Conference Report

Magmatism and the causes of continental break-up

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A two-day meeting of the Tectonic Studies Group was held in London at the Geological Society on 3-4 October 1991, to consider relationships between continental extension, supercontinent break-up, magmatism and mantle plumes. The approach was multidisciplinary, with contributions from geophysists, geochemists and tectonic geologists. There were 28 talks and 11 poster presentations, with about 150 people attending.

The conference was opened by convenor B. C. Storey (British Antarctic Survey, Cambridge) followed by a session on relevant geophysical and geochemical principles. D. L. Anderson (California Institute of Technology) gave a stimulating keynote lecture on mantle reservoirs and seismic tomographic evidence for mantle circulation. He suggested that the source of all ‘enriched’ basalts such as ocean island basalts (OIB) and continental flood basalt was in a shallow mantle layer relative to the source of depleted mid-ocean ridge basalts (MORB). He presented new, high resolution global seismic tomography data, and argued from these that deep-rooted hot mantle upwells underlie mid-ocean ridges and back arc basins, but that mantle plumes, as narrow jets underlying hot spots cannot be observed by seismic means, nor are required by geochemical data. M. A. Menzies (Royal Holloway and Bedford New College) reviewed the petrological, age and thickness variations in continental lithospheric mantle, and its suitability as a mantle source for continental basalts. He described reaction zones and metasomatic fronts generated by intrusion of magmas into the mantle, and argued that such processes generate a range of mantle compositions like those of source regions of continental flood basalts. M. H. P. Boot (Durham University) described the stress regime in developing rifts during continental break-up, and the change in stress at the start of ocean spreading. He argued from a static model that tectonic stress in continents is the most important factor in generating continental break-up, with the possible role of mantle plumes being of secondary importance.

A. D. Saunders et al. (Leicester University) gave a keynote lecture on plume–lithosphere interactions, and the genesis of continental flood basalts. They stressed the dominance of the thermal input to CFB from plume-convected asthenosphere, but the dominance of the chemical input from lithospheric mantle. They presented an ‘incubation’ model for subcontinental plumes, in which the overlying lithosphere is intruded by low-degree melts from the plume, and is thus progressively chemically enriched, heated and thinned, to the point where the now-shallower plume head can melt to large degrees to generate continental flood basalts. M. Al’Kadasi, M. Menzies & D. Bosence (Royal Holloway and Bedford New College) talked about the large-volume Cenozoic magmatism in Yemen related to the opening of the Red Sea and possibly to a mantle plume centred at Afar, and made comparisons with similar outpourings in Saudi Arabia and Ethiopia. M. Menzies, who gave the talk, stressed that there was no evidence that uplift took place prior to the volcanism, contradicting some recent models. D. K. Bailey (Bristol University) reviewed the orientation of the Mesozoic–Cenozoic African rifts that follow older lithospheric structures. He argued, from the age of volcanic events, that magmatism in the African rifts was mainly controlled by changing stresses in the African plate. R. S. White (Cambridge University) gave a keynote lecture on hot-spot magmatism during continental break-up. He described the large volume of magma generated by lithospheric extension in the presence of mantle plumes, and stressed that geophysical data from continental margins indicate that three quarters of the volume of continental flood basalts may be trapped as intrusions beneath the lower crust. He discussed the problem of voluminous off-rift axis volcanism and suggested that dyke swarms may be important in moving continental flood basalts laterally, from the site of maximum rifting, to the site of eruption.

The next group of presentations concerned the opening of the N. Atlantic Ocean. This is the best-documented example of continental separation accompanied by very voluminous magmatism, for which the Iceland plume is thought to have been responsible. J. Skogseid et al. (University of Oslo) described the geological development of the rifted margins of the N. Atlantic, focusing on the Voring Margin, and using seismic reflection data. They argued that extensional faulting preceded volcanism by c. 15 Ma. H. C. Larsen & C. Marcussen (Geological Survey of Greenland) presented a detailed study, using seismic reflection data, of a basin in the area of Scoresby Sund Fjord, east Greenland. The basin was intruded by voluminous basaltic sills in the Tertiary, but developed at a site of much earlier crustal extension, which focused the magmatism. M. F. Thirlwall et al. (Royal Holloway and Bedford New College) described temporal variations in the Hold with Hope series of Tertiary basalts from NE Greenland. Many of the basalts have lithospheric (crust and mantle) chemical characters, but some of the lower lavas came from a mantle source which they specified as being convected in the Iceland plume. P. M. Holm, N. Hald & T. F. D. Nielsen (University of Copenhagen and Geological Survey of Greenland) compared the geochemical compositions of picrites and tholeiites from east and west Greenland, and showed that these were consistent with the interaction of the Iceland plume with Greenland continental lithosphere. K. Louden et al. (Dalhousie University) presented seismic refraction data for a high-flow area of the Labrador Sea, off SW Greenland. These data indicate that the continental margin is of non-volcanic type, originally formed beyond the influence of the Iceland plume, but now underlain by hot asthenosphere.

There were several poster contributions associated with this session. J. A. Chalmers & K. H. Laursen (Geological Survey of Greenland) presented seismic reflection data, with geological interpretations, for the east rifted margin of the Labrador Sea. T. Pedersen & J. Skogseid (University of Oslo) used seismic data and information from scientific drilling to describe the relationship of igneous intrusive and extrusive rocks to the structure and evolution of the Voring margin. M.-C. Williamson (Geological Survey of Canada) showed that the Sverdrup Basin in the Canadian Arctic had a depositional and extensional
history extending back to the early Carboniferous, that it was offset from the main rift axis and yet was the focus of Cretaceous magmatism. L. M. Larsen et al. (Geological Survey of Greenland) used biostratigraphic data on marine to non-marine mudstones to assign volcanism associated with N. Atlantic opening in west Greenland to nannoplankton zones NP3 to NP8. The volcanism was early in comparison with other parts of the North Atlantic Tertiary Igneous Province, but was on the fringe of the area thought to have been influenced by the Iceland plume. R. C. O. Gill, A. K. Pedersen & J. G. Larsen (Royal Holloway and Bedford New College, University of Copenhagen and Haldor Topsoe A/S) discussed the geochemistry of Tertiary picrites from west Greenland. Although these lie the other side of the Greenland continent from the generally accepted position of the Iceland plume during Atlantic opening, they have very high MgO contents (many over 20%), implying that they may have been generated from very hot (>1600 °C) plume mantle. A. M. Joy & J. Cartwright (Imperial College) documented heat flow in the North Sea and its relationship to basin subsidence during the time when the N. Atlantic opened, and suggested that lithospheric cooling implied by subsidence data is not consistent with the presence of hot, plume-convected asthenosphere.

Two talks were given in a session on the Yellowstone mantle plume and crustal extension in the western USA. S. A. Gibson et al. (Durham University) reviewed the tectonic setting of the extension. She described a c. 700 km geochemical transect across the Oligo-Miocene Rio Grande rift, whose geochemical character is well-documented. Strongly potassic magmas derived from lithospheric mantle are found on the rift flanks, where lithospheric mantle was thick, and basalts from an asthenospheric source are restricted to the axial part of the rift, where lithospheric thinning was greatest. R. Westaway (Durham University), in a paper on the Yellowstone plume and crustal deformation, showed that, as the Yellowstone plume moved NE relative to the continent, the deformation to the sides of the trail of the plume migrated with it, continually creating new normal faults.

The second day of the conference was mainly devoted to consideration of the southern continents and the break-up of Gondwana in the Mesozoic. K. G. Cox (Oxford University) gave a keynote lecture on continental flood basalt magmatism in the Karoo and Ferrar provinces and its relationship to tectonic processes during the rifting of Africa from Antarctica. He stressed the possible importance of the back-arc setting of the Karoo and Ferrar relative to the Pacific margin of Gondwana and how this may have influenced the chemistry of the basalts.

T. Alabaster & B. C. Storey (Sunderland Polytechnic and British Antarctic Survey) discussed the geochemistry of volcanic rocks from West Antarctica associated with Gondwana break-up. They suggested that the Ferrar basalts may have had a similar lithospheric mantle source to the Antarctic Peninsula Mesozoic magmatic arc. They documented transitions from basalts dominated by sources in lithospheric mantle, to basalts of MORB composition, as an asthenospheric source was progressively tapped during opening of the South Georgia basin. Break-up was due to variations in the regional stress field associated with changing plate boundary forces. M. P. R. Light, M. P. Maslanyj & N. L. Banks (Intera ECL Petroleum Technologies) presented seismic reflection data for the Namibia continental shelf. These revealed Basin and Range-type extensional features which were compared to Mesozoic structures along the S. American margin. They also reviewed the development of the Gondwana mobile belt and the translocation of microcontinental blocks during break-up. D. H. Elliot (Ohio State University), in describing the geological setting of the Kirkpatrick basalts of the Ferrar, argued that the basin into which they were erupted was in a back-arc setting, because preceding sediments contain volcanic clasts. He discussed the trace element and radiogenic isotopic geochemical composition of the Ferrar, and its wider tectonic setting of eruption within Gondwana. T. S. Brewer et al. (Nottingham University) described the geochemistry of Ferrar rocks from the Theron Mountains, which represents the zone where magmas of Karoo and Ferrar geochemical types met. He reviewed evidence from trace elements and radiogenic isotopes that the Ferrar mantle source was subduction-modified lithospheric mantle, and that an asthenospheric chemical end-member has yet to be identified. A contribution by R. C. Bostrom (University of Washington), on the effects of pressure changes in mantle, possibly causing volcanism and generated by wander of Gondwana relative to the poles, was read by the convenor. I. W. D. Dalziel (University of Texas at Austin), in a keynote lecture, presented reconstructions of Gondwana break-up incorporating new palaeomagnetic data, and summarized recent claims that East Antarctica broke away from the western margin of the N. American continent at around the end of the Precambrian, in a much earlier episode of supercontinent break-up. R. J. Pankhurst & C. W. Rapela (British Antarctic Survey and La Plata University) described a suite of Triassic-Jurassic I-type granitoid intrusions in Patagonia, which were emplaced in a dextral shear zone that was suggested to have been active during the early stages of rifting of the Falklands Plateau from Africa. M. Storey et al. (Leicester University) described the geochemistry of Cretaceous basalts from Madagascar, which erupted when Madagascar rifted from the Seychelles/India close, to the Marion mantle plume. Geochemically, many of the basalts contain input from lithosphere or MORB-source mantle. Others, tholeiites, are very like Marion basalts, which means that their source must have been in mantle convected by the Cretaceous plume. M. F. Coffin (University of Texas at Austin) reviewed data on the volumes and eruption rates of the Ontong Java and Kerguelen oceanic plateaus, the two largest extrusive igneous provinces, and their relationship to continental flood basalts.

C. J. Hawkesworth et al. (Open University), in the last keynote lecture, discussed the geochemistry of the Paraná continental flood basalts, and their relationship to the Tristan da Cunha mantle plume and the opening of the S. Atlantic. Most of the basalts have compositions indicating sources in the lithospheric mantle, but one group of dykes it was argued, were derived from mantle connected by the Tristan da Cunha mantle plume. They discussed the correlation of the increasing asthenospheric input to continental flood basalts with amount of lithospheric stretching. W. E. Stephens, C. W. Devey et al. ( Universities of St Andrews and of Kiel) discussed magmatism on the Seychelles, which formed when the continental fragment rifted from India and the Deccan traps were erupted. C. W. Devey, who gave the talk, described the similarities of alkaline complexes which were emplaced on both sides of the rift a few million years after the main basaltic outburst. R. W. Kent et al. (Leicester University) reviewed the magmatism associated with the rifting of India from Antarctica in the vicinity of the Kerguelen plume, with emphasis on the geochemistry of lamproites that pre-dated basaltic volcanism and rifting. M. Wilson (Leeds University) described rifting and magmatism in West Africa and eastern Brazil that pre-dated the opening of the Atlantic in the vicinity of the St Helena mantle plume. She
suggested that relationships between tholeiitic and alkaline magmas and the plume implied that the plume pre-dated, but did not cause, break-up.

Several posters depicted aspects of Gondwana break-up. B. C. Storey et al. (British Antarctic Survey) described magmatism in Marie Byrd Land associated with the Cretaceous separation of New Zealand from West Antarctica, and suggested that the rift was underlain by a mantle plume. T. S. Brewer et al. (Nottingham University) used $^{40}$Ar/$^{39}$Ar age determinations to date Ferrar magmatism in the Theron and the Pensacola Mts between 180 and 170 Ma, overlapping Karoo volcanism, with one date of 195 Ma. N. C. Ghose et al. (Patna University) described the subaerial volcanological features of the compositionally-diverse, voluminous Rajmahal volcanics whose eruption was associated with rifting of India from Antarctica.

R. W. Brown, A. J. W. Gleadow & M. A. Summerfield (Universities of La Trobe and of Edinburgh) presented apatite fission track analyses for the SE and SW margins of Africa, and argued that cooling ages which post-date ocean opening by 40–50 Ma record periods of tectonic re-organization.

K. H. Brodie & E. H. Rutter (Manchester University), in describing mafic intrusions in the granulite and amphibolite facies post-Hercynian extensional Ivrea Zone, Italy, showed they take several forms, but a major one is a laccolith which became deformed owing to density contrasts with surrounding granulite. The Ivrea Zone is a plausible analogue for younger areas of stretching of continental crust associated with underplating of basalt.

What was learnt from this meeting? The link between magmatism and continental break-up is clearly not simple, as continental rifts and margins range from strongly volcanic to virtually non-volcanic. Nevertheless, most of the world’s continental flood basalts provinces are associated with continental break-up. Ideas on the origin of such basalts have developed rapidly during the last few years. A popular model is that they result from lithospheric stretching over mantle plumes, which consist of mantle specified as being hotter than normal. One thread of the meeting was that such plumes (if they indeed exist) play a subordinate role in continental break-up, the driving forces coming from a continent-wide extensional stress regime. A new and encouraging trend in geochemical studies of continental flood basalts and other basalts, is a much more rigorous attempt to identify compositional end-members that were derived from particular mantle plumes. First attempts have been successful, and provide more evidence in favour of the mantle plume model for genesis of continental flood basalts. Nevertheless, in some cases, notably the Ferrar, no clear asthenospheric composition has (yet) been identified. Another thread is that magmatism, especially when of large volume, tends to concentrate where continental lithosphere is thinnest and weakest. This can result in magmatism following pre-existing lineaments, or in magmatism occupying the sites of much earlier basins, with potential for confusion over the trail of a possible plume head. If mantle plumes are coincidental to continental break-up, they do seem to have been rather common as the separate pieces of Gondwana rifted apart. Was this a product of insulation of heat within the convecting mantle by the supercontinent, leading eventually to increased mantle upwelling in the form of plumes? Anyone attending the meeting in the hope of discovering such underlying cause of continental break-up would not have been totally satisfied, and there is clearly plenty of scope for future research. Contributions to this stimulating meeting will be published as a Special Publication of the Society.