PENROSE CONFERENCE REPORT

Volcanic Rifted Margins

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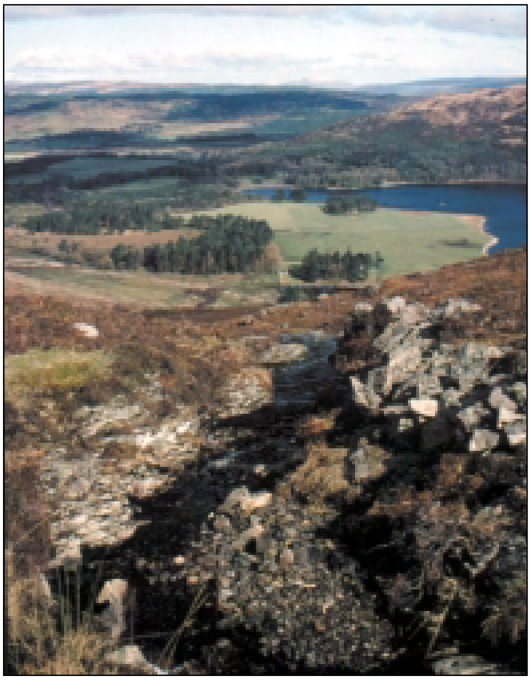
Active rifting (plume-driven) models are the traditional explanation for the formation of volcanic rifted margins with significant surface uplift occurring prior to flood volcanism and break-up extension. However, recent research on volcanic rifted margins indicates that their evolution is more complex than that defined by earlier models, and several hybrid models have been proposed. At the Penrose 2000 Volcanic Rifted Margin Conference held at Royal Holloway, University of London, discussion centered on the margins of the north, central, and south Atlantic Ocean, the western and eastern coasts of Australia, the southern Red Sea, the west coast of India and its conjugate margins in Madagascar and the Seychelles. The characteristic features of volcanic rifted margins were summarized and it was agreed that formation of a volcanic rifted margin required complete rifting of a continent to form an ocean above an upper mantle with a temperature 100–200 °C above "normal" asthenosphere. This should be contrasted with rifting without additional thermal perturbation which leads to non-volcanic rifted margins (e.g., Newfoundland, Iberia) and thermal perturbations in the absence of rifting which lead to formation of intraplate large igneous provinces in ocean basins (e.g., Ontong-Java oceanic plateau) and on continents (e.g., Siberian flood basalts).



Unroofed Loch Ba center and late caldera on Mull, Scotland.

Continental Flood Volcanism, Underplating and Seaward-Dipping Reflector Sequences

Volcanic rifted margins are characterized by subaerial volcanic rocks (~4–6 km thick) on a continental margin. Ar-Ar and K-Ar dating indicates that, in the majority of volcanic rifted margins, 70%–80% of the subaerial mafic and/or basaltic volcanism occurred over a relatively short period of time (2 m.y. in the case of the Red Sea and East Greenland plateau lavas and <0.5 m.y. in the case of the Deccan). The short phase of basaltic volcanism is followed by a lengthy period of silicic volcanism that can last for 5–10 m.y. In some volcanic rifted margins, silicic volcanic rocks erupted from multiple caldera complexes tend to dominate the upper volcano stratigraphy (Argentina-Antarctica, eastern Australia, Etendeka-Namibia, Scotland, Yemen), but in the Parana-Etendeka and Ethiopia, silicic units are interbedded with the basaltic lava flows. In the Deccan and the British Tertiary the presence of ash layers in the volcano stratigraphy indicates "silicic" volcanism between periods of basalt volcanism. The switch from basaltic to silicic volcanism reveals the importance of high-level magma chambers and crustal melting in the formation of volcanic rifted margins of magma. In Etendeka, individual silicic eruptive units have thicknesses of up to 100 m, aerial extents >8000 km^2 and volumes of 3000 km^3, indicating large-scale explosive eruptions. Eruption rates in volcanic rifted margins have not been adequately constrained by volume-time studies of individual eruptive units and, as a first approximation,

Deccan volcanic stratigraphy exposed by scarp retreat at King Arthur's Seat, Mahabaleshwar.

thickness-time relationships reveal a marked decline in eruption rate from the mafic to the felsic eruptive stages of volcanic rifted margins. This is consistent with the requirement for longer time periods to allow basaltic magmas to pond in shallow magma chambers and to evolve toward silicic derivatives by a combination of fractionation processes and assimilation of surrounding basement and/or roof rocks. While the emplacement of thick mafic flows within volcanic rifted margins has no modern analogues, a possible explanation for the mechanism of emplacement may be found in the recently proposed "self-inflation" model for basaltic lavas (single or compound) with thicknesses ranging from 1 to 100 m (e.g., Etendeka, Deccan).

Underplating, or formation of an over-thickened oceanic layer 3 and adjacent stretched continental crust, is evident as distinctive high-seismic velocity (7.2–7.4 km/s) and associated gravity anomalies, but only sometimes by lower-crustal reflectivity. Because bright lower-crustal reflectivity can have other causes, surface denudation should be sought as independent verification of underplating. Magmatic underplating may involve multiple dike-sill systems, multiple igneous intrusions, or single magma bodies. In southeast Greenland, the maximum igneous crustal thickness varies from 30 to 40 km close to the thermal anomaly (i.e., track of Iceland hotspot), thinning to 18 km at 500–1000 km from the anomaly. On the northwest Australian margin, the underplated thickness is ~7 km near the ocean-continent boundary. These thicknesses have been widely used to infer the magnitude of mantle temperature anomalies, but if average Vp is also measured, and used as a proxy for composition, one may also infer the degree of mantle upwelling. Along the Iceland hotspot track, there is a clear requirement for active upwelling, defined as a mantle upwelling velocity exceeding that due purely to the plate separation rate. In contrast, 500 km off the hotspot track, upwelling appears to be passive and can be explained purely by plate velocity. On the Greenland–northwest Europe conjugate margins, crustal-generation rates as high as 2000 km^3/m.y. per km of margin occurred at breakup, declining rapidly over a few m.y. Magma production rates of volcanic rifted margins (i.e., per kilometer of active margin) seem similar to that of island arcs, but volcanic rifted margins are less effective in generating new continental crust because the total length of active arcs exceeds that of active volcanic rifted margins by a factor of 5–10.

Seaward-dipping reflector sequences, first recognized along the North Atlantic margin, are a characteristic of volcanic rifted margins and are recognized by reflectors which steepen and diverge downward to dips of over 15 degrees. These reflector packages reach up to a maximum estimated thickness of 10 km and extend for up to 200 km perpendicular to the margin and up to 4000 km along strike (e.g., Argentina-Brazil margin). Seaward-dipping reflector sequences are interpreted to be largely subaerial eruptions, and their seaward termination may typically mark the transition to submarine eruptions. The sequences may be predominantly volcanic rocks with associated sedimentary rocks. On the Namibian margin, models of seismic data, tested against magnetic data, suggest that the seaward-dipping reflector sequences package is a mixture of volcanic and sedimentary rocks, and on the Norwegian volcanic rifted margin, seismic sections have been interpreted as documenting a transition from subaerial to submarine volcanic deposits that comprise lavas and volcaniclastic sedimentary rocks. Underplating is an integral part of the architecture of volcanic rifted margins and, with the extrusive part of the sequences, is what may distinguish volcanic from nonvolcanic rifted margins. However, there are possible complications in margins like Sergipe-Alagoas, Brazil. The lack of pre- and synrift volcanics is a classic nonvolcanic margin characteristic while the thick wedges of postrift seaward-dipping reflectors are a classic volcanic margin characteristic.

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Plumes and Upwellings: Magmatism and Rifting

Melt production at volcanic rifted margins requires (1) mantle potential temperatures of 1400–1600 °C (which may or may not be expressed as geochemical or geophysical anomalies), and (2) lithospheric thinning to (or preexisting lithospheric thickness no more than) ~90 km to allow adiabatic decompression melting. Geophysical and geochemical data, backed up by theoretical modeling, support the presence of one (or more) plume(s) during the formation of the volcanic rifted margins of the Atlantic, the Red Sea, India-Seychelles, and the volcanic rifted margins in Antarctica. However, some controversy exists over the extent to which various geochemical parameters (e.g., helium-lead isotope ratios and trace-element parameters) can be used to define plumes. While magma geochemistry clearly indicates input from mantle and crustal sources, at present, geochemical and geophysical data cannot, to everyone's satisfaction, distinguish between core-mantle boundary plumes and upper-mantle upwellings related to topography at the lithosphere-asthenosphere boundary beneath continents. Overall, at the Penrose, geochemical and geophysical data were found to be far from conclusive when it came to deciphering the presence or absence of deep-mantle plume structures. What is clear is that thermal anomalies exist on Earth and that their distribution, shape, and size appear to be variable, and their duration and genesis manifest themselves to different degrees and in nonspecific order, in the uplift/subsidence, extension/volcanism, of the lithosphere.

Some models of volcanic rifted margin formation that involve input from the mantle require that rifting and magmatism were essentially synchronous, but in many volcanic rifted margins (e.g., Yemen, North Atlantic, Australia), several million years lapsed between the onset of flood volcanism and widespread rifting. In the Parana-Etendeka, it can be argued that the Etendeka magmatic province was erupted prior to onshore rifting because the main volcanic units can be traced from the Etendeka into the Parana, so there could not have been major topographic depressions ponding sequences. Alternatively, it can be argued that the transcontinental correlation of eruptive units is possible because the rift topography was quickly blanketed by sheetlike eruptive units. While "offshore valley systems" appear to be filled with lavas and have been interpreted as evidence of rifting having predated volcanism, later deformation and faulting may explain the apparent "channeling" of units. On the North Atlantic volcanic rifted margins, basaltic volcanism overflowed the conjugate margins, as it did in the Deccan, and as such must be largely synrift. In the case of the volcanism associated with the central Atlantic Ocean (200 Ma) there is geochronological evidence that volcanism postdated rifting

Volcanic Rifted Margins
continued on p. 10

Volcanic Rifted Margins
continued from p. 9

by 30 m.y. in some cases, but was synchronous with basin formation in others.

Denudation = Surface Uplift–Rock Uplift

In many volcanic rifted margins, what we observe today are erosional remnants, and the degree of preservation is inextricably linked to climate, elevation, and the amount or rate of denudation. The youngest volcanic rifted margins (Ethiopia-Yemen) are characterized by incised 3-km-high uplifted flanks atop a broad plateau. Volcanic rifted margins formed at the Cretaceous-Tertiary boundary are characterized by major scarp retreat in India and an eroded mountain range in Scotland. The central Atlantic magmatic province in the eastern United States and West Africa was reduced to a feeder dike swarm during 200 m.y. of erosion. Within volcanic rifted margins, unconformities provide important temporal information about denudation and the potential supply of sediments to extensional basins. In some cases erosion postdated the main magmatic episode and was synchronous with breakup extension (e.g., Yemen), and in other volcanic rifted margins (e.g., eastern Australia) erosion and sediment input (i.e., with >1.4 million km^3) into adjacent or preexisting sedimentary basins coincided with the main magmatic episode.

Apatite fission track analyses and U-Th/He dating are used to quantify the timing and rate of denudational processes (tectonic and erosional) as measures of crustal cooling, and cosmogenic isotopes are used to date paleosurfaces (e.g., Deccan). Fission-track dating has been applied to many volcanic rifted margins and, whereas young, hot volcanic rifted margins (e.g., Yemen) have a relatively simple cooling history, older and colder volcanic rifted margins tend to have a more complex cooling history that may be difficult to unravel (e.g., United Kingdom–Greenland, India). Studies in Antarctica indicate that landscape evolution was very slow with a cessation to scarp retreat in the past 15 m.y. On the Yemen margin of the Red Sea, denudation peaked in the Miocene during breakup, with scarp retreat determining landscape evolution since that time.

Theoretical models require 500 m–2 km of uplift prior to, or concurrent with, magmatism depending on proximity to the plume head or stem and lithospheric heating. To properly understand rock and/or surface uplift, constraints must be placed on the prerift paleogeography (relative to sea level) and the denudational history. According to the prevolcanic sedimentary rock record of eastern Greenland and Scotland, the southern Red Sea, and north, west, and east Australia, the prebreakup continental masses were close to sea level. However, it is apparent that some variation existed in the North Atlantic as west Greenland is characterized by incised fluvial systems, east Greenland by a landscape close to sea level and northwest Scotland–Faeroes by a low-relief, vegetated land surface. In Yemen, a shoreline existed close to the present location of a mountain range (~3 km) but, judging from paleocurrent information and the maturity of the prevolcanic sediments in Yemen, a hinterland must have existed in the Danakil horst, Eritrea. In contrast to these volcanic rifted margins, the Drakensburg mountains (South Africa) are believed to have inherited "relief" at the time of Gondwana breakup. While the nature of the Deccan-Seychelles land surface prior to breakup (relative to sea level) is unknown, in the Parana-Etendeka it is characterized by a large aeolian erg system.

Denudation coincides with the peak of extension in Yemen and eastern Australia, while in west Greenland, major unconformities beneath the volcanic rocks are associated with fluvial peneplanation and valley incision, indicating a period of substantial prevolcanic uplift and denudation. In Antarctica, landscape development followed the onset of uplift and a change in base level. Scarp retreat, planation surfaces, and incision by fluvial systems produced a landscape that has changed little in 15 m.y. In the Deccan of India, some topographic expression must have existed, perhaps triggered by uplift, because palynological data indicate the presence of floodplain or lacustrine environments. The western Ghat escarpment is believed to have an erosional rather than a tectonic origin, and scarp retreat is believed to be the major determinant of landscape with the original continental margin ~75 km west of its present location. Thus, it appears that there may be spatial separation of plume head or stem material driving uplift and zones of melt generation (thinned lithosphere) within broad plume provinces.

Characteristics of Volcanic Rifted Margins

The Penrose Conference participants concluded that the defining characteristic of a volcanic rifted margin (that which distinguishes it from a nonvolcanic margin) is the presence of a significantly greater thickness of new intrusive and extrusive igneous crust, ≥~10 km, at a rifted margin than is formed in normal oceanic crust or nonvolcanic margins. However, as we learn more about the 3-dimensional crustal architecture of volcanic rifted margins, we should perhaps be identifying them as *magmatic* at all levels, rather than merely as *volcanic*. Nonetheless, Penrose 2000 suggests that the following observations are sufficiently common at volcanic rifted margins to be regarded as characteristic features:

(a) Subaerial volcanic rocks reached 4–6 km in thickness on the continental margin prior to denudation.

(b) Magmatic underplating, evident as high velocities (~7.4 km/s) in the lower crust interpreted as new mafic igneous crust—the intrusive counterpart of extrusive volcanic rocks on the continental margin or seaward-dipping reflector sequence in the continent-ocean transition.

(c) 70%–80% of the erupted volume was emplaced over a 1–2 m.y. period, with basaltic magmas erupted from fissure systems. Individual eruptive units can be ~100 m thick and cover several 1000 km^2.

(d) Silicic volcanic rocks, erupted from caldera-type complexes, can be a significant part of the upper (and lower) volcano stratigraphy of volcanic rifted margins (Ethiopia-Yemen, Parana-Etendeka, eastern Australia) with individual eruptive units comprising 100s to 1000s km^3.

Volcanic Rifted Margins
continued on p. 11

About People

Member John W. Gibson Jr. was named president and CEO of Landmark Graphics Corporation, a supplier of integrated exploration and production technical and economic software designed to help petroleum companies worldwide find, produce, and manage oil and gas reservoirs.

Member Robbie R. Gries has been elected president-elect of the Association of Petroleum Geologists for the 2000–2001 term. She will serve as president of the association for the 2001–2002 term.

Member Thomas L. Wright, a consultant in San Anselmo, California, received the American Association of Petroleum Geologists' (AAPG) Michel T. Halbouty Human Needs Award. Wright was honored at the 85th AAPG Annual Convention in New Orleans on April 17. The Michel T. Halbouty Human Needs Award honors an individual for the outstanding application of geology to the benefit of human needs, recognizing scientific excellence.

continued from p. 10

(e) Rift flank uplifts atop broad plateaus reach up to 4 km above sea level and act as a source for clastic sediments in adjacent extensional basins. Some of this uplift is permanent as opposed to time-decaying thermal uplift. A gradual decrease in the elevation of these mountains away from the rift axis is evident in both young and/or active (i.e., Ethiopia, Yemen) and old and/or inactive (i.e., Greenland and Scotland) volcanic rifted margins.

(f) Seaward-dipping reflector sequences appear to consist of a mixture of volcanic rocks (lavas ± ignimbrites), volcaniclastic and nonvolcanic sedimentary rocks.

(g) The ocean-continent boundary is abrupt (e.g., Greenland, East Coast of the United States, Namibia).

(h) Magmatism and rifting in volcanic rifted margins are not necessarily synchronous. Magmatism may predate rifting by several million years, may be synchronous with rifting, or may postdate rifting.

(i) Prior to formation of the volcanic rifted margin, the continental land masses were close to sea level (Yemen, east Greenland, United Kingdom, Etendeka) and displayed a variety of sedimentary environments (e.g., fluvial, aeolian, etc.).

(j) Kilometer-scale uplift prior to magmatism is not demonstrable on most volcanic rifted margins, but uplifted and rapidly denuded continental margins are observed, indicating that uplift and/or base-level change is a vital part of the formation of volcanic rifted margins.

(k) Unroofing of mantle rocks is not observed in volcanic rifted margins in contrast to at least some nonvolcanic margins (e.g., Iberia, northern Red Sea).

Ultimately, the degree to which we search for similarities or distinctions between different volcanic rifted margins may owe as much to our personal philosophical predilections, whether we are by nature "lumpers" or "splitters," than to the existence of an underpinning geological truth.

Acknowledgments

This report stems from a Penrose Conference held at the Department of Geology, Royal Holloway, University of London, on March 28–29, 2000.

Conference Participants

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