Episodic Rift Magmatism: the Need for a New Paradigm in Global Dynamics

Kenneth D. BAILEY[1] *and Alan R. WOOLLEY*[2]

[1] *Department of Geology, Bristol University, Queens Rd., BS8 1RJ, United Kingdom*
[2] *Department of Mineralogy, Natural History Museum, Cromwell Rd., London SW7 5BD, United Kingdom*

ABSTRACT. Intracontinental rift magmatism is characteristically alkaline, but a vital feature of alkaline magmatism in general, is repetition of such activity through the same segment of the lithosphere over geologic time. Severe constraints are thereby imposed on source compositions, and processes of magma generation, which may be overlooked where attention is focussed on a single period of magmatism and rifting. When the canvas is broadened to other rifts in the same plate the constraints are multiplied, because with increasing age data it is becoming apparent that in many cases igneous episodes in different rifts are synchronous. Petrogenetic options are still further constrained when intracontinental rift episodes are found to coincide with external, global events.

Since the late Precambrian, when the African plate became essentially anorogenic, the carbonatite/alkaline igneous age pattern emerges as spikes of activity, which correlate with external events. Until the Cretaceous the spikes are of similar form, but in the Cretaceous and in Tertiary–Recent, unprecedented levels of activity were unleashed across the African plate. The Cretaceous "storm" is also signalled in kimberlite activity peaks, especially in southern Africa.

The clearly-defined surge in igneous intensity during the Cretaceous correlates with the Magnetic Quiet Zone (CN superchron), and is matched by major magmatic bursts in other plate interiors, and by changes in sea floor spreading rates, sea levels, sedimentation and chemical stratigraphy. It may be noted also that magmatic outbursts marking the Early and Late Cretaceous are neither exclusively alkaline, nor continental. Both of the biggest oceanic Large Igneous Provinces, Ontong-Java and Kerguelen plateaux, have their main eruption dates around 120 Ma and 85 Ma. Such correlations are consistent with the geophysical inference that the CN superchron marks a critical perturbation in mantle dynamics over this period.

Petrogenetic hypotheses currently in vogue are clearly inapt for the new scenario emerging from the improving chronology of magmatism, tectonics and other worldwide phenomena. Continental rifting and magmatism, therefore, must be manifestations of a larger, global process, which simply triggers the re-opening of old zones of weakness in plate interiors. Re-opening of the channels allows a new flux of volatile and incompatible elements to move into the lithosphere, with all the potential for metasomatic enrichment, and ultimately to near-solidus melting and typical alkaline magmatism. No matter what melt mechanism is preferred, continental rift magmatism declares that the final control is plate structure, and the process cannot be lithosphere independent.

Global correlations of magmatism, plate motion changes, and surface responses call for a new paradigm for global tectonics

KEY WORDS: permissive, repeated, synchronous, magmatism, global correlations, core, lithosphere.

Introduction

In the consideration of magmatism and rift basin evolution in continental interiors the defining question must be:is the magmatism active or permissive?

"Active", requires a driving mechanism below the lithosphere, i.e., the magmatism is lithosphere independent. Rifting should thus be possible anywhere, any time, regardless of the lithosphere condition. "Permissive" is where the existing lithosphere condition (governed by its previous evolution) controls the rift formation and associated magmatism (if there is any). Understanding basin development must hinge on the choice between the two alternatives, because magmatism is a marker in time and space, and therefore a vital key to any story of evolution.

These alternative hypotheses cannot be rigorously tested directly by either geochemical or geophysical measurements alone, although obviously these provide vital information for the total geological picture. Trace element and isotope geochemistry patterns in the magmas have been used to argue in favour of sub-lithosphere plume sources, but these are nearly all (if not all) model dependent, the identifiers being derived from oceanic island volcanism, where a plume has been assumed as the source, making the argument circular, i.e., in this scenario the "active" case has been set a priori, for intra-continental magmatism.

The only real test is geology, because this takes account of magma composition ranges and variations, timing, and spatial relations, with the potential to examine event synchroneity across plates and between plates. Such evidence, from the African rift magmas shows that these are permissive and must be expressions of global forces acting on the African plate. Constraining parameters are: location of magmatism at ancient lithosphere defects; repeated activity at the same sites; synchronous activity across the plate; repeated synchronous activity; and correlations with other global events.

Magmatism and lithosphere stucture

In the African case, it has been long recognised that the rift pattern is largely determined by the structural grain of the crystalline basement. An outstanding example is seen in the southern end of the modern E. A. rift, around the Tanzania craton, where the W and E branches re-join, and from whence they pass southwards into the older rifts of Luangwa (Zambia) and Malawi. The fundamental lithosphere lineament patterns (NE and NW) were already established by Precambrian, where two orogenic belts intersect as they wrap round the south end of the

Tanzania craton. The rifts follow these earlier structural trends and mark a modern reopening of the old lesions in the lithosphere. This girdling of the craton nucleus was described as "rift and shield structure" by McConnell (1949).

Located exactly on the rift intersection is the most southerly expression of modern E.A.rift magmatism, in the small, isolated nephelinite–basanite province of Rungwe (Harkin 1960). Four hundred kilometres to the WNW is the deep modern rift basin occupied by Lake Tanganyika, and there the lack of associated volcanism, in the most spectacular rift basin on Earth, is a useful reminder that magmatism is not a prequisite of continental rifting.

It has been hypothecated that the Rungwe volcanics are the surface manifestation of an underlying plume, i.e., the magmatism is active (Burke and Dewey 1973): and some interpretation of recent rift structures has been linked to the supposed plume activity (Ebinger et al. 1989). No independent evidence for a plume has been put forward, so its existence is inferred. Hence, this invokes a lithosphere independent column from the deep mantle arriving, by chance, exactly underneath a lithosphere weak spot that has existed for more than 2 Ga. But Rungwe is just a specific case of the general relationship across Africa, where the rifting and associated magmatism correlate with pre-existing lithosphere lesions. This fact alone has always put an active mechanism in question, but the geologic record shows that this has happened not just once but repeatedly.

Repeated magmatism at the same sites

A well known feature of continental alkaline magmatism is repetition of the activity at the same sites (Bailey 1961, 1977; Barker 1974), and constraints on the possible relationship between magmatism and rifting become clear in cases where they have both been repeated in time. Around the Rungwe intersection, there have been at least 5 earlier episodes stretching back to the Precambrian, Table 1 and Fig.1. During this time the African plate shows a polar-wander shift of over 110 degrees of latitude: thus, the same lithosphere anisotropy would be required to have alighted on at least six different plumes as it migrated over the deep mantle.

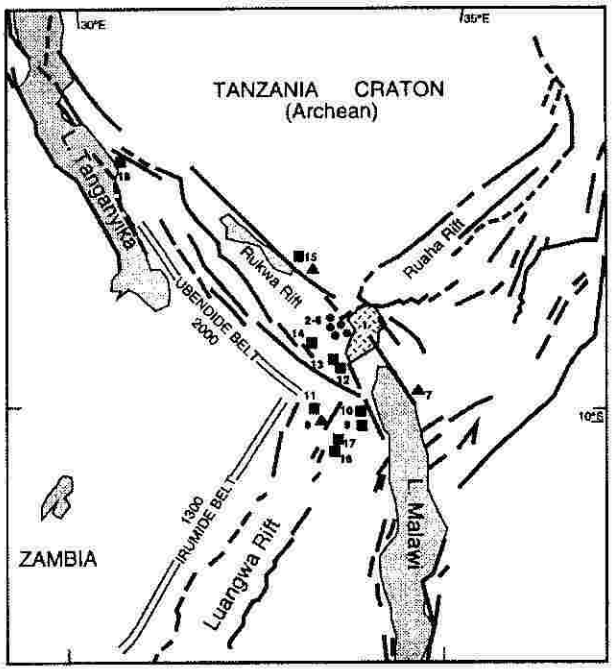

Fig. 1. Intersecting rift zones at the south end of the Tanzania craton. The Rungwe volcanic field (1) is shown ornamented: older complexes are numbered as in Table 1, (which gives ages, and main rock types). For ease of visualisation in the diagram, igneous ages are grouped: filled circles – Cretaceous; squares – Proterozoic; triangles – age uncertain. Fold belt structural trends indicated by fine continuous lines, rift faults by heavy lines.

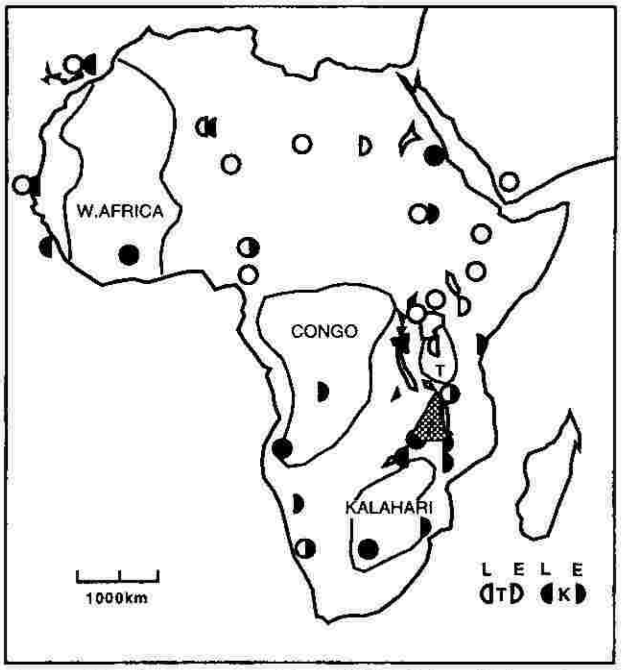

Fig. 2. Synchronous repetition of CALK in widely scattered provinces across the African plate. Since Gondwana break-up the activity peaks E-K, L-K, E-T, T-R in Fig. 1, are registered in 29 provinces, most of which have already yielded records of two or three of the four episodes. This space-time distribution requires that triggering of CALK eruptions must be a plate-wide episodic phenomenon, exploiting pre-existing anisotropies in the lithosphere. (For localities and references see Bailey 1992). The stippled area south of L.Tanganyika shows the approximate position of the Precambrian upland bounded by the rift zones of Luangwa–Zambesi–Malawi, as referred to in the text.

To counter the difficulty imposed by rift magmatism correlating with lithospere structure, some advocates of the plume hypothesis (e.g.Thompson and Gibson 1991), have suggested that the plume head is not under the rift, but below an adjacent craton (its precise position unspecified). Direct surface eruption from the plume head is supposedly prevented by the thick, impenetrable craton lid, while magmatism in the rift is a distal expression of the plume spreading and ultimately exploiting a "thin spot" in the lithosphere. It is important to realise that this is merely re-affirming that there is no direct evidence for a plume, which has been invoked purely as an explanation for the thermal anomaly, and/or the chemistry, registered in the rift magmatism. Furthermore, it tacitly concedes that the magmatism is permissive, and consequently not lithosphere independent, anyway! To hold that this has happened repeatedly around the Rungwe intersection would require a total faith in sub-lithosphere plumes as the only conceivable cause of intraplate magma generation. As the vast bulk of the Earth's magmatism (MORB and

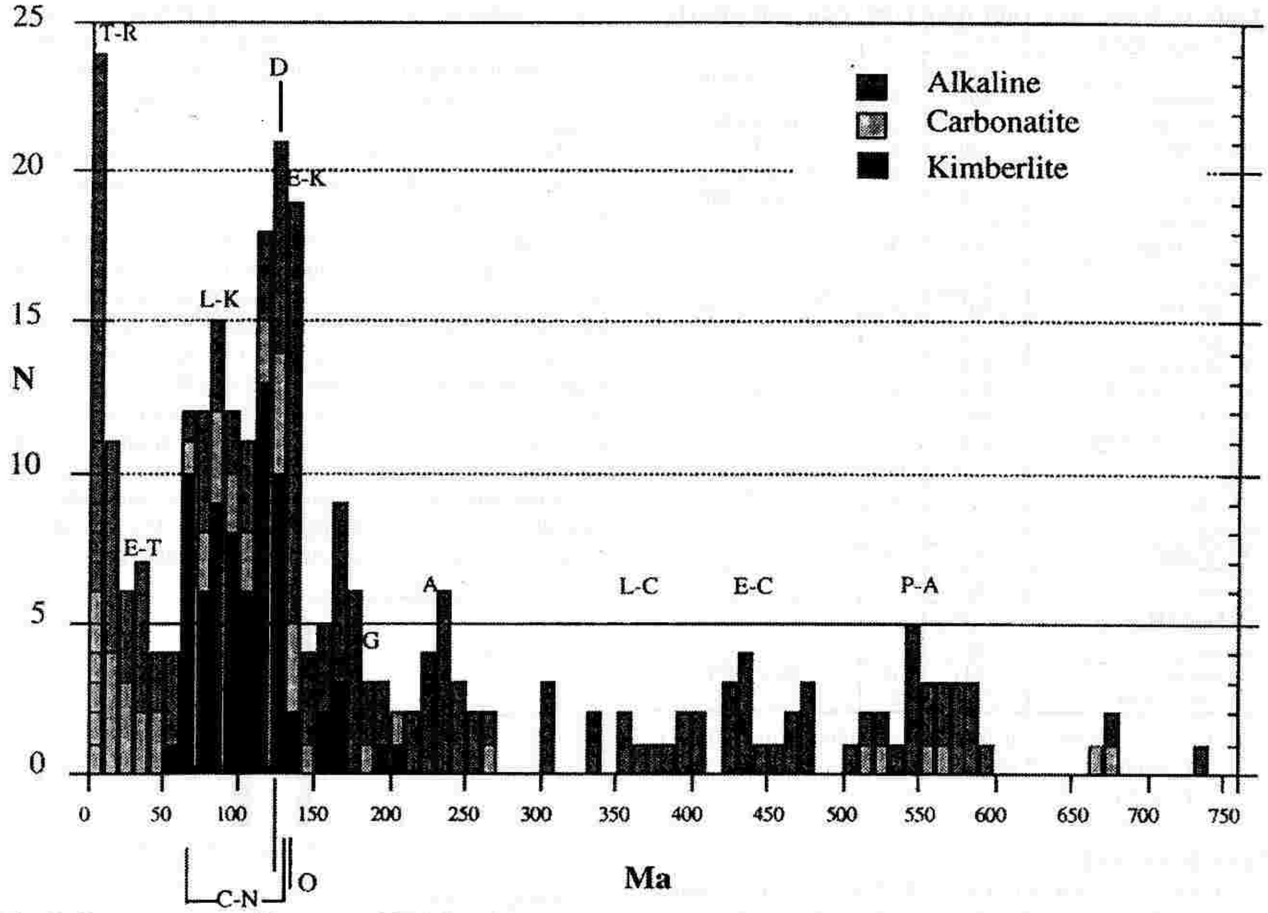

Fig. 3. Frequency vs. age histogram of CALK activity across Africa (A&L combined). Episodes: P-A – Pan-African; E-C – Early Caledonian; L-C – Late Caledonian; A – Armorican; G – Gondwanaland starts to break up. Africa/Europe start to collide: O – according to Olivet et al. (1987); D – according to Dewey et al. (1989). C-N shows span of CN superchron. Cretaceous–Recent peaks: E-K; L-K; E-T; T-R. From Bailey and Woolley (1995). Details on igneous ages, data, methods, sources, in Woolley (in prep.).

subduction related) does not call for plume generation, a total reliance on unseen plumes for continental rift magmatism, would seem to require an abnegation of scientific scepticism. Difficulties for the active (plume) hypothesis do not end here, because synchronous magmatism in other rifts calls not only for coincidences of repetition in one place, but for multiple outbreaks at different places.

Synchronous activity

At Rungwe there are at least six complexes with Cretaceous dates, of which the two oldest match the time of onset of the classic Chilwa activity in Malawi, and Rufunsa in Zambia, the others fitting the broader age spectrum of Chilwa/Lupata (Mozambique). This Early Cretaceous activity is localised by the older rift system of Malawi/Luangwa/Zambesi (shaded, in Fig. 2). If there were indeed an "active" (plume) source for this magmatism, it would presumably have to be hidden under the narrow wedge of Precambrian between these rifts, which hardly qualifies in size or age (being partly Pan-African, ~500 Ma) as a thick cratonic lid. But this group of contemporaneous complexes is, in any case, merely one facet of Early Cretaceous activity, which is registered all across Africa (Fig. 2) and beyond.

Furthermore, Fig. 3 shows that synchronous activity like that of the Early Cretaceous has also been repetitive through time.

Repeated synchronous activity

Over the last 700 Ma, the carbonatite/alkaline igneous/lamproite/kimberlite (CALK) age pattern in Africa emerges as spikes of activity, the major ones correlating with external events (Fig. 3). Until the Cretaceous, the spikes are of similar size. In the Cretaceous and in Tertiary–Recent, however, unprecedented levels of activity were unleashed across the African plate. The Cretaceous "storm" is also signalled in exceptional kimberlite activity, especially in southern Africa. Within the high CALK levels of the Cretaceous–Recent at least four peaks emerge: Early Cretaceous (E-K~130 Ma); Late Cretaceous (L-K~85 Ma); Early Tertiary (E-T~40 Ma); Late Tertiary–Recent (T-R~20 Ma): this data comes from 29 distinct areas scattered across Africa, with CAL notably coinciding with regions affected by the Pan-African thermal event, more than 400 m.y. earlier (Thorpe and Smith 1974). Furthermore, of these 29 Cretaceous–Recent CALK provinces, from Canaries to Kalahari, only 6 have so far failed to record more than one of the four activity peaks. These patterns require repeated control of the magmatism by the structure of the lithosphere in terms of time, space and magma compositions.

ERUPTIVES (MAP No's)	AGE (Ma)	TYPE	CONTEMP.EVENTS
1.Rungwe Volcanics	10--0	A	
Interval	*90*		Zero Closure
2.Songwe	100	C	
3.Musensi	100	C/A	ALPIDES
4.Sengeri	100	C	
5.Panda Hill	113	C	Africa/Europe
6.Mbalizi	120	C	collision starts
7.Makonde	<200	C	
8.N. Luangwa	<200	L&K	
Interval	*400*		
9.Tambani	551	A	PAN-AFRICAN
Interval	*100*		
10.Chikangwa	650	A	
11.Nkumbwa Hill	679	C	
12.Ilomba	685	A	
13.Nachendezwaya	685	C/A	
Interval	*60*		
14.Mbozi	745	A	PAN-AFRICAN
Interval	*300*		
15.Ngualla	1041	C/K	?
Interval	*90*		
16.Lusenga	1134	A	?
Interval	*200*		
17.Mivula	1341	A	IRUMIDES
18.Sangu-Ikola	(Prot.)	C	?

Tab. 1. CALK episodes at the Rungwe intersection (Fig. 1). Complexes 2–17 are within 120 km of Rungwe Volcanics (1).

Global events

The Early (~130 Ma) and Late (~85 Ma) Cretaceous peaks, defining a broad surge in igneous intensity during the Cretaceous, correlate with the start and end of the Magnetic Quiet Zone (CN superchron), matched by major magmatic bursts in other plate interiors, (e.g.contemporaneous kimberlite activity in west Africa, and Brazil). At the same times there were global changes in sea floor spreading rates, sea levels, sedimentation, chemical stratigraphy, and in plate motion patterns and velocities. Such correlations may be linked with the geophysical inference that the CN superchron marks a critical perturbation in core dynamics over this period (Piper 1987). It may be noted also that magmatic outbursts marking the Early and Late Cretaceous are not confined to CALK. Both the most voluminous of the large igneous provinces (LIP's) on the oceanic plates, Ontong-Java (M. Coffin pers. comm.) and Kerguelen plateaux (Pringle et al. 1995), each give peak dates around 120 Ma and 85 Ma (Fig. 4), and the same may be true for many sea-mounts (Pringle pers. comm.). Pre-Mesozoic episodes of intracontinental igneous activity may prove to be the best signals of similar global events, where the detailed magnetic record is not available.

Two points may be emphasised: firstly, it is clear that a magnetic quiet zone in itself is not a requirement for CALK, even for high intensity levels, because activity is equally, or more intense in the Tertiary–Recent, when magnetic reversals have been multiple; secondly, the major pre-Cretaceous peaks correlate with orogenic periods outside Africa itself (in other parts of Pangea, prior to breakup). This suggests that CALK activity is triggered by stresses transmitted across the plate; nicely exemplified in the Early Cretaceous outbreak (~130 Ma). This marks not only the start of the CN superchron, but also coincides with the initiation of Africa/Europe collision (Fig. 4): the connection may be that the profound change in mantle dynamics linked to the superchron, registers in the lithosphere as a major change in plate motion patterns, here resulting in collision. Intraplate magmatism coinciding with collision events is concentrated along rift zones where old lineaments have yielded to extensional stresses. A second marked burst in the Late Cretaceous (~85 Ma), signals the end of the CN superchron: in the Alpine collision sequence this also heralds a period of zero closure rate (~40–70 Ma), coinciding with a marked lull in CALK activity across Africa (Fig. 4).

The second igneous peak, in the Late Cretaceous (L-K, Fig. 3), correlates with a major change in the movement patterns during the dispersal of the Gondwana plates, marked by the dramatic switch to the "northward flight" from Africa of Australasia and India (Olivet et al. 1987). In Africa, at this time, magmatism mainly took the form of kimberlite (Group 1) activity across the craton interiors, with less in the girdling rift zones, indicating a different stress regime from those episodes correlating with plate collisions. Instead the rifts appear to be partly accommodating the regional strain across the plate, while also transmitting a large part through the cratons. One explanation is that the African plate was subject to rotational forces by the

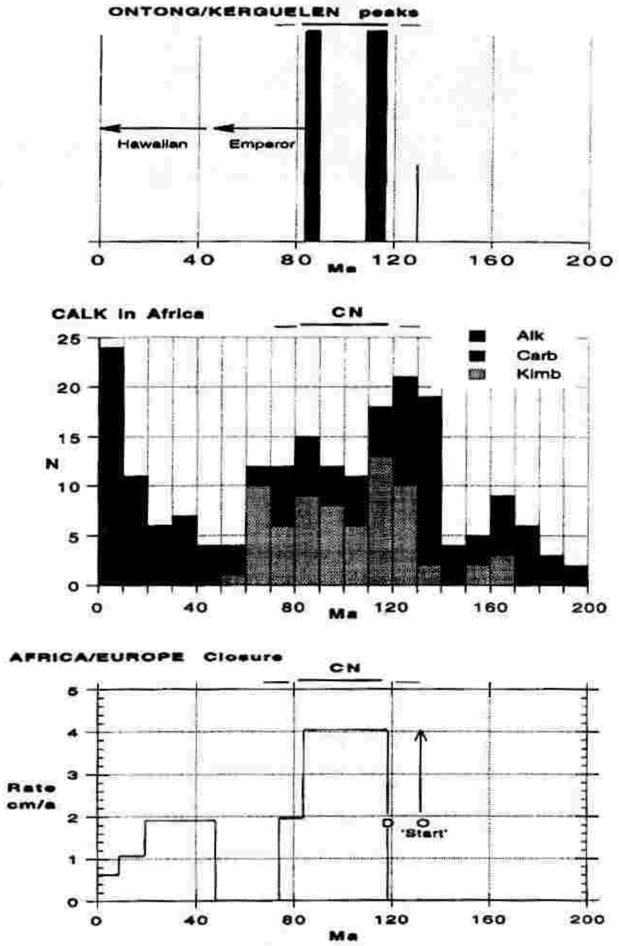

Fig. 4. Age correlations of magmatic events with the CN Superchron (time span shown at top). Two main age peaks of the large igneous provinces (LIP's) of Kerguelen and Ontong-Java plateaux (Pringle et al. 1995; M. Coffin pers. comm. 1995; A.D. Saunders pers. comm. 1995), and key dates in Emperor– Hawaiian line. Igneous ages histogram for CALK across Africa (sources as for Fig. 3). Closure rates for Africa/Europe collision (calculated from Dewey et al. 1989: Fig. 1, east end of Mediterranean).

changes in plate movement directions. Thus, instead of the rifts acting as loci of extension (as in a backlash from collision events) they were yielding by transcurrent shear. Such a rotational movement pattern, imposing torque stresses across the interior cratons, could cause yielding by brittle failure, permitting the release of fluids and melts through the cratonic lithosphere lid. Contemporaneous kimberlite activity is registered in west Africa, southern Africa, and Brazil, suggesting an important connection between the style of this tectonism and the nature of the associated magmatism. It may be inferred that Group 1 kimberlite is available for eruption from beneath the cratons and merely requires the type of brittle failure registered in the late Cretaceous, for its release.

Another global episode of kimberlite activity is recorded in the Proterozoic, ~1,200 Ma (Skinner et al. 1985), and presumably marks a similar fundamental switch in plate movement patterns. A new appraisal of the regional stress patterns prevailing during kimberlite eruptions may provide a critical test of the links with global dynamics.

Contraints from source composition and melting history

A lithospheric contribution to the magmatism is widely invoked, and a popular source rock for carbonatite/kimberlite/alkaline ultramafic activity is carbonated phlogopite peridotite. Such a protolith must be the product of sub- to near-solidus metasomatism of the mantle source, which can have occurred only after the last major melting and extraction event in that segment of the mantle. Subsequent levels and types of igneous activity must therefore partly reflect the extent of CO_2 and incompatible element sequestration to the continental lithosphere.

Thus, if the lithosphere mantle has been depleted in incompatible elements by earlier melting events, as widely believed, then a new influx prior to rift magmatism must be a pre-requisite.

A model for continetal lithosphere controlled alkaline magmatism

For alkaline magmatism to be controlled by rifts in the continental lithosphere, permissive release of a heat and materials flux from the sub-lithosphere is the essential factor. Focussing is achieved by the narrow zone through the plate acting as an easy escape channel for fluids drawn from a large sub-lithosphere reservoir (the "pie funnel" effect). Over a long period this leads to metasomatic pre-conditioning of the lithosphere below the rift, ultimately leading to melting when the flux intensifies in a new episode of rift re-activation. Melt types, and degree of melting, would be largely dependent on the pre-existing geothermal gradient (so that long sectors of the rift may not exhibit magmatism at all): by contrast, extensive magmatism marks the site of melt segregation and diapirism within the lithosphere mantle. This may end in "thermal runaway", with high volume basalt generation, and, given appropriate freedom for plate movement, finally to lithosphere separation and asthenosphere upwelling (Bailey 1983). To the essentials of this hypothesis, particular aspects were subsequently developed, such as flux melting, felsic melts in the mantle, styles of eruption (Bailey 1986; 1987), and the consequences of thermal/gravitational anomalies below the rift (Bailey 1992). Some such permissive release through rift zones is necessary to reconcile all the observations on lithosphere structure, melt and ultramafic xenolith compositions, magma siting, timing, repetitions, synchroneity, and correlations with global events.

Global events and core/lithosphere correlations

Close correlation between the Cretaceous surface record and the magnetic quiet period impose severe constraints on the driving mechanism:

1. Such episodes cannot be reconciled with plume activity that is independent of the lithosphere, or its movement pattern, and must be signalling Earth-wide changes in the interior dynamics.
2. Generally accepted flow velocities for mantle circulation (3–10 cm/year) mean that the surface record could not register 'instantaneous' responses to convective changes initiated at the core/mantle boundary, as required by correlation with the start and end of the CN superchron. The lithosphere must be more closely coupled dynamically with the reversal mechanism (most dramatically underlined by rapid surface responses at the end of the superchron). In searching for the core lithosphere link, Vogt (1975), elected for fast rising plumes, but these need rise speeds in excess of 50cm/year. Even if this were the link mechanism, it still offers no support for "active" intracontinental magmatism, because the "superplumes" are elsewhere. It is difficult to envisage a mechanism within the limitations of present convection concepts.

Essentially, global magmatic synchroneity must be linked with plate movement patterns (and the processes that drive them), which we suggest requires a new concept involving rapid stress transmission through the mantle, to explain how events marking changes in the Earth's core could impact so rapidly on the lithosphere, and on surficial processes.

References

BAILEY D.K. 1961. The mid-Zambezi–Luangwa rift and related carbonatite activity. *Geol. Mag.*, 98, 277–84.

BAILEY D.K. 1977. Lithosphere control of continental rift magmatism. *J. Geol. Soc. London*, 133, 103–106.

BAILEY D.K. 1983. The chemical and thermal evolution of rifts. *Tectonophysics*, 94, 585–597.

BAILEY D.K. 1986. Fluids, melts, flowage and styles of eruption in alkaline ultramafic magmatism. *Trans. Geol. Soc. S. Afr.*, 88 (2), (1985), 449–457. Special Issue: "Alkaline and Alkaline-Ultrabasic Rocks and their Xenoliths".

BAILEY D.K. 1992. Episodic alkaline igneous activity across Africa: implications for the causes of continental break-up. In STOREY et al.: Magmatism and the causes of continental break-up. *Geol. Soc. Spec. Publ.*, 68, 91–98.

BAILEY D.K. 1987. Mantle metasomatism: perspective and prospect. In FITTON J.G. and UPTON B.G.J. (eds.): Alkaline Igneous Rocks. *Geol. Soc. Spec. Publ.*, 30, 1–13.

BAILEY D.K. and WOOLLEY A.R. 1995. Magnetic quiet periods and stable continental magmatism: can there be a plume dimension ? In Anderson D.L., Hart S.R., and Hofmann A.W., convenors, Plume 2, *Terra Nostra*, 3/1995, 15–19, Alfred-Wegener-Stiftung, Bonn.

BARKER D.S. 1974. Alkaline rocks of North America. In SØRENSEN H. (ed.): *The Alkaline Rocks.* Wiley and Sons, London, 160–171.

BURKE K. and DEWEY J.F. 1973. Plume-generated triple junctions: key indicators in applying plate tectonics to old rocks. *J. Geol.*, 81, 406–33.

DEWEY J.F., HELMAN M.L., TURCO E., HUTTON D.H.W. and KNOTT S.D. 1989. Kinematics of the western Mediterranean. In COWARD M.P., DIETRICH D. and PARK

R.G. (eds.): Alpine Tectonics. *Geol. Soc. Spec. Publ.*, 45, 265–283.

EBINGER C.J., DEINO A.L., DRAKE R.E. and TESHA A.L. 1989. Chronology of volcanism and rift basin production: Rungwe Volcanic Province, East Africa. *J. Geophys. Res.*, 94, 14785–15803.

HARKIN D.A. 1960. *The Rungwe volcanics at the northern end of Lake Nyasa.* Memoir II, Geological Survey of Tanganyika.

McCONNELL R.B. 1951. Rift and shield structure in East Africa. *International Geological Congress*, 14, 199–207.

OLIVET J.-L., GOSLIN J., BEUZART P., UNTERNEHR P., BONNIN J. and CARRE D. 1987. *The break-up and dispersion of Pangea.* Coedition Elf Aquitaine (Pau) and IFREMER (Brest) (Wall map, with text on reverse).

PIPER J.D.A. 1987. *Palaeomagnetism and the continental crust.* Open University Press, Milton Keynes, 434 pp.

PRINGLE M.S., MITCHELL C., FITTON J.G. and STOREY M. 1995. Geochronological constraints on the origin of Large Igneous Provinces: examples from the Siberian and Kerguelen flood basalts. In ANDERSON D.L., HART S.R. and HOFMANN A.W. (convenors): Plume 2, *Terra Nostra*, 3/1995, 120–121, Alfred-Wegener-Stiftung, Bonn.

SKINNER E.M.W., SMITH C.B., BRISTOW J.W., SCOTT SMITH B.H. and DAWSON J.B. 1985. Proterozoic kimberlites and lamproites and a preliminary age for the Argyle lamproite pipe, western Australia. *Trans. Geol. Soc. S. Afr.*, 88, 335–340.

THOMPSON R.A. and GIBSON S.A. 1991. Continental mantle plumes, hotspots and pre-existing thinspots. *J. Geol. Soc. London*, 148, 973–977.

THORPE R.S. and SMITH K. 1974. Distribution of Cenozoic volcanism in Africa. *Earth Planet. Sci. Lett.*, 22, 91–95.

VOGT P.R. 1975. Changes in geomagnetic reversal frequency at times of tectonic change: Evidence for coupling between core and upper mantle processes. *Earth Planet. Sci. Lett.*, 25, 313–321.

WOOLLEY A.R. (in prep.) *Alkaline rocks and carbonatites of the world. Part 3: Africa.* Chapman and Hall, London.