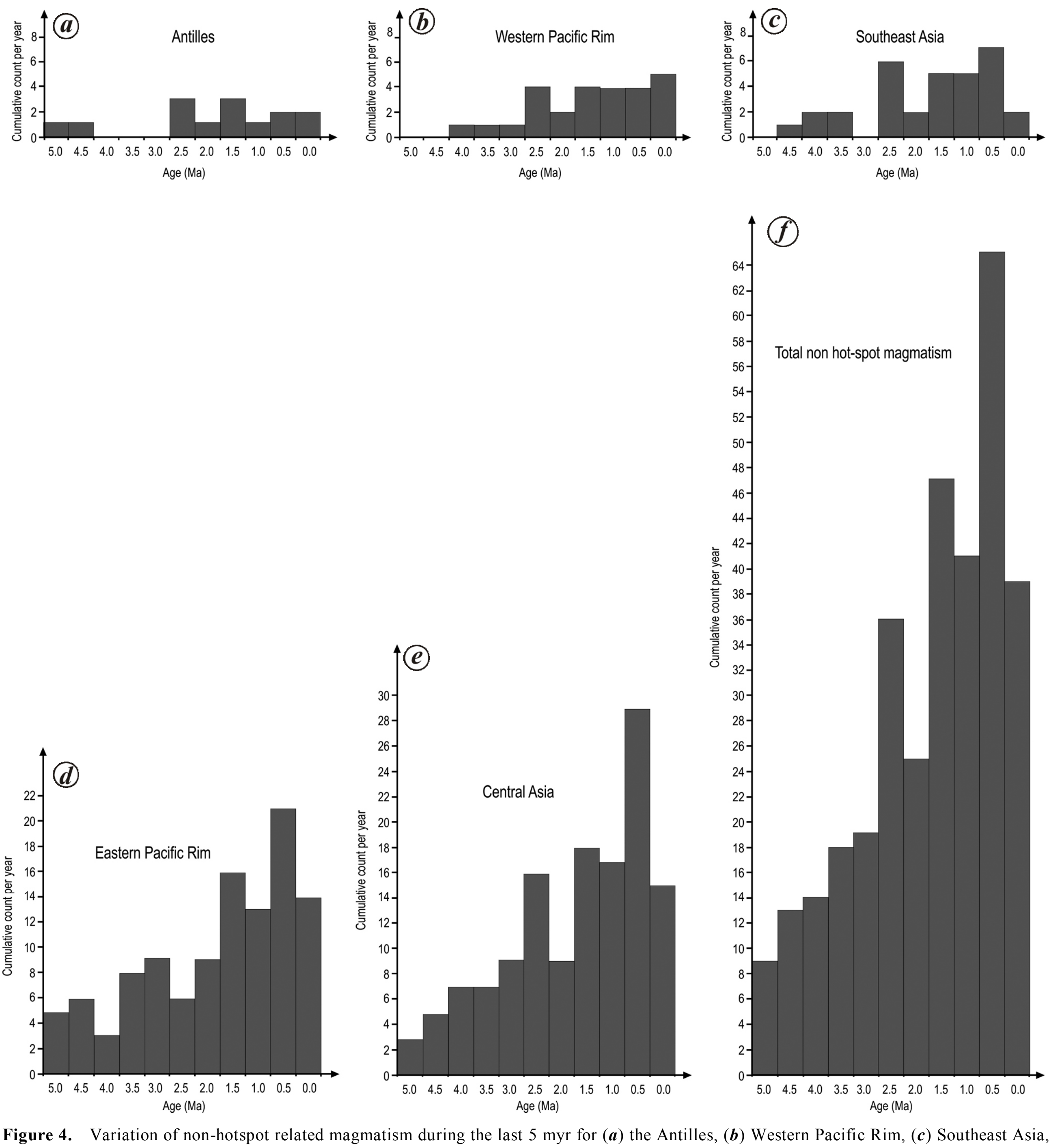

Figure 4. Variation of non-hotspot related magmatism during the last 5 myr for (***a***) the Antilles, (***b***) Western Pacific Rim, (***c***) Southeast Asia, (***d***) Eastern Pacific Rim, (***e***) Central Asia and (***f***) sum of (***a***)–(***e***).

the main plate tectonics changes since mid-Miocene are driven by renewed heat flow from the African and Pacific anomalies (base-up causality).

The similar increasing trend in hotspot and non-hotspot magmatism since 5 Ma (Figures 2 and 4) and the apparent syncronicity in magmatic events since mid-Miocene might suggest a common cause. The remaining variations in magmatism expressed in Figures 2 and 4 can be related to complexities in the interaction with the lithosphere, as well as differences in magma-generating processes at upper mantle/lithospheric levels for hotspot and non-hotspots regions.

It is possible that syncronized slab avalanches into the lower mantle might occur, but since these slabs are already detached from their corresponding subduction zones, it is unlikely that they could cause syncronicity in surface magmatism as discussed by Mjelde *et al.*[3] and further elaborated here. The new results from the present study are in favour of the base-up causality, implying syncronized pulses from the rim of the African and Pacific lower mantle anomalies. The resulting pulses in hotspot magmatism will induce stress on the corresponding lithospheric plates, which subsequently might be transferred to the non-hotspot magmatic regions discussed here. The continental break-up in the North Atlantic represents an example of such stress transfer, in that the break-up induced by the Icelandic Plume[11] caused an apparently simultaneous kink in the motion of the Eurasian Plate[46]. This interpretation is supported by studies of non-hotspot magmatism around the Pacific Rim, where volcanic pulses were related to variations in the tectonic stress regime of the arc lithosphere, not changes in subduction rate[37].

Core–mantle interaction

The hot lower mantle regions extract less heat from the fluid outer core than the colder regions. This heterogeneous heat flux can maintain convective structures in the outer core, causing spatially related aspherical inner core growth[47]. This pattern of aspherical growth is compatible with measurements of inner core seismic anisotropy and attenuation[48]. Large-scale deformations of the inner core may also be caused by Joule heating related to the magnetic field[49]. This process implies fluid motion in the inner core and mass exchange through the inner core boundary.

The interpretation of Aubert *et al.*[47] requires a small rotation of the inner core with respect to the lower mantle. The rotation is assumed to be caused by surface stresses at the inner core boundary induced by a mean eastward flow in the fluid outer core, counteracted by a gravitational torque caused by misaligned inner core topography and density anomalies in the mantle[50]. The present-day inner core rotation rate has been estimated from different seismological methods, and the results vary from zero to about 1°/yr (ref. 48). The gravitationally driven rotational rate at 50°/myr (one rotation in about 7 myr) estimated by Dumberry[50], is of the same order of magnitude as the rate of magmatic pulsing discussed here (about 10 myr). It is possible that the heterogeneous heat flux in the outer core can be modulated by inner core processes of aspherical growth and rotation on 10 myr scale, subsequently leading to plume pulses from the rim of the hot lower mantle anomalies. If this hypothesis is correct, it implies that the observation of 10 myr pulsations can be used as a constraint in testing various geodynamical models for inner core growth and rotation.

It is also possible that the pulsations might be related to a nuclear fission chain reactor at the center of the Earth's core. Herndon[51] discussed the feasibility of a georeactor consisting of an inner subcore of radioactive elements, surrounded by a shell with decay products. If present, it is likely that such a georactor will lead to fluctuating heat production[52], and thereby mantle plume pulsations.

Interaction between volcanism and glaciations

Sea-level changes reflect evolution from the existence of ephemeral ice sheets in Antarctica from about 100 to 33 Ma, large ice sheets in Antarctica from 33 to 2.5 Ma, to a state of a large ice sheet in Antarctica and variable northern hemisphere ice sheets from 2.5 Ma to the present[53]. The existence of feedback mechanisms between glaciations and volcanism is well documented[54]. In this section, a possible link between the magmatic pulses (Figure 2) and sea-level changes will be discussed.

The increase in volcanism after the last glaciation at 12 kyr is particularly well documented in Iceland, where a 30-fold increase in lava production at the onset of the Holocene has been reported[55]. The ice unloading may enhance volcanism due to stresses induced above shallow magma chambers, accumulated magma may be released from decreased overburden pressure, or increased decompression melting in the mantle may occur[55]. On the other hand, Bay *et al.*[56] argued that volcanism documented in Antarctica triggered millennium timescale cooling observed in Greenland, while Prueher and Rea[57] suggested that explosive volcanic eruptions in the Kamchatka–Kurile and Aleutian arcs triggered the mid-Pliocene onset of northern hemisphere glaciations. The cooling effect from volcanism has been documented from studies of the 1991 Mount Pinatubo eruption[58]. These authors estimated the emission of aerosols from this eruption to half a degree Celsius for about a year at the Earth's surface. The mutual influence between glaciation and volcanism may in some cases lead to syncronization[59].

Ice unloading cannot explain the inferred co-pulsation of hotspot magmatism, since only Iceland, Europe, Kerguelen and Yellowstone have been strongly influenced by glaciations[54]. On the other hand, more than half of the non-hotspot areas studied have been covered by Quaternary ice sheets. These are: Alaska, California (partly), Andes (partly) for the East Pacific Rim, New Zealand and Kamchatka for the West Pacific Rim, as well as Central Asia and Antarctica. Figure 5 shows data from Figure 4 sorted into glaciated and non-glaciated areas. The two curves show the same trend, documenting that the increase in magmatism cannot be caused by interaction between volcanism and local ice sheets.

Figure 6 shows the eustatic sea-level curve of Haq *et al.*[60]. The first-order fall in sea level from Late Cretaceous (85–270 m higher than today) can be primarily attributed to a slow decrease in seafloor production rate from about 5 to 3 km^2/yr, caused by a decrease in the average spreading rate[61]. A second important influence

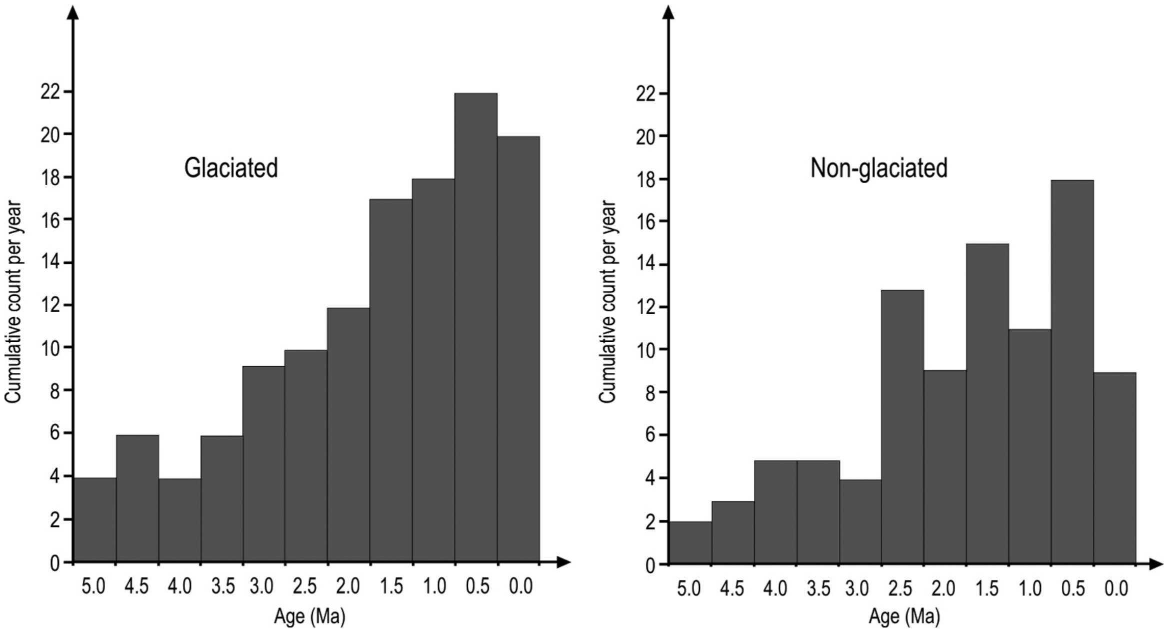

Figure 5. Same as Figure 4 sorted into glaciated (left) and non-glaciated (right) areas.

from plate tectonics through the Cenozoic was the closing of four equatorial deep-water gateways and opening of three polar gateways, altering the global heat transfer from a Greenhouse to an Icehouse world[45].

Sea-level changes related to glaciations can be related to orbital forcing on 10 and 100 kyr scale, but eustatic changes with periods of 3 and 6–10 myr, as documented by Miller *et al.*[53], have defied explanation. In Figure 6, these events appear as large sea-level drops followed by a 3–5 myr long period of slight sea-level increase. Such events are identified at 40, 30, 21 and 11 Ma, which is coincident with the main magmatic pulses discussed in this article. The inferred syncronized magmatic pulsations since 15 Ma cannot be related to glaciations, since large changes in sea level have contrasting effect on coastal and island volcanoes. Finite-element analysis indicates that a 100 m fall in sea level will reduce radial compressive stresses by 1 MPa for island volcanoes thereby favouring expulsion of stored magma, whereas a rise in sea level of 100 m is needed in order to reduce compressive stresses near a coastal volcano by about 0.1 MPa (ref. 62). Based on this it is suggested that the 10 myr period sea-level falls were triggered by volcanism, causing glaciations due to the cooling effect from the emission of aerosols. Such components are removed from the atmosphere within a few years after each eruption, whereas CO_2 released from magmatism may induce more steady warming[54], explaining the 3–5 myr periods of sea-level increase after the abrupt drops. Significant amounts of CO_2 may be released gradually from cooling magma (e.g. Yellowstone)[63] and ice sheets may form an impermeable layer over such passive emission regions inhibiting CO_2 release during glaciations[54].

Huybers and Langmuir[54] showed that the feedback between volcanism and glaciations was consistent with fluctuations of about 40 ppm atmospheric CO_2 concentrations, similar to magnitudes inferred from ice core observations. Pagani *et al.*[64] estimated a strong decrease in atmospheric CO_2 concentrations from 1000 to 1500 ppm in middle Eocene to modern levels (300 ± 100 ppm) at about 25 Ma (Figure 6). The Early Cenozoic decrease in CO_2 concentrations may be partly related to plate tectonic reorganizations, forming the Eurasian-Himalaya mountain belt[45]. This orogenic rejuvenation caused increased continental erosion and chemical weathering, thereby reducing the atmospheric CO_2 content[65]. In addition, the decrease in seafloor production rate would reduce the CO_2 output from ocean ridge volcanoes.

Uncertainties

A statistical analysis of the Cenozoic hotspot curve (Figure 2) suggests that the apparent co-pulsation might be statistically insignificant (S. Howell and E. Gaidos, pers. commun.). This does not imply that the co-pulsation hypothesis is falsified, but suggests that more data points are needed to allow robust statistical analyses to be performed. The hotspot curve is a result of a variety of measurements with different uncertainties, which are difficult to assess.

It is recommended that future sampling and dating of magmatic rocks are related to estimates of magmatic production. In parts of the present-day literature it is difficult to verify if a magmatic age peak is related to a true magmatic pulse, or whether it is primarily a function of

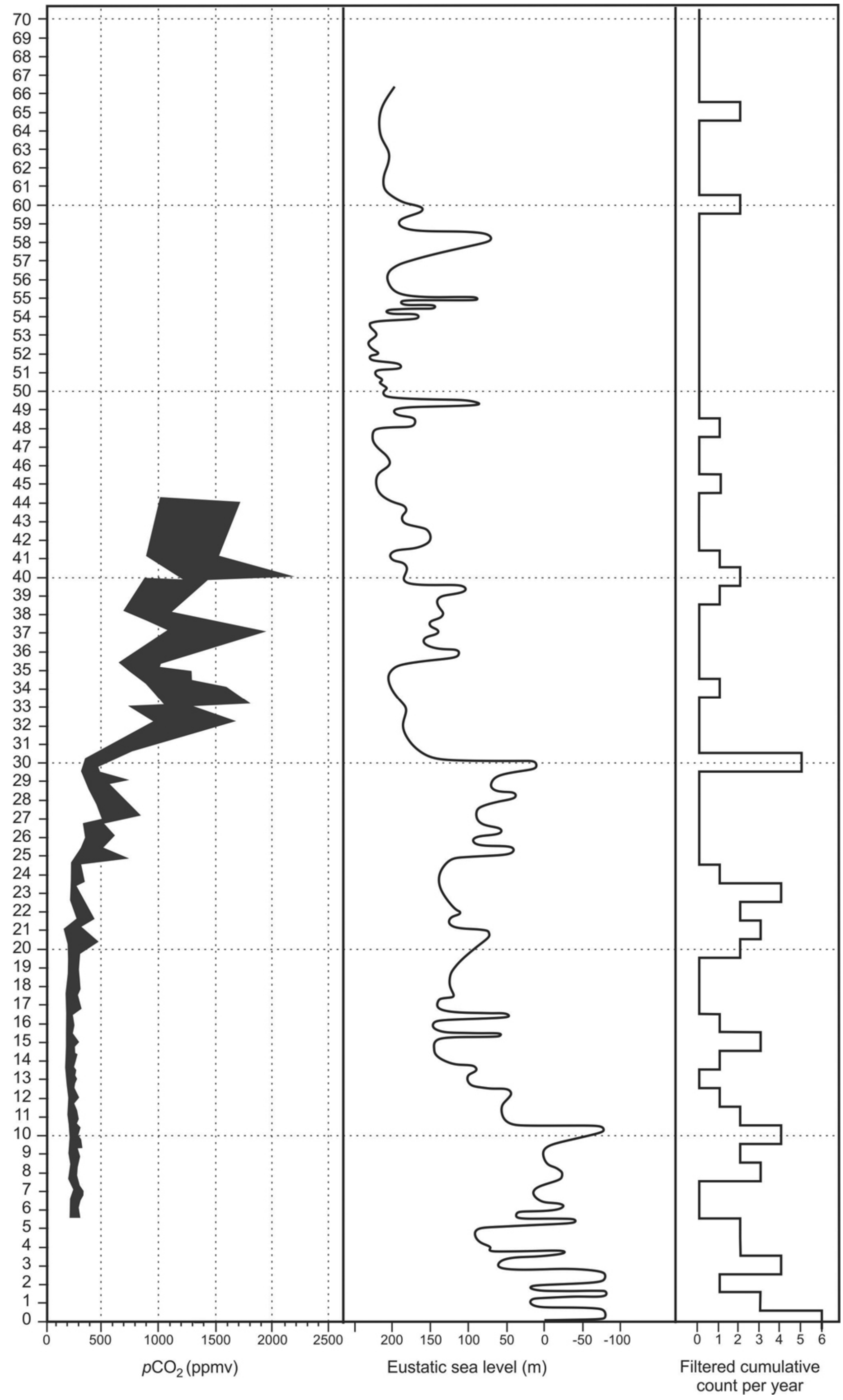

Figure 6. (Left) Atmospheric CO_2 concentrations from Pagani *et al.*[64]. (Middle) Eustatic sea level curve from Haq *et al.*[60]. (Right) Variation of Cenozoic magmatism related to the hotspots studied (same as Figure 2, right column).

logistic accessibility to exposed rocks. The co-pulsation hypothesis is strengthened by the analysis of the non-hospot magmatism since 15 Ma.

Conclusion

The Earth's main hotspots have been studied with regard to variations in magmatism during the last 5 myr. A magmatic peak appears at present, supporting the c. 10 myr copulsation hypothesis discussed by Mjelde *et al.*[3]. A study of magmatism dominantly related to plate tectonics at the East Pacific Rim, West Pacific Rim, Central Asia, Southeast Asia and the Antilles, indicates the same pattern of co-pulsation since 15 Ma.

These observations are related to two large areas under Africa and the central Pacific expressing anomalously slow *S*-wave velocities in the lower mantle. Most of the studied hotspots are located near the edges of these anomalies, indicating that the hotspots are sourced predominantly from the deepest mantle. It is proposed that syncronized pulses from the rim of lower mantle anomalies will induce stress on the corresponding lithospheric plates, which might be subsequently transferred to the non-hotspot magmatic regions.

The hot lower mantle regions extract less heat from the fluid outer core than the colder regions. This heterogeneous heat flux can maintain convective structures in the outer core, causing spatially related aspherical inner core growth. This interpretation requires a small rotation of the inner core with respect to the lower mantle. It is speculated that the heterogeneous heat flux in the outer core can be modulated by inner core processes of aspherical growth and rotation on 10 myr scale, subsequently leading to plume pulses from the rim of hot lower mantle anomalies. If this hypothesis is correct, it implies that the observation of 10 myr pulsations can be used as a constraint in testing geodynamical models for inner core growth and rotation.

The magmatic pulses at 40, 30, 22 and 10 Ma appear to coincide with abrupt drops in eustatic sea level followed by 3–5 myr long periods of slight sea-level increase. The inferred syncronized magmatic pulsations cannot be related to glaciations, since large changes in sea-level have contrasting effect on coastal and island volcanoes. It is thus suggested that the 10 myr period sea-level falls were triggered by volcanism, causing glaciations due to cooling effect from the emission of aerosols. Such components are removed from the atmosphere within a few years after each eruption, whereas CO_2 released from magmatism may induce more steadily warming, explaining the 3–5 myr periods of sea level increase after the abrupt drops.

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