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Environmental impact of volcanic margin formation

Olav Eldholm [a] and Ellen Thomas [b]

[a] *Department of Geology, University of Oslo, N-0316 Oslo, Norway*
[b] *Center for the Study of Global Change, Department for Geology and Geophysics, Yale University, New Haven, CT 06511, USA*

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ABSTRACT

Late rift stage uplift and subsequent massive, transient volcanism during breakup of rifted volcanic continental margins constrain paleoenvironments by modifying basin geometry and the composition of the atmosphere, hydrosphere and thus biosphere on regional and global scales. The early Tertiary North Atlantic breakup history shows that lava emplacement was accompanied by regional ashfalls, and that extrusive complexes influenced Paleogene oceanic and continental margin circulation and sedimentation. Temporal correspondence with the terminal Paleocene deep-sea extinction event and the earliest Eocene greenhouse suggests a global impact, possibly by enhanced atmospheric CO_2 levels, leading to polar warming and thereby changing patterns of deep-water formation. In this context, transient subaerial volcanism at continental margins should be considered with the much discussed continental flood basalt provinces and oceanic plateaus.

1. Introduction

Large-scale transient geological events in the earth's history have influenced paleoenvironments by changing oceanographic and atmospheric circulation patterns and compositions. The marine environment responds to plate tectonic events causing breakup of continents, and the establishment of gateways is well documented in the sedimentary record [1]. Similarly, the effects of transient magmatic events such as emplacement of large volumes of flood basalts have been postulated as being associated with major biotic changes or extinctions [2,3], although time control has commonly been poor.

Continental breakup may be accompanied by massive, transient volcanism resulting in rifted volcanic continental margins [4,5]. Together with continental flood basalt and oceanic plateaus, these margins comprise a series of large igneous provinces (LIPs) characterized by emplacement of voluminous basaltic lavas over short time spans [6]. Breakup and initial accretion of new crust on volcanic margins, however, occur in a tectonomagmatic setting different from that of nonvolcanic margins, and may have had important paleoenvironment consequences. Scientific drilling and extensive geophysical surveys in the North Atlantic Ocean have provided environmental boundary conditions not recognized previously, and calculations of magma volumes and rates show that the transient igneous pulse during the early Tertiary opening of the North Atlantic represents a major geologic event [6,7].

This report investigates the impact on regional circulation and sedimentation as well as possible effects on the global environment from this geologic event.

2. North Atlantic gateways

The opening of the North Atlantic (used for the basins between Charlie-Gibbs Fracture Zone and Fram Strait (Fig. 1); the Norwegian–Greenland Sea north of Greenland–Faeroe Ridge constitutes the northernmost North Atlantic) created the main gateway between the Arctic Ocean and the world's ocean for both deep and surface waters [e.g., 8]. It established the present circulation pattern, connecting the polar basins of both hemispheres, through the contiguous Atlantic Ocean, in which the Norwegian–Greenland Sea is a major source of North Atlantic Deep Water. Thus, the evolving basin configuration created a

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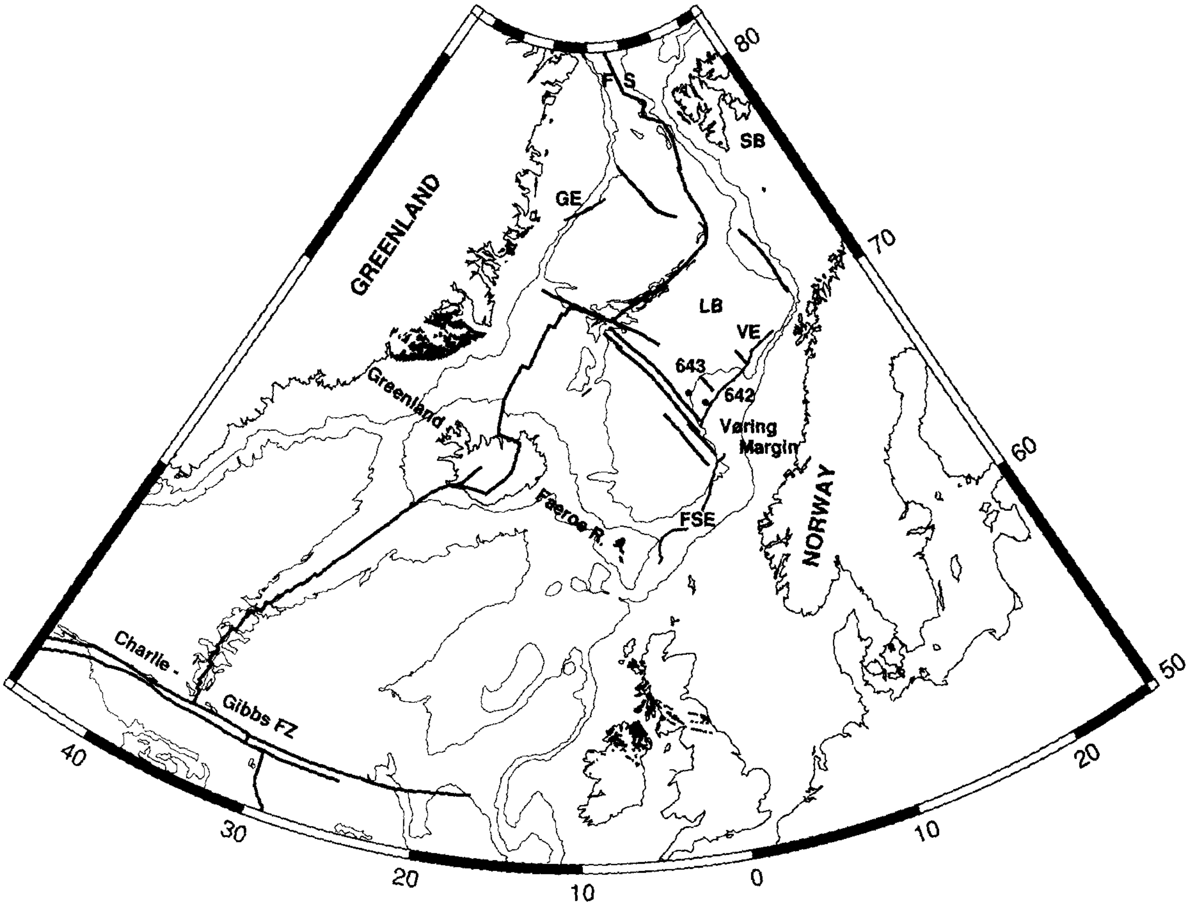

Fig. 1. North Atlantic bathymetry (500 and 2000 m contours), early Tertiary onshore igneous rocks (black), present plate boundary and fracture zones (heavy lines) and location of ODP Sites 642 and 643. Margin escarpments: *GE* = Greenland; *VPE* = Vøring Plateau; *FSE* = Faeroe-Shetland. *FS* = Fram Strait; *LB* = Lofoten Basin; *SB* = Svalbard.

hydrographic regime which has not only governed northern hemisphere climate but also had an impact on the deep-water exchange globally. The North Atlantic, and the Norwegian-Greenland Sea in particular, is therefore an excellent laboratory for studying the interaction of tectonomagmatic events, during opening and sea floor spreading, and paleoenvironment. The circulation is, however, governed by a strong basin segmentation, particularly during Paleogene times. The division into a number of sub-basins is primarily caused by the plate tectonic evolution and the igneous pulse during early opening.

The plate tectonic fragmentation is caused by offsets in the initial plate boundary, a two-stage opening of the Norwegian-Greenland Sea and local migration of the ridge axis [e.g., 9]. In particular, the delayed continental separation in the Fram Strait region and the elevated trail of the Iceland plume, the Greenland-Faeroe Ridge (Fig. 1), formed major Cenozoic water mass barriers. This setting must have restricted the ventilation of intermediate and deep-water masses between the Norwegian-Greenland Sea sub-basins throughout the Paleogene. Although this effect diminished as the ocean widened and deepened, a circulation system similar to that of the present can only be traced back through the late Miocene [9].

3. Transient breakup pulse

The transient breakup pulse, or volcanic margin formation, had near-field (North Atlantic)

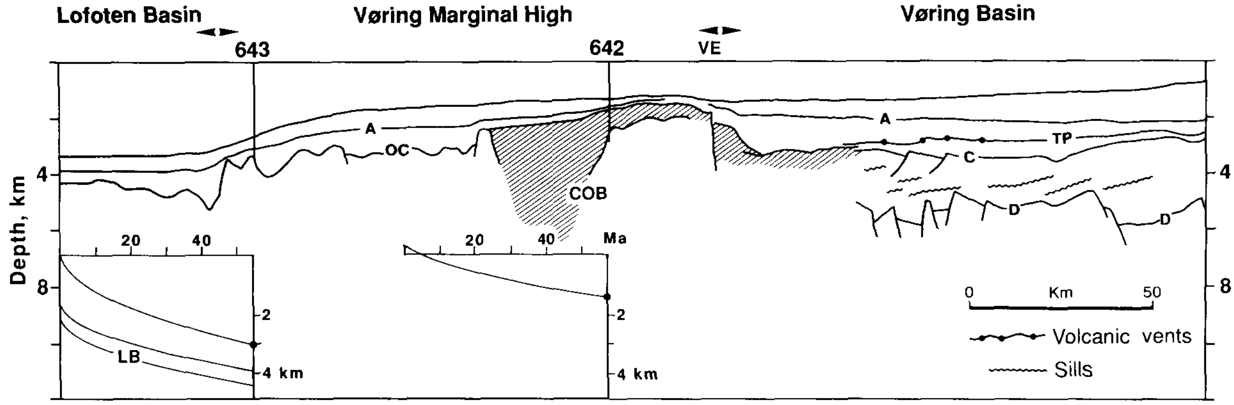

Fig. 2. Profile through ODP Sites 642 and 643 (Fig. 1), respectively near the top and on the outer flank of the Vøring marginal high. The profile shows flood basalts (shaded) and the influence of the marginal high on Paleogene sedimentation. The subsidence, corrected for sediment load, of the two sites [4] is indicated with reference to subsidence curves for normal oceanic crust in the Lofoten Basin (*LB*). *D* = near-base Cretaceous; *C* = base Tertiary; *TP* = near-top Paleocene; *A* = lower Miocene; *OC* = oceanic crust; *COB* = continent–ocean boundary; *VP* = Vøring escarpment.

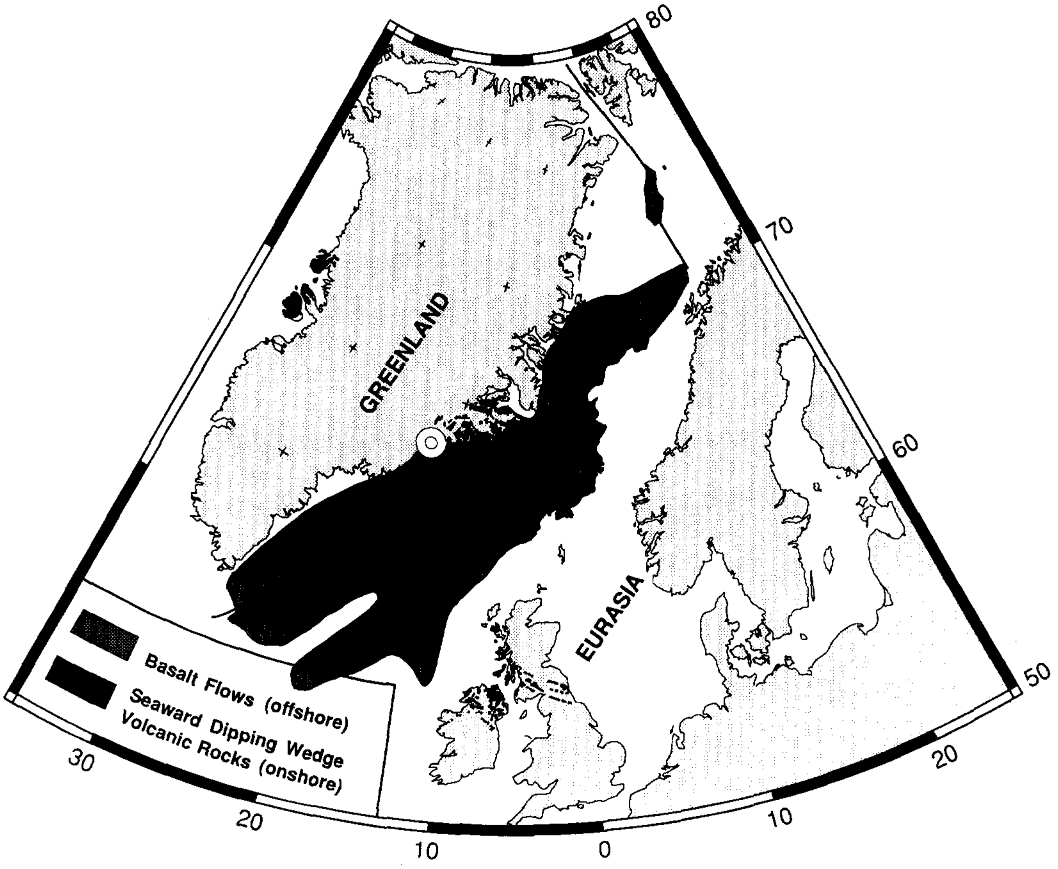

Fig. 3. Extent of NAVP at magnetic anomaly 23 time (~ 54.5 Ma [11]). Hotspot location (double circle) from White and McKenzie [5].

and possible far-field (global) effects. We first discuss the regional implications by focusing on the best studied area, the Vøring margin (Fig. 1), and by analogy infer that a similar sequence of events could have occurred along other volcanic margins in the North Atlantic. The discussion relies on scientific drilling results [4,8] supported by sequence stratigraphy and geodynamic modeling [10].

Ocean Drilling Program Site 642 (Figs. 1 and 2) penetrated ~ 930 m into basement below sediments that record a change from shallow, high-energy terrigenous to open-water, pelagic, biogenic-dominated deposition [8]. The basement is composed of two distinct lava flow units and interbedded volcaniclastic sediments [4]. The lower lavas are dacitic, emplaced by infrequent eruptions during the late rift stage. The interbedded sediments indicate fluvial or shallow-water deposition. The upper lavas correspond to a wedge of seaward-dipping reflectors in the seismic record, and consist of transitional, mid-oceanic tholeiitic basalts and altered, interbedded, basaltic vitric tuffs. Many flows have reddened tops and some flows and intercalated sediments indicate shallow-marine environments. Subaerial and neritic environments are inferred during and subsequent to breakup when the wedge was constructed by an intense phase of explosive, subaerial basaltic volcanism.

Subsequent to Paleocene syn-rift uplift, continental breakup between Eurasia and Greenland occurred during chron 24r [4]. The numerical chron 24r age of 56.14–58.64 Ma [11] has recently been re-estimated to 53.250–55.981 Ma [12]; the Paleocene/Eocene boundary is placed at ~ 57.5 Ma by [11] and ~ 55 Ma by [12]. Because chron 24r is the primary temporal reference in this study its numerical age is less important for the discussion.

Breakup was accompanied by voluminous volcanic activity along the almost 3000 km long rifted plate boundary (Fig. 3). The oldest oceanic crust accreted above or close to sea level. The intense volcanism abated 2–3 m.y. after breakup, and the injection center submerged with sporadic, but waning, volcanism. Subsequently, the injection center moved to bathyal depths, leaving an isostatically compensated igneous complex trailing behind new oceanic crust accreted at a normal spreading axis. As the ocean basin widened and deepened, the oldest oceanic crust subsided at rates similar to normal oceanic crust, maintaining the difference in basement relief [4].

The continent–ocean transition along the rifted margins is thus characterized by voluminous extrusive complexes. A part of these features forms a region of elevated basement, commonly a marginal high, with respect to the adjacent oceanic crust. The extrusive edifice contains prominent wedges of seaward-dipping reflectors, and tholeiitic lavas cover both the oldest oceanic crust and large areas of adjacent continental crust (Figs. 2 and 3). Early Cenozoic onshore magmatism also took place in a broad zone from Great Britain across the Faeroes and East Greenland to Baffin Bay. This is the North Atlantic Volcanic Province (NAVP). The most voluminous flood basalts erupted during chron 24r [13]. Hence, the lavas connected by the Greenland–Faeroe Ridge (Fig. 1) represent persistent subaerial volcanism that was associated with the Iceland hotspot for ~ 60 m.y., whereas the extrusive constructions along the margins represent transient volcanism lasting only ~ 3 m.y. [4].

Evidence for dynamic uplift followed by transient igneous activity along the entire North Atlantic rifted plate boundary suggests that a region of elevated crust between both continental landmasses existed some time before and after breakup. The elevated region, which probably had an accentuated along-plate boundary relief, was rapidly denuded. Thus, a major Paleogene sedimentary source region existed first in the central epicontinental sea between Greenland and Eurasia and later on the young continental margins, dominating the sediment supply and deposition at these times. The corresponding basin fragmentation may also have led to lateral changes in sediment composition and depositional environment.

On the Vøring margin, these events are documented first by rift uplift within the Late Cretaceous and Paleocene epicontinental sea and later by an extrusive barrier between subsiding continental crust and the growing ocean basin. Paleocene lithospheric extension resulted in faulting and a prominent unconformity shows considerable erosion of the elevated region both during late rifting and immediately after breakup, depositing large volumes of sediment farther east. In fact, most Paleogene sediment in the Vøring Basin has a western source [10]. Sediments from the east first reached the marginal high in the middle Eocene. Then, the relief was gradually smoothed and the high became, except for isolated peaks, fully sediment covered during the middle Oligocene to early Miocene (Fig. 2).

Even allowing for the shallow North Atlantic crust Fig. 3 shows a dramatic ~ 3 km elevation difference between the high and adjacent oceanic crust. At Sites 642 and 643, the basal sediments were derived from continental soils formed in a hot, seasonably humid climate, followed by an initially restricted marine depositional regime [8]. Bathyal depths were first reached 5–6 m.y. after breakup at Site 643; the top of the high passed through sea level at about the same time. Thus, the establishment of bathyal waters was delayed until the transient igneous pulse had abated enough to allow accretion of oceanic crust at a mid-oceanic ridge.

4. Regional environmental effects

One would expect a major environmental impact from extensive, subaerial flood basalt activity. The 1783–1784 Lakagígar fissure eruption on Iceland [14], for example, produced about 15 km^3 of basaltic lava, one to two orders of magnitude less than the estimated volume of 500–1500 km^3 for lava flows in the Columbia River Basalt Province [15]. The weather was unusually cold in the years after eruption, and this relatively small eruption led to the death of about 75% of all the livestock in Iceland, probably as a result of acid gas emissions; this resulted in a famine that killed 24% of the population. Dust veils, fog and haze were seen over most of Europe and adjacent parts of Asia and Africa at this time, and acid deposition from the eruption has been recognized in Greenland ice cores [16].

The subaerial volcanic acitvity during the Paleocene–Eocene transition was unusually violent. In and around the North Sea Basin volcanic ash and bentonite beds are widespread in the uppermost Paleocene to lowermost Eocene [e.g., 17], and are most concentrated in the Balder and Sele formations (Fig. 4). Some individual ash layers may be correlated over large distances, from the Bay of Biscay to Denmark. The ashes have been attributed to local volcanoes [e.g., 18], largely because the grain size was thought to be too large for long-distance transport. The most abundant ash layers occur in the lower part of the Balder Formation, deposited in nannofossil zone NP10, which is correlated to chron 24r (Fig. 4). These ashes, which are of reversed magnetic polarity and of a composition similar to sediments between tholeiitic flows at Site 642, constitute a regional seismic marker that has been attributed

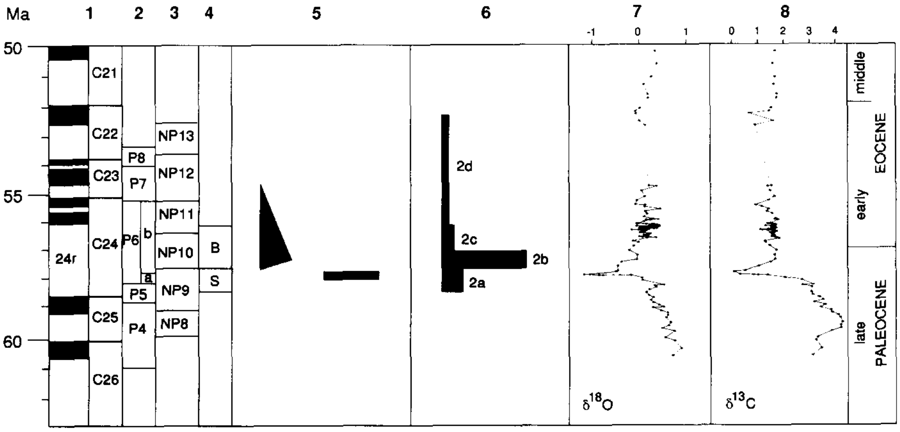

Fig. 4. North Atlantic basaltic breakup volcanism and environmental parameters. *1* = Magnetic polarity timescale of Berggren et al. [11]. *2* and *3* = Foraminiferal (P) and calcareous nannoplankton zones (NP) [49]. *4* = North Sea Sele (S) and Balder (B) formations [17]. *5* (*left*) = Timing and relative intensity of main basaltic phase during North Atlantic volcanic margin formation [4]; (*right*) = benthic foraminifera extinction [31,32]. *6* = North Sea pyroclastic phases [17]. *7* and *8* = Bulk oxygen and carbon isotope ratios at Maud Rise, Weddell Sea, Antarctica. Numerical ages calculated using correlations and data from scientific drillholes [34,50, E. Thomas and N.J. Shackleton, unpublished data]. Paleocene/Eocene boundary placed at 57.0 Ma [49].

to the most intense volcanism at crustal breakup [4].

Although Knox and Morton [17] place the source volcanoes at the proto-Iceland plume, the nature of the volcanic margins, the widespread tephra distribution, and the observation that the Vøring margin basalts were most likely erupted by phreatomagmatic eruptions [19], suggest a model of individual eruption centers along the entire rifted plate boundary where local magma–water interaction amplified the explosive nature of the eruptions. This model is supported by the presence of numerous volcanic vents in the adjacent Vøring Basin at the level of the ash marker [10] (Fig. 2), a setting which would enhance the explosive character during the onset of basaltic volcanism. Nonetheless, the far-reaching signature and the magnitude of the tephras demonstrate that igneous activity during the North Atlantic opening had a significant regional environmental impact.

The ash-rich Balder and Sele formations in the North Sea (Fig. 4) contain benthic foraminiferal faunas suggesting a bottom-water environment that was corrosive for $CaCO_3$, and low in dissolved O_2 [20]. Calcareous species, including cosmopolitan ones, disappeared from the central North Sea Basin with the first occurrence of volcanic ashes, and were confined to the shallowest areas rimming the basin [21] for the duration of deposition of these formations. The agglutinant benthic foraminifera in the Balder and Sele formaztions have very low diversity [20], and many species have a local last appearance just before ash deposition, or a local first appearance just after, resulting in a turnover of almost 60% of the species. Likewise, major faunal reorganizations occurred in the neritic benthic foraminiferal faunas between the Thanetian and Ypresian in the Paris, London [22] and northern Spanish basins [23]. Low oxygen conditions also probably occurred during uppermost nannofossil zone NP9 and NP10 times on the New Jersey continental margin at shelf depth [24].

The resulting Paleogene circulation model between Greenland and Eurasia includes a Paleocene epicontinental sea which became increasingly segmented by syn-rift uplift and breakup volcanism. The subaerial landmass gradually changed into a series of shallow-marine basins, restricting surface-water interaction. Regional subsidence of the injection center near the end of the early Eocene provided open-marine conditions, leading to formation of a series of widening ocean basins from the middle Eocene onwards. Restricted circulation and interaction of bottom waters may have prevailed in the Norwegian–Greenland Sea, possibly well into the Miocene, when the Greenland–Scotland and Fram Strait gateways opened. This Paleogene isolation may explain biotic provincialism within the Norwegian–Greenland Sea sub-basins: endemism and low diversity are common, inhibiting the establishment of a consistent ocean-wide biostratigraphic framework for that region [9].

The abundance and geographic distribution of biosiliceous sediments increased globally in the late early and middle Eocene [25,26]. In spite of volcanism, silica is not abundant in Paleocene and lower Eocene sediments in the North Atlantic [27]. A significant North Atlantic contribution to the Eocene bloom is probable, because the increase in biosiliceous sedimentation is coeval with establishment of large open-ocean basins which would stimulate surface water exchange, upwelling and, possibly, productivity [28].

5. Global impact?

The latest Paleocene through to earliest Eocene (chron 24r) has been recognized as a time of global plate tectonic reorganization and climatic and evolutionary changes [26]. Indeed, major changes during this period have been called the 'chron-24' event [29]. A number of climatic and environmental indicators record important changes in this period [e.g., 30–32].

In the latest Paleocene the world was starting to warm up, to the warmest period in the Cenozoic, as indicated by terrestrial vegetation and major turnover of mammalian faunas on the North American continent. The intensity of eolian circulation decreased rapidly. The climate on and around Antarctica was warm and very humid, as shown by paleovegetation and by clay mineral associations, and warm-water planktonic species reached far into the high southern latitudes. At some time between the Paleocene and Eocene the precipitation patterns may have changed from year-round wet to more seasonal, as suggested from vegetation changes. Planktonic species were undergoing extremely rapid evolutionary turnover.

Oxygen isotope records show that latitudinal temperature gradients were low [33,34], and that surface waters at high latitudes and deep waters were warm (10–15°C). Carbon isotope values show a very large long-term decline from the highest values in the Cenozoic (similar to typical Cretaceous values), which were reached in the middle Paleocene [e.g., 35]. Superimposed on the longer term (10^6 yr) trends of decreasing values in $\delta^{13}C$ in planktonic and benthic organisms, and decreasing temperature gradients between high- and low-latitude surface waters, there was a short-term extreme excursion to lower values of both oxygen and and carbon isotopes in planktonic and benthic foraminifera (Fig. 4); this was first recognized in material from the Weddell Sea [33]. The excursion started quickly, over several thousand years, and values returned to the baseline slowly, in several *hundred thousand* years. This short-term excursion has now been recognized in the southern and eastern Indian Ocean, in the southern Atlantic Ocean, in the equatorial Pacific and in the Bay of Biscay [e.g., 32,34]. These excursions, if explained simplistically, suggest that there was a short-term whole-ocean warming of several degrees, as well as a major upset in the global carbon cycle, during which the complete oceanic reservoir became lighter in terms of stable carbon isotope values. The exact magnitude of the excursions is difficult to estimate; existing records vary in magnitude from 1 to almost 3‰. Because the event was short it is not clear whether its maximum extent was measured at all sites.

The latest Paleocene had not been recognized as a period of mass extinctions in compilations such as those of Raup and Sepkoski [36], but evolutionary turnover rates were very high in many groups of organsims (e.g., planktonic foraminifera, shallow-water benthic foraminifera, mollusca, mammals and gastropods). The most extreme and unusual faunal change occurred, however, in the deep-sea benthic foraminifera, which did not undergo major extinctions at the end of the Cretaceous [31]. Their only mass extinction in the last 90 m.y. occurred in the latest Paleocene [31,32,37,38]. This global extinction of the deep-sea faunas occurred rapidly (i.e., within a few thousand years), and was followed by a period of low-diversity, impoverished faunas. The synchroneity of the benthic foraminiferal extinction and the short-term excursions in carbon and oxygen isotopes strongly suggest that the extinction was globally synchronous. Preliminary data from the Bay of Biscay [34] suggest that the benthic extinction may have occurred shortly before the eruption of the widespread ashes in the Danish Fur Formation, which is coeval with the North Atlantic seismic marker [17] interpreted to represent breakup. The Fur formation has recently been dated at 55.1 Ma [39], i.e. in the lower part of chron 24r [12]. The extinction also occurred within chron 24r, in the topmost part of nannofossil zone NP9 (the upper boundary of which has been dated at 55.7 Ma [39]), and in planktonic foraminiferal zone P6a, placing it in the lowermost part of chron 24r, i.e. just before the Paleocene/Eocene boundary (Fig. 4). Thus, it corresponds to the North Sea Sele Formation, which contains ashes (phase 2a, Fig. 4) considered to be of the same derivation, and is a precursor to the prominent ashfalls produced during breakup in the lowermost NP10 [17] (phase 2b, Fig. 4). These temporal relationships depend on long-distance, indirect correlations, and the apparent time period between extinctions and massive volcanism is probably within the limit of error.

Such an extinction is difficult to explain [32]. It has been suggested that there was a global drop in productivity at the time [e.g., 35], but such a drop in productivity was certainly much less extreme than the collapse in productivity at the end of the Cretaceous—and the benthic foraminifera did not become extinct at that time. Several authors have suggested that a change in deep-oceanic circulation is the most probable cause of the extinction [31–33,38]. The extinction occurred globally, so such a circulation change must have involved most of the world ocean. The circulation change was postulated to have been a strong increase in the volume of deep to intermediate waters formed by evaporation at low latitudes, where high salinities may have existed in the Tethys basin [40]. The actual extinction could then have been caused by either changing oxygen content because of decreased solubility at higher temperatures, or higher temperatures themselves.

In addition, the changing deep-sea circulation could be expected to lead to changes in the location and nutrient content of upwelling waters, which in turn affect surface-water productivity [32].

We could speculate on the following scenario: Long-term volcanic activity during a period of global warm climate, without polar ice caps, led to warming up, especially at high latitudes, where changes in density of the surface waters would play an important role in the forcing of deep-water formational processes [41]. One or several extremely violent pulses of volcanic activity put large amounts of isotopically light carbon ($-6‰$) into the atmosphere as CO_2, leading to even more warming at high latitudes, which is recorded by isotopic and faunal and floral records. The high temperature of the surface waters could then possibly have resulted in the formation of a low-density surface layer, effectively preventing formation of deep to intermediate waters at high latitudes. Thus, deep-water formation could have been dominated by waters derived from low to mid-latitudes. The situation then returned to more normal over several hundred thousand years, possibly because heat transport from low to high latitudes decreased as a result of decreasing wind strength [30], so that the high latitudes cooled again.

Kennett and Stott [33] decided that the short-term isotopic events and the coeval benthic foraminiferal extinction could not have been caused by volcanic effusions, because of the longer time scale of the latter. In general, volcanic eruptions have indeed been correlated to short-term cooling as a result of sulfate emission [e.g., 42]. Warming as a result of CO_2 emissions, largely from mid-oceanic ridges, has been seen as a more long-term effect [30,43,44], although the net effect of such emissions has been called into question [45]. Because there is no counteracting sink (subduction) for flood basalts in continental rifting episodes, their atmospheric effects could be expected to be more severe than those from submarine activity [45].

Mass extinctions have been suggested as resulting from flood basalt activity, but the actual environmental effects causing the mass extinctions have not been clearly delineated. Due to the large land area and the K–T age of Deccan Trap emplacement, many studies have focused on this LIP. Indeed, the Deccan Traps and the NAVP have been considered as contemporaneous, or at least as having occurred very close together in time [3], whereas the NAVP is ~ 10 m.y. younger than the Deccan Traps [4]. The onshore part of the NAVP is indeed small compared with other continental flood basalts; however, if the volcanic margins are included, NAVP extrusives (Fig. 3), excluding West Greenland, cover an area $> 1.3 \times 10^6$ km^2 and have a volume $> 1.8 \times 10^6$ km^3 [7]. Thus, NAVP ranks among the world's larger igneous provinces.

We suggest that subaerial flood basalt activity as related to continental breakup may have a larger effect than submarine effusions, because the direct input of CO_2 is into the atmosphere instead of into the oceans. We also suggest that in the late Paleocene extinction we might see geologic evidence for rapid environmental effects of CO_2 input into the atmosphere. Quantitative modeling, which is needed to evaluate the feasibility of the proposed scenario, is complex because of the many unknowns: Was the atmospheric reservoir of CO_2 larger than the pre-industrial value of 0.495×10^{17} moles of CO_2 (i.e., 2.18×10^{18} g; [46])? Values have been suggested that range from not much more than that level to several times higher than it [47]. What was the size of the much larger deep oceanic reservoir at the much higher Paleogene temperatures and thus lower solubility of CO_2? And, most important, what was the maximum rate of lava effusion during eruption of massive flood basalts?

The increased igneous activity during emplacement of NAVP increased the annual global production of oceanic crust by only $\sim 8\%$ [7]. At a total NAVP crustal volume of 6.6×10^6 km^3 [7], and with a scaling factor of ~ 300 moles of CO_2/m^3 of oceanic crust produced [43], the total amount of CO_2 emitted could be of the order of 10^{20} g. About the same value, which is two orders of magnitude more than the pre-industrial atmospheric reservoir, is obtained using the estimate of 0.065% CO_2 [48]. The total volume, however, was formed over 2.5 m.y. or more (Fig. 4), resulting in an average annual CO_2 output of the order of several times 10^{13} g CO_2, which is considerably less than the present fossil fuel output of $\sim 5 \times 10^{14}$ mol/yr (2.2×10^{16} g CO_2/yr). This appears to argue against possible involvement of flood basalt CO_2 in rapid climatic change, but it should be remembered that climate response from a world with little or no polar ice to start with, as was probable for the Paleocene, may have been very different from the response of the precent, 'ice-house' world. The present fossil-fuel burning rates have been in effect for only ca. 30 yrs, with much lower rates for the 170 yrs prior to ca. 1960 [46], whereas massive flood basalt activity could last for centennia at least.

It has been suggested that eruption intensity and volume were not constant throughout the 2.5–3 m.y. period of transient igneous activity, being most intense during and directly after breakup [4,5]. This contention is supported by the volume and the wide distribution of tephra in the lower Balder Formation relative to adjacent ash layers [17] (Fig. 4). Therefore, we suggest that the maximum outgassing rate during massive effusion of flood basalt should be much higher than the average rate over several million years.

During the small Lakagígar flow event (~ 15 km^3 compared to 1500 km^3 for large flood basalt flows) the maximum lava flow rate would have been ~ 75 km^3/yr [14], whereas the average flow of the NAVP extrusives, assuming that two-thirds of the lavas were emplaced during a short breakup period of only 0.5 m.y., has been estimated at only 2.4 km^3/yr [7], i.e. a factor of ~ 30 lower. On the other hand, if we use the Lakagígar volume as a scale, the more than 1.8×10^6 km^3 of NAVP extrusive volume would produce a comparable eruption every sixth year. The Lakagígar fissure was only 25 km long, and produced a 565 km^2 flow in 8 months. Flow rates have been linked to fissure length and width [e.g., 15], suggesting that the much longer fissures of truely large flood basalts could have had much larger flow rates.

We thus suggest that the CO_2 effusion from the NAVP basalts could possibly have been the trigger for rapid climate change through the pathway of increased high-latitude surface temperatures, and changing deep-sea circulation.

The variety in the size of transient LIPs is the result of mantle melt anomalies on many scales. Indeed, the emplacement of Ontong Java Plateau, the largest LIP, may have exceeded the contemporaneous production rate of the entire mid-ocean ridge system [6,44]. Therefore, the formation of the mid-Cretaceous Ontong Java LIP in particular has been suggested to have had major global environmental consequences [43,44]. Although the total magmatic output during emplacement of the two giant oceanic plateaus (Ontong Java and Kerguelen) appears much larger than for NAVP and Deccan [6], estimates of their extrusive components suggest more comparable dimensions [7]. This suggest to us that, for high eruption rates, the geologic setting during LIP emplacement may be equally or more important for environmental impact than total crustal volume.

Finally, our study shows the importance of the igneous complexes at volcanic margins when considering environmental implications of continental flood basalt provinces adjacent to rifted margins. For example, the inclusion of the South Atlantic and Indian–Mascarene volcanic margins [6] will greatly increase both extrusive and total crustal dimensions of, respectively, the Parana–Etendeka and Deccan LIPs.

6. Summary and conclusions

Continental flood basalts are thought to result from impingement of a plume head on the lithosphere. If the plume captures lithosphere under extension, the North Atlantic being a case in point [5,10], volcanic margins will contribute significantly to the total extrusion budget and must be accounted for when considering possible environmental effects of the mantle anomaly. The North Atlantic data record the regional effects of the both the volcanism and the influence of the magmatic event on basin segmentation and sedimentation.

The nature, transience and magnitude of the igneous event during the North Atlantic opening and the apparent contemporaneity with global environmental changes suggests a link between the two, and that the process of volcanic margin formation may induce or amplify environmental stress over large areas.

Rea et al. [30] proposed a link between the global change at the Paleocene/Eocene boundary and major tectonic events. The seafloor tectonism corresponds to enhanced seafloor hydrothermal activity, but effects on atmospheric CO_2 levels might be less than effects from subaerial flood basalt activity. Extensive flood basalt activity could have effects on the whole earth and on life in the deep oceans through climate links to high latitudes and deep-water formation. Although these relationships are as yet tenuous, it is suggested that the environmental change is triggered by tectonomagmatic processes related to mantle dynamics inducing transient, increased crustal accretion rates on regional or global scales. The environmental impact may become particularly significant when mantle conditions allow regional along-plate boundary emplacement of huge igneous complexes during continental breakup—formation of a volcanic margin. Thus, important oceanographic and climatic changes caused by breakup of the lithosphere are not only due to laterally evolving and/or changing basin geometry, but may also occur when an intense short-lived episode of excess magmatism is associated with the onset of seafloor spreading. Such processes could have global environmental results even on geologically short (10^3 yr) time scales.

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