Journal of African Earth Sciences, Vol. 3, No. 1/2, pp. 5–16, 1985
Printed in Great Britain

0731–7247/85 $3.00 + 0.00

The structural setting of alkaline complexes

R. Black, J. Lameyre

Laboratoire de Pétrologie (ERA 1011), Université P. et M. Curie, 4 Place Jussieu, 75 230 Paris, France

and

B. Bonin

Laboratoire de Pétrologie, Université Paris XI, Orsay, France

(*Received* 9 *September* 1984)

Abstract—The structural setting of major alkaline provinces in Africa are reviewed and compared with examples from Siberia, Europe, southern Greenland, and North America. It is concluded that the lithosphere has a very active role. Alkaline magmatism may be repeated over a long period of time in the same region and its degree of alkalinity and silica saturation are largely controlled by the age and thickness of the lithosphere. Alkaline magmatism occurs in a distensive regime which may or may not be associated with rifts and is often accompanied by crustal doming. Strike-slip movements and reactivation of transcurrent faults play a major role as do transform faults whose position may well have been determined by older lineaments in the continents. Processes of magma generation: mantle plumes, shear heating in the zone of decoupling at the base of the lithosphere, and pressure release accompanied by volatile input, are discussed. Importance is given to the "harpoon effect" which is believed to occur when there is reversal in the general sense of movement in a tear fault system. It is concluded that pre-existing abyssal faults determine the location of alkaline magmatism, and their reactivation is caused by lithospheric stresses related to changes in plate motion and orogenic events along plate margins. Thus alkaline within-plate magmatism is triggered from above, and hot spots may be regarded as passive centres of abundant volcanism whose location in ancient zones of weakness is determined by the dynamics of the lithosphere.

INTRODUCTION

A striking feature of the African continent, centre of past Pangeae configurations and of the break-up of Gondwanaland, is the display of spectacular arrays of alkaline intrusions often in the form of ring complexes whose ages range from over 2000 to 25 Ma. Many of them have been thoroughly investigated and include some of the best studied examples in the world. Their geodynamic significance, however, is a matter of controversy between tenants of the plume hypothesis (Morgan 1972, Gass *et al.* 1978) and those who favour lithospheric structural control (Bailey 1964, Bonin *et al.* 1972, Sykes 1978, Lameyre and Bonin 1978). In this review paper attention will be focused on the geological environment of alkaline within-plate magmatism.

The adjective alkaline to qualify a province or a rock association is given a wider sense than by Sørensen (1974) and Streckeisen (1976) to encompass hypersolvus metaluminous and subaluminous granites, which plot in the alkali granite field, and subsolvus granites of similar chemical composition, which in the modal diagram fall in the syenogranite field (Lameyre and Bowden 1982, Bonin 1982). The latter, although bearing some resemblance to end-members of calcalkaline series and to some leucogranites often associated with large tholeiitic bodies and which may be partly of anatectic origin, are typically associated with peralkaline granites and nordmarkites in within-plate anorogenic environments.

A distinction will be made between: (1) strongly undersaturated provinces which may be associated with ultrabasic rocks, carbonatites and kimberlites; (2) mixed silica saturated and undersaturated provinces; (3) oversaturated provinces, e.g. Younger Granites of Nigeria.

MAJOR ALKALINE PROVINCES OF AFRICA

A glance at Africa (Fig. 1) shows that the Phanerozoic oversaturated alkaline provinces occur exclusively in the Pan-African domains whereas mixed and dominantly undersatured provinces, ignoring Tertiary to Recent volcanism, tend to be located on the cratons or in the southern prolongation of the Mozambique Belt which is devoid of Pan-African granitoids.

In West Africa, *the Iforas oversaturated alkaline province* of ring complexes (Fig. 2), composed of nordmarkites, peralkaline and metaluminous granites and granite porphyries, have yielded Cambrian Rb–Sr whole-rock ages between 560 and 540 Ma (Liégeois and Black 1983, 1984, Ba *et al.* 1985). In this region, the Pan-African has been interpreted as the result of an oceanic closure with collision around 600 Ma ago between the passive margin of the West African craton and the active margin of the eastern edge of the Tuareg shield (Black *et al.* 1979a,b, Caby *et al.* 1981, Fabre *et al.* 1982). The alkaline ring complexes cut a late Pan-African cordilleran type composite calcalkaline batholith which during collision has been subjected to rapid uplift and unroofing (Liégeois and Black 1983). The switch from calcalkaline to alkaline magmatism around 560 Ma ago is marked by the intrusion of spectacular acid dyke swarms feeding extensive plateaux of rhyolite and ignimbrites which cap the eroded batholith

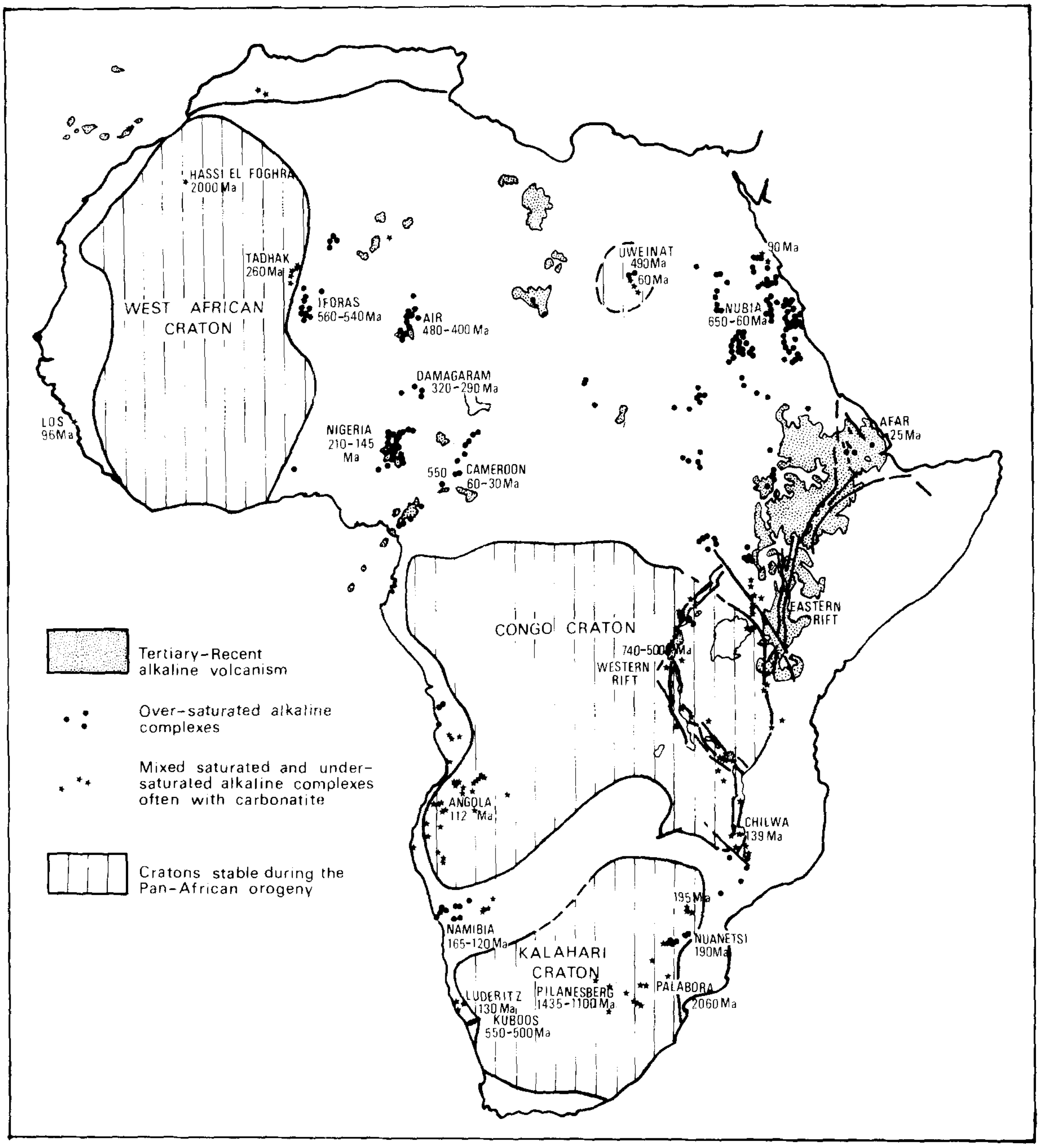

Fig. 1. Distribution of alkaline complexes in Africa.

and is followed by the emplacement of the alkaline ring complexes. This regime of distension can be attributed to a Riedel fracture pattern with intermittent movement along north–south mega shear zones and related secondary transcurrent faults which offset some of the complexes. It is important to note that the appearance of alkaline rocks is related to a change in the stress field: early calcalkaline dyke swarms striking WNW–ESE are cut by alkaline dyke swarms striking NNW–SSE. Alkaline massifs of similar age have been recorded in north-western Hoggar (e.g. In Zize) and in southern Benin (e.g. Fita) in the Pan-African close to the West African craton. In Central Hoggar the Taourirt granites, which are high level post-tectonic intrusions often disposed concentrically, are transitional in character and display both calcalkaline and alkaline trends (Boissonnas 1973). Their emplacement appears to have been controlled largely by movements along the 4°50′E mega shear zone and related transcurrent faults.

In contrast the *Tadhak province* (Sauvage and Savard 1985) situated 150 km to the west of the Iforas province, is strongly undersaturated and associated with carbonatites. It lies on the edge of the West African craton stabilized 2000 Ma ago which is devoid of Pan-African magmatism. Permian in age, it is structurally and spatially related to a north–south rift (Tesoffi graben) close to the suture (Liégeois *et al.* 1983).

The Aïr (480–400 Ma), *Damagaram* (320–290 Ma) and *Nigerian* (215–140 Ma) alkaline "Younger Granite" provinces are a unique feature in the world of practically continuous within-plate anorogenic volcanism and plutonism with progressive southern shift of centres of

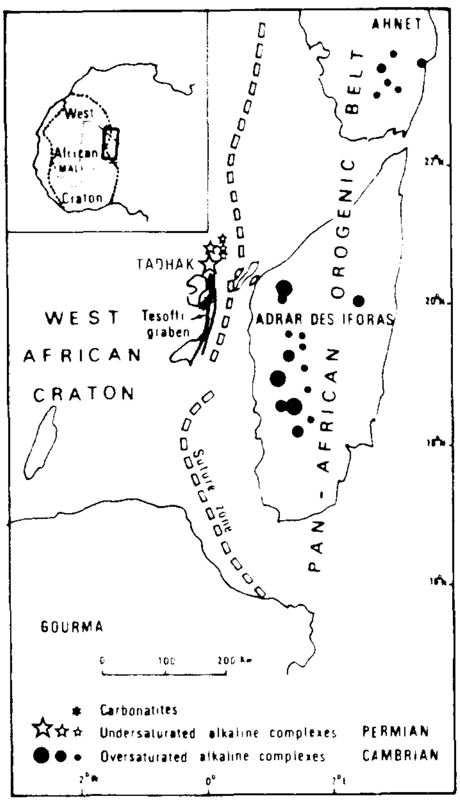

Fig. 2. Location of the Iforas oversaturated alkaline province and the Tadhak undersaturated province with respect tc the West African craton.

magmatic activity (Bowden *et al.* 1976, Karche and Vachette 1976). Whilst similar rock types are developed throughout the three provinces, the main varieties being acid lavas (rhyolites, comendites and ignimbrites), nordmarkites, aegirine–arfvedsonite granites, fayalite–hedenbergite granites, amphibole–biotite granites, biotite granites and minor amounts of intermediate and basic rocks, their relative proportions change from north to south: peralkaline granites and quartz syenites predominate in the Aïr where they may be associated with anorthosites (Black 1965, Black *et al.* 1967, Moreau, 1982, Leger 1985), and in the Damagaram (Black 1963, Mignon 1970), whereas metaluminous and subaluminous granites are the most prevalent rock types in Nigeria (Jacobson *et al.* 1958, Bowden and Turner 1974, Hossain and Turaki 1983). The three provinces lie between longitudes 8°E and 10°E in a 1300 km long north–south belt bound by shear zones which correspond to a polycyclic segment of the Pan-African orogenic belt invaded by abundant calcalkaline granites, which probably are largely of crustal origin (Black 1982). In Aïr extensive transcurrent faulting occurred prior to the emplacement of the ring complexes (Fig. 3) and was accompanied by crustal doming as indicated by the southerly tapering out of the Palaeozoic along the western border of the Aïr (Karche and Vachette 1976). To the south in Nigeria Rahaman *et al.* (1984) have shown that the migration of centres occurred along ENE–WSW and NNW–SSE lineaments (Fig. 4); the ENE–WSW lineaments correspond to the direction of late Pan-African dextral transcurrent faults in the basement and are parallel to the marginal faults of the Benue trough which has recently been interpreted as a pull-apart basin determined by sinistral shear (Benkhelil 1982), and which contains transitional basalts and alkali rhyolite which have yielded an Rb–Sr age of 113 ± 3 Ma (Umedji and Caen-Vachette 1983).

The Cameroon silica saturated alkaline province ranging in age between 60 and 30 Ma, but which includes an early complex dated at 550 Ma, also occurs within the Pan-African domain with abundant calcalkaline granitoids (Lasserre 1978). The massifs are aligned on the north–north-easterly "Cameroon line" defined by the Fernando Po, Principe and Sao Tomé islands. The NNE-faults observed in southern Cameroon are sinistral transcurrent faults which offset the Cretaceous basin (Reyre, personal communication). The "Cameroon line" should not be confounded with the late Pan-African Ngaoundéré shear zone which is the prolongation of the Pernambuco shear zone of NE Brazil and which in the Cretaceous guided the development of the Central African rift system as well as a rift system in Brazil (Almeida and Black 1968).

The north-eastern African province (Egypt, Sudan, Ethiopia) comprises over 130 ring complexes with ages ranging from 650 to 25 Ma showing peaks *ca* 550, 465–400, 245–230, 165–90 and 45–35 Ma, the most recent being Miocene in the Afar (Vail 1985, Black *et al.* 1972*a,b*). This time range is quite comparable to that of the Aïr, Damagaram, Nigerian and Cameroon provinces, but here there is no progressive southerly migration of igneous activity and alkaline magmatism recurs at different periods in the same region. With the exception of the Uweinat occurrences which cut basement stabilised around 2000 Ma ago (Klerkx 1979), the ring complexes occur in regions affected by the Pan-African and in the eastern part of the province, they are intrusive into Upper Proterozoic metavolcano-sedimentary sequences invaded by Pan-African calcalkaline granitoids. Some complexes in the Red Sea Hills may be post-tectonic calcalkaline granites related to a Pan-African subduction zone (Vail 1985). The anorogenic alkaline complexes show a distinctive change in the degree of alkalinity and silica-saturation with time: Palaeozoic complexes are generally oversaturated, whereas undersaturated rocks and a carbonatite appear in the Mesozoic. This evolution reflects cooling and thickening of the lithosphere after the Pan-African (de Gruyter and Vogel 1981, Harris 1982). As in West Africa reactivation of pre-existing fault pattern and transcurrent faults in particular appear to control the location of the ring complexes and the role of tensional tectonics has been stressed by Embleton *et al.* (1982). In Egypt ENE alignment of intrusions corresponding to onshore extension of transform faults, pre-date ocean-floor spreading (Serencsits *et al.* 1979).

Alignments of alkaline intrusions oblique to the continental margin are also a feature of Mesozoic provinces situated along the West coast of Africa south of Cameroon. *The Angola province* (112 ± 8 Ma), essentially

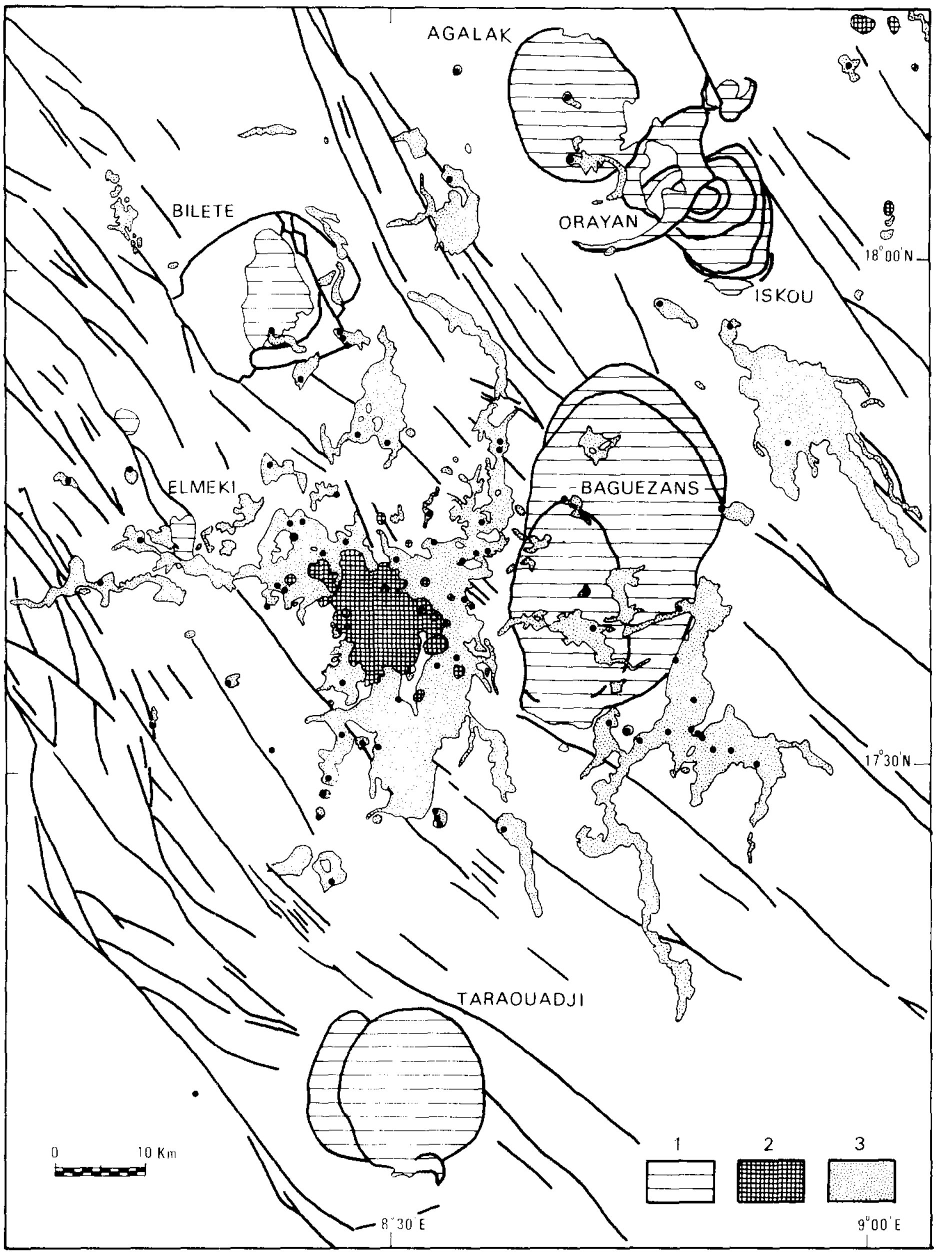

Fig. 3. Structural pattern of the southern part of the Aïr alkaline province showing the relationships between sinistral wrench faults and ring fractures. (1) Oversaturated alkaline ring complexes and plutons, (2) Tertiary to Quaternary trachytes and phonolites. (3) Quaternary olivine basalts. Note that volcanic emission points, black dots, tend to be located along reactivated wrench faults and ring fractures.

composed of alkaline undersaturated and ultrabasic complexes including carbonatites, lie on the Angola–Kasai craton stable since 1800 Ma and occur in a zone of NE parallel faults which extend inland to link up with the Lucapa kimberlite-bearing graben (Rodriguez 1972, Mathias 1974).

The Namibian province (164–123 Ma) consists of acid and basic rocks and undersaturated complexes including carbonatites. They are also aligned along a NE lineament coinciding with the axis of the central zone of the Damaran orogenic belt (late Pan-African) and are parallel to the Walvis Ridge. It is interesting to note that the oversaturated complexes occur to the west in a zone characterised by abundant Pan-African granites.

The Luderitz province (130 Ma) forms another NE alignment of ring complexes composed essentially of foyaites (Marsh 1975).

The Nuanetsi ring complexes occur in the Messina Block of the Limpopo Belt separating the Kaapvaal and Zimbabwe cratons, close to the intersection with the Lebombo monocline, a zone of intense Karroo and post-Karroo volcanicity. They lie in a straight E–W line coinciding with the axis of a syncline which has been interpreted as a tensional feature localised as the result of concentration of stress at the point of the re-entrant in the margin of the shield (Cox *et al.* 1965). The complexes are composed of gabbros, nordmarkites metaluminous and subaluminous granites and granophyres and the most westerly complex (Marangudji) contains a variety of undersaturated rocks and has yielded a K–Ar age of

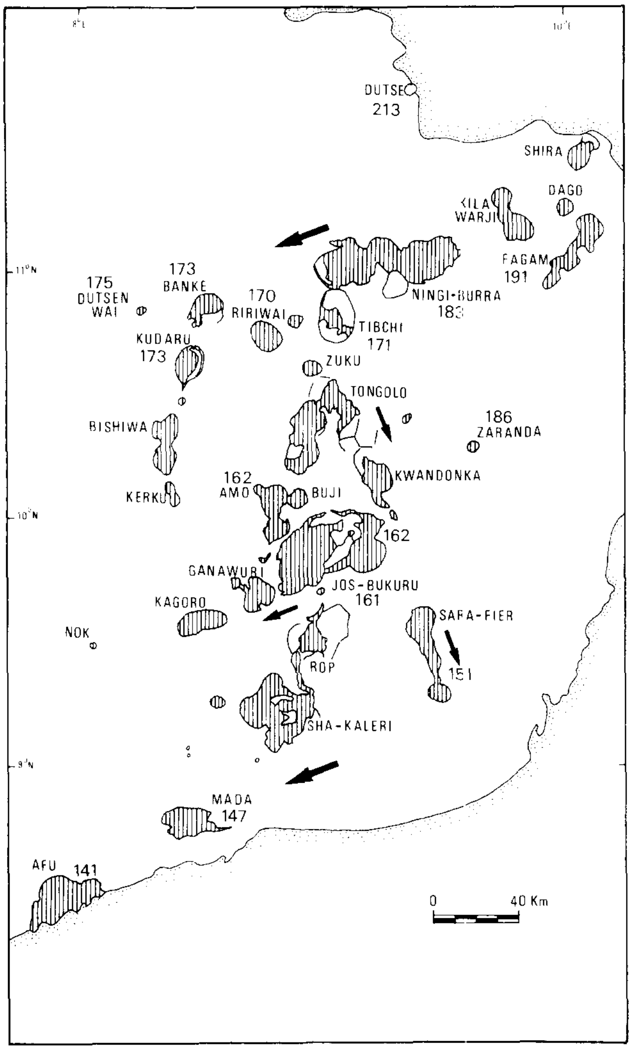

Fig. 4. Migration of ages in the Nigerian alkaline Younger Granites province (after Rahaman *et al.* 1984).

190 ± 12 Ma (Gough *et al.* 1964, Mathias 1974, Foland and Henderson 1979). The Karroo volcanics, largely of fissural origin, start with nephelinites, olivine basalts, passing upwards into normal tholeiites and ignimbrites of rhyolitic and rhyo-dacitic composition; the cycle ends in the Cretaceous with flows of the basalt–trachyte-phonolite association. The presence of wide zones of antithetical faulting suggests crustal stretching and attenuation in relation to the separation with Antarctica.

The Chilwa intrusions, also of Karroo age, form a mixed silica saturated and undersaturated province with which are associated carbonatites (Dixey *et al.* 1955, Bloomfield 1965, Woolley and Garson 1970). They occur in the southern part of the Mozambique Belt, which is devoid of Pan-African granitoids, and are related to the reactivation of deep fractures at the southern extremity of the East African rift system which was already active in Karroo times (Woolley and Garson 1970).

By the *Tertiary–Quaternary* the process of cratonisation of the African continent had reached an advanced stage and there is a total absence of alkaline volcanism on the Archean cratons (Black and Girod 1970, Thorpe and Smith 1974). Highly undersaturated K-rich and Na-rich lavas associated with carbonatites are restricted to the Western Rift where they cut Kibaran (1350 Ma) and Ubendian (2000 Ma) basement. Mixed silica saturated and undersaturated alkali basalt–phonolite–trachyte–rhyolite volcanism is now widely developed in the Pan-African domain (600 Ma), where it is associated with domal uplifts and reactivation of pre-existing fault patterns, often on the site of former silica-saturated alkaline provinces (Aïr, Nigeria, Cameroon, Bayuda), and along the Eastern Rift; silica-saturated transitional basalt–pantellerite–comendite–rhyolite type of volcanism occurs in the Ethiopian Rift, and the Afar triangle, where one assists at the formation of a new passive continental margin with thin lithosphere (Black 1976).

Turning to the *Precambrian*, a mixed province of oversaturated and undersaturated rocks including carbonatites, which have yielded ages between 735 and 450 Ma (Vellutini *et al.* 1981, Tack *et al.* 1983, Lubala *et al.* 1985) occurs in Burundi, Ruanda and Zaïre along the Western Rift in the foreland of the Pan-African Lufilian arc. This is yet another example of repeated alkaline magmatism along the same zone of weakness and confirms the old age of vertical shear zones that have guided the development of the East African Rift system (McConnell 1972).

Cahen and Snelling (1984) have pointed out that oversaturated alkaline anorogenic granites, which in the Phanerozoïc are widely developed in Pan-African domains, also occur with ages ranging between 2000 and 1550 Ma in Eburnean–Ubendian domains stabilised around 2000 Ma ago and cite examples from Morocco, Mauritania, Ivory Coast, SW Angola, Zambia, Zaïre and Tanzania.

Undersaturated complexes including carbonatites (Spitskop, Pilanesberg and its NW-trending dyke swarm) with ages ranging between 1435 and 1100 Ma (Ferguson 1973) cut the Bushveldt complex (2050–1950 Ma). The oldest known alkaline ring complexes in Africa are Palabora which include a carbonatite dated at 2060 Ma (Holmes and Cahen 1957) and cuts the Kaapvaal craton stabilised around 3000 Ma ago, and Hassi el Foghra, a mixed silica saturated and undersaturated complex on the West African craton, which has given an age of 2000 Ma (Lameyre and Lasserre 1967).

COMPARISON WITH OTHER ALKALINE PROVINCES IN THE WORLD

Siberia

In her excellent review (Butakova 1974) no mention is made of oversaturated alkaline rocks in the Siberian platform, neither in the mainly Archean cratons nor in their Mesozoic cover. The alkaline rocks of the platform, which are mainly Late Proterozoic to Cretaceous in age are all strongly undersaturated comprising peridotites, ijolites, meltegeites, urtites, accompanied by carbonatites, and there is a considerable lapse of time between their emplacement and the age of cratonisation. In contrast, oversaturated provinces characterised by the presence of nordmarkites and alkali granites are found in the mobile zones around the Siberian platform where successive orogenies occurred between the Baikalian (equivalent to the Pan-African) and the Tertiary. These complexes are post-tectonic and may be emplaced up to 300 Ma after the orogeny. Undersaturated alkaline complexes in the same region are always later and postdate the orogeny by over 400 Ma. Butakova (op. cit.) stresses the importance of lithospheric control, reactivation of abyssal faults and rifting in the localisation and genesis of alkaline rocks, and draws attention to the synchronism of spatially separated orogenesis and alkaline igneous activity.

Europe

Undersaturated alkaline rocks and carbonatites are extensively developed in the Baltic shield (e.g. Alno) and particularly in the Kola peninsula and Northern Karelia, where three successive periods of alkaline magmatic activity corresponding to the Middle Proterozoic, Caledonian and Hercynian are superimposed over a period of 1400 Ma (Gerasimovski *et al.* 1974). Whereas the Middle Proterozoic occurrences, although including some undersaturated rocks, are composed largely of alkali granites, the Caledonian and Hercynian complexes are exclusively undersaturated. Late Caledonian undersaturated intrusions also occur in Assynt, e.g. Borolan (Scotland) where it cuts the Lewisian foreland and Cambrian beneath the Caledonian Moine thrust.

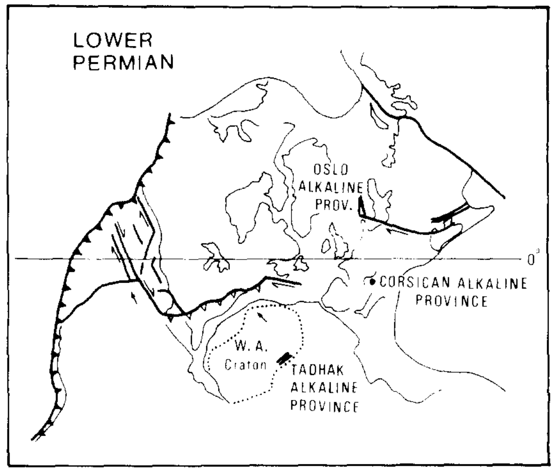

Fig. 5. Early Permian alkaline provinces and palaeotectonics of the Appalachian/Hercynian (after Dewey 1982).

The Permian is a period of extensive rifting in the Midland Valley of Scotland, North Sea and Oslo graben and also in West Africa (Liégeois *et al.* 1983) (Fig. 5). It is interesting to note that the mixed silica saturated and undersaturated province of Oslo is underlain by a very much older Grenville basement; whereas the contemporaneous silica-saturated alkaline province of Corsica cuts a Hercynian calcalkaline batholith (Bonin 1980), a geological event similar to that of the Iforas province in West Africa (Fig. 5) where alkaline magmatism follows after a regime of subduction.

The Mesozoic–Cenozoic alkaline and tholeiitic activity in Europe has been presented in a very stimulating manner by Dewey (1982) (Fig. 6). The igneous activity owes its origin to the intricate interplay of tectonic events related to:

(1) Several phases of marginal rifting and continental

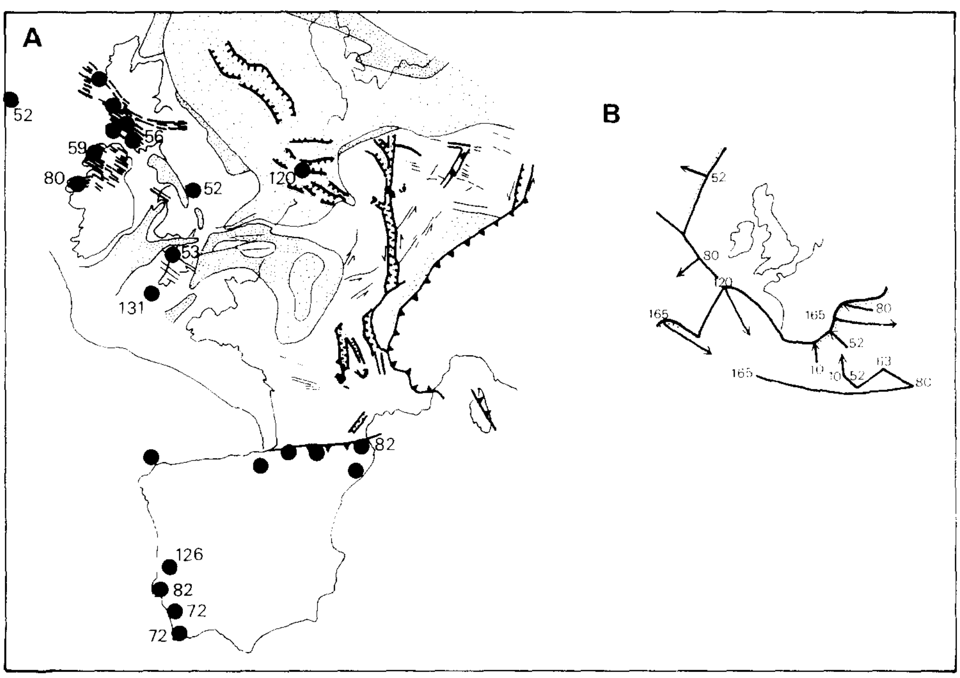

Fig. 6.(A) Outline of the Cenozoic tectonics of NW Europe and the location of alkaline complexes (fine stipple = Mesozoic basins; coarse stipple = Cenozoic basins; thin lines = structural lineaments, mainly strike-slip faults; thick lines = mafic dykes; after Dewey 1982 and Rock 1982). (B) Timing, direction and amount of Mesozoic/Cenozoic motion of plates and blocks relative to "stable" NW Europe. Numbers indicate ages in million years (after Dewey 1982 and Rock 1982).

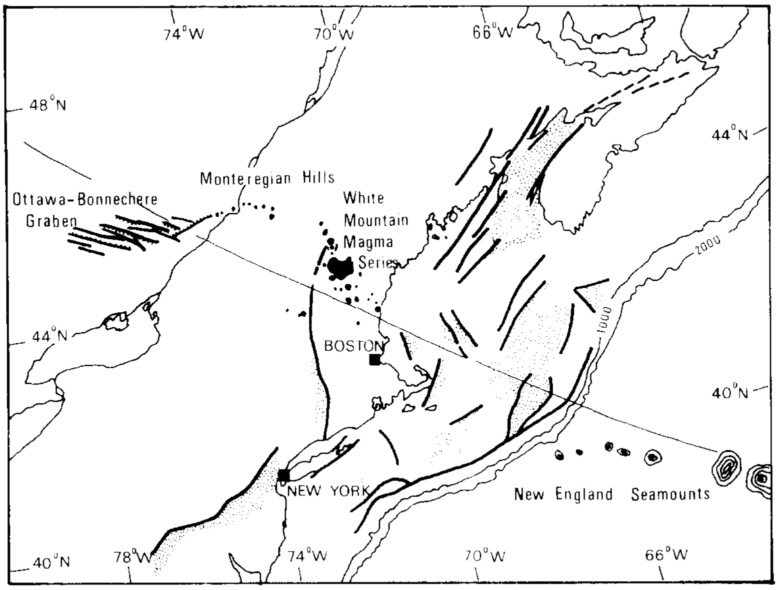

Fig. 7. Location of the White Mountain magma series, Monteregian Hills and New England sea mount chain along a small circle drawn about the pole of rotation for the early opening of the Atlantic ocean (after Sykes 1978).

rupture (opening of the Bay of Biscay at 120 Ma, Wolf Rock and the Iberian Province), of the Labrador Sea at 80 Ma causing a fundamental change in the relative motion of Africa and Europe so that the Alpine trough comes under compression, whereas alkaline magmatism occurs in the Pyrenees and Iberian provinces in relation to strike-slip movements, and finally opening of the North Atlantic at 52 Ma (Thulean province). (2) Foreland compression resulting from the stacking of Alpine nappes as a response to changes in Africa–Europe relative motion at 52 Ma and which causes the northerly propagation of the Rhine graben accompanied by sinistral strike-slip movement, and the development of rifts in the Massif Central (Dewey op. cit., Rock 1982, Wimmenauer 1974).

South-west Greenland

The Gardar province (1300–1150 Ma), composed of mixed silica saturated and undersaturated ring complexes, cut the Ketilidian orogenic belt stabilised around 1800 Ma ago. Apart from the presence of foid-bearing rocks, the association gabbro–anorthosite–nordmarkite and granites displaying both peralkaline and aluminous trends is very similar to that of the West African Younger Granite provinces. Likewise from a structural point of view the entire province is affected by an intermittently active set of conjugate transcurrent faults and cut by dyke swarms, indicative of distension (Upton 1974, Blaxland *et al.* 1978).

North America

Like the African cratons, the Baltic shield, and the Siberian platform, undersaturated alkaline complexes and carbonatites are often encountered in the North American Archean–Lower Proterozoic shield and are generally much younger than cratonisation. Phanerozoic alkaline intrusions occur all over the North American continent including the mobile belts (Appalachians and Cordillera) (Barker 1974). Frequently they occur in linear belts and may be accompanied by crustal doming. Examples of structural control are hidden rifts, e.g. Kapusaking and Mid-Continental (Innes 1960), the Mississippi embayment which has been interpreted as the failed arm of an RRR triple junction (Burke and Dewey 1973) or alternatively as a reactivated aulacogen (Ervin and McGinnis 1975), and zones of crustal attenuation accompanied by block tilting, like the Basin and Range provinces, where magmatism of transitional basalt–pantellerite–comendite type prevails as in Afar (Cook 1969, Black *et al.* 1972a,b).

A demonstration of the influence of the age of consolidation of basement, with respect to the degree of silica saturation of intrusive alkaline complexes, is provided by the White Mountain Magma Series (New England) and the Montegerian Hills (Quebec), a Mesozoic province with ages ranging between 230 and 110 Ma (Gold 1967, Foland and Fall 1977), which straddles the Appalachian and Grenville orogenic domains (Fig. 7). The alkaline complexes occurring in the internal zones of the Appalachians characterised by abundant Acadian (400–360 Ma) calcalkaline granites are exclusively silica saturated, whereas those cutting the thin external nappes of the Appalachians and the Grenville foreland (stabilised around 1000 Ma ago), are either mixed or strongly undersaturated and associated with carbonatites and kimberlite (western Montegerian Hills). The Montegerian complexes in the Grenville are situated at the junction between the EW-trending Ottawa graben, a reactivated Precambrian failed arm of a triple RRR junction (Rankin 1976) and the NNE-trending St Lawrence graben individual massifs occurring on fault intersections (Philpotts 1974); in contrast the New England intrusions in the Appalachians are not directly related to rifting but occur in a zone of domal uplift, individual complexes occurring on nodular points of a regional lattice suggesting the existence of a conjugate transcurrent fault system (Chapman 1968) as in the West African Younger Granite provinces. Older alkali granites dated at 470–430 Ma intrude the Avalonian of SE New England. Lameyre *et al.* (1984) pointed out the remarkable rhombic outline of the province when including the Vermont dyke fields and proposed the term "georhomb" to describe such series of within-plate alkaline magmatism.

Recurring alkaline magmatism is also a feature of the St Lawrence and Ottawa grabens underlain by Grenville (Doigt and Barton 1968). The Chatham–Grenville and Rigaud intrusions to the west of Montreal are undersaturated and have been dated at 450 Ma. Further west, close to the Grenville–Archean shield boundary, undersaturated rocks (syenites, lamprophyres and carbonatites) were emplaced around 565 Ma ago. Earlier intrusions with ages ranging between 1000 and 820 Ma are mainly syenogranites but include some carbonatites. Thus it appears that oversaturated complexes predominate during a period of 500 Ma after the end of the Grenville orogeny, subsequent intrusions being either mixed or strongly undersaturated, like the Montegerian province.

TRANSFORM FAULTS

Much emphasis has been laid on the importance of transcurrent faults which, by their nature, must cut the lithosphere. It is appropriate therefore to examine their relationship to oceanic transform faults which have long been recognised as the loci of oceanic alkali basalts (Barberi *et al.* 1974), and of alkaline ring complexes (Giret and Lameyre 1985).

In North America, Sykes (1978) drew attention to the fact that the Mesozoic Montegerian, White Mountain Magma Series and New England Sea Mounts, lie on a line corresponding to the arc of rotation for the early opening of the central Atlantic (Fig. 7). Radiometric dating shows that the alkaline magmatism precedes and succeeds the opening of the central Atlantic. If one follows the transform faults across the Atlantic, one links up through the Canary Islands to the Moroccan Haut Atlas Mesozoic alkaline province located in an early Jurassic pull-apart basin formed by sinistral displacement along the South Atlas fault zone. Here there has been a reversal in the sense of movement, the South Atlas fault having acted dextrally in the late Palaeozoic (Mattauer *et al.* 1972).

As one moves southwards along the African coast, the Tertiary Dakar alkali basalts located at the intersection of NS and EW faults are aligned on a transform zone going through the Cape Verde Islands to link up with the Blake fault zone. The 96 Ma old Los alkaline complex (Lazarenkov 1970) and the Triassic Freetown igneous complex (Briden *et al.* 1971) occur respectively 100 km to the north of and on the Guinea fault zone which connects with the Barracuda fault zone. Mesozoic kimberlite pipes also occur along ENE–NE lineaments that connect up with the Guinea fault zone (Williams and Williams 1977).

Sibuet and Mascle (1978) have shown that the Nigerian alkaline Younger Granite province and the Cameroon line lie roughly on arcs corresponding to the early pole of rotation (before 80 Ma) for the opening of the southern Atlantic. Recent structural studies of the Benue trough suggest that it is a pull-apart basin formed by overall sinistral shear in line with the Charcot fault zone (Mascle 1976, Benkhelil 1982). Whereas the Nigerian alkaline Younger Granite province precedes the oceanic opening, the Cameroon occurrences are later. Note that in a reconstruction to anomaly 34 the Noronha sea mounts off the north-eastern coast of Brazil line up with the Younger Granite Province of Nigeria and the 97–87 Ma old Cabo peralkaline granite and associated volcanism in NE Brazil (Asmus and Ponte 1973) and lie along the Cameroon line (Fig. 8).

Similarly, Marsh (1973) pointed out that the Angolan (112 Ma), Namibian (164–123 Ma) and Luderitz (130 Ma) Mesozoic alkaline provinces, that form NE-trending lineaments, lie along small circles around the Cretaceous centre of rotation for the opening of the South Atlantic and appear to be correlated with transform faults that offset the Mid-Atlantic Ridge and with similar alkaline complexes in Brazil (145–120 and 85–45 Ma) and Uruguay (120 Ma).

To sum up, alkaline magmatism precedes and succeeds the opening of an ocean. Intrusions are located along old lines of weakness near the ends of transform faults and may extend far inland. Major pre-existing zones of weakness orientated parallel to the direction of relative continental separation may predetermine the position of the transforms that develop in the new ocean (Sykes 1978, Reyre 1983).

DISCUSSION

The geological setting of alkaline provinces shows that their location is not random, but is controlled by structural weaknesses in the lithosphere, whose age and thickness to a large extent determine their degree of alkalinity and silica saturation. Whereas mixed and strongly undersaturated provinces are frequently associated with well-defined rifts, abyssal faults and transform faults, oversaturated provinces are related to reactivated tear fault systems in a regime of distension, where lithosphere is relatively thin, either in a recently stabilised mobile belt (e.g. West African Younger Granites cutting Pan-African, White Mountain Magma Series intruding Acadian, Permian Corsican alkaline granites in a Hercynian domain), or in a region of crustal stretching related to continental fragmentation (e.g. Rockall, Afar). Lastly we have seen that alkaline magmatism is often repeated over a long period of time in the same region.

These observations are difficult to reconcile with the plume hypothesis (Morgan 1972). The southerly migration of the Aïr, Damagaram and Nigerian complexes

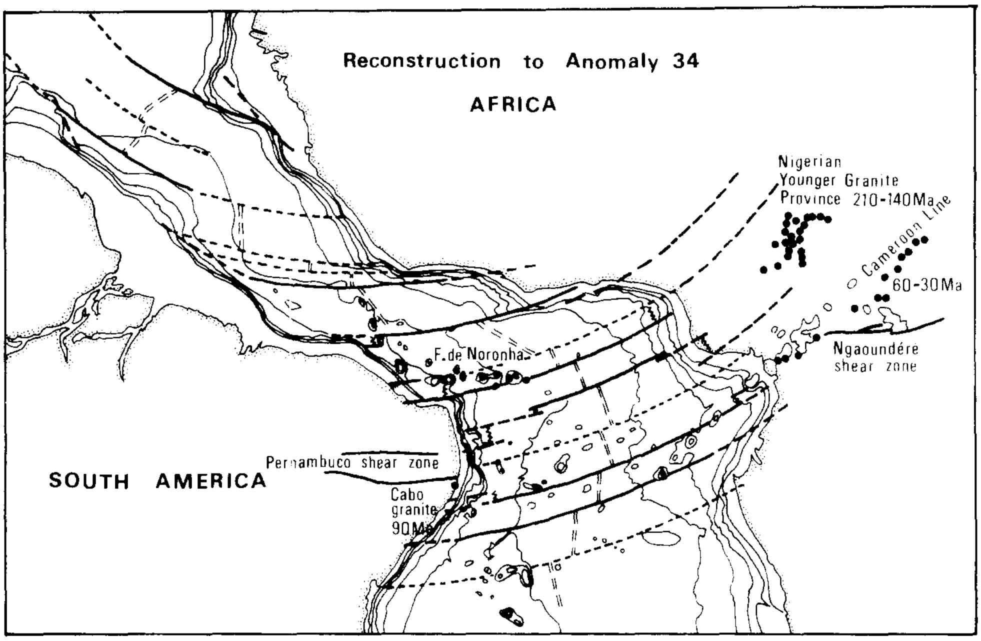

Fig. 8. Location of alkaline magmatism and sea mounts on a reconstruction of continents at the end of phase II (79 Ma, late Santonian) (after Sibuet and Mascle 1978).

has been interpreted in terms of a northward moving African plate over the Ascension "plume" (Bowden *et al.* 1976, Karche and Vachette 1976) but it has been pointed out that there is a discrepancy between the rate of movement of the African plate as indicated by palaeomagnetic data and that of the displacement of the complexes (Wright 1973). Moreover, with reference to a fixed set of plumes one would expect to find a similar plume trace formed by contemporary complexes of north-eastern Africa, which is not the case. If a solution is sought by invoking moving and intermittent plumes the elegance of the hypothesis is lost. We favour, therefore, a conservative view (Sykes 1978) of hot spots as passive centres of abundant volcanism whose location is determined by pre-existing zones of weakness.

De Gruyter and Vogel (1981) have proposed an attractive shear heating model for the production of alkaline magmas in areas of relatively low heat flow. They point out that an increase of plate velocity or a rapid change in the direction of plate motions causes an increase of the shear stress at the base of the lithosphere. This leads to temperature increase, viscosity decreases, and diffuse melts may be generated in the zones of decoupling at the base of the lithosphere, their ascent being facilitated by reactivation of pre-existing fault patterns and strike-slip movements. The correlation between alkaline magmatism and changes in the direction of plate movements which incidentally correspond to changes in the stress field, may well be justified. The correlation with periods of acceleration of plate motions, however, is in contradiction with the findings of Briden and Gass (1974) indicating that alkaline magmatism took place in periods when the African plate was more or less stationary, and Harris (1982) who has shown that there is an inverse correlation between periods of rapid plate motion and within-plate magmatic activity.

Periods of slow plate movement are likely to correspond to the time preceding continental fragmentation and to periods of collision and interaction between continental lithosphere along plate margins. In both cases intense fields of stress must build up which will provoke reactivation of lithospheric shear zones and rifting far within the plates. An alternative approach to that of de Gruyter and Vogel (1981) and to the plume hypothesis, where faulting plays only a passive role, is to see how reactivation of an old fault pattern to produce only small displacements may trigger off or enhance partial melting in the mantle. An important process may be due to the *harpoon effect* that occurs when there is a reversal in the sense of movement in a pre-existing fault system. For instance, in a Riedel system, if the direction of motion is inverted along the major shear zones bounding a set of oblique transcurrent faults, with only a small displacement, the latter which were under compression are likely to open and propagate as tensional faults to reach the asthenosphere. Such inversions, in the sense of movement we have seen, occur in Morocco and Iforas, and this may also be a feature of Aïr, Nigeria and Northern Africa. We suggest that it is pressure release in a distensive environment that favours the channeling of volatiles and is the major cause of partial melting. In contrast to Bailey (1964) we regard the doming which frequently accompanies alkaline magmatism as not the cause but the result of the density change accompanying the formation of melts (Lameyre *et al.* 1984).

A histogram plot of ages of Phanerozoic within-plate magmatism in Africa shows peaks which may be related to major tectonic events along plate margins (Cahen and Snelling 1984). Similarly, Barker (1969) pointed out that the time of emplacement of alkaline complexes in North America centred around 1700, 1100, 560, 440, 190, 100 and 40 Ma, which correspond to widespread orogenic events in North America. In this connection one must bear in mind that although one commonly regards an orogenic event as relatively short-lived with radiometric dates reflecting cooling ages and the emplacement of granitoids, when one looks at an orogen on the global scale, the picture changes: events are seen to be heterochronous at different places along plate margins and stresses developed within individual plates can be maintained over a long time. This we believe can explain the practically continuous within-plate magmatism during the Palaeozoic and Mesozoic in the Pan-African sheared domains of northern Africa.

To conclude, in global plate reconstruction of the past, it is essential to portray contemporary within-plate alkaline magmatism. Its locus along pre-existing zones of structural weakness is determined by a system of stress in the lithosphere and thus is triggered from above and not from the mantle.

Examining alkaline ring complexes in their regional setting may also lead to conclusions of economic interest. So far no explanation has been given as to why tin mineralisation, which characteristically is concentrated in S-type granites, is important in some silica saturated alkaline provinces and absent in others. A possible answer comes out of this review. When the country rock is composed mainly of mantle-derived calcalkaline granitoids or volcanic assemblages, e.g. Iforas, Corsica, New England, Saudi Arabia, Red Sea Hills, or oceanic crust, e.g. Kerguelen Islands, there is little or no tin. On the other hand, the chances of finding economic tin deposits are considerably enhanced, when the province cuts crustally derived granitoids which have already redistributed and concentrated tin, e.g. Nigerian Pan-African granites and Sn-bearing pegmatites (Clifford 1966; Black 1984).

Looking to the future, a new generation of field work is now needed to study the stress fields prevailing prior to and during the emplacement of within-plate alkaline complexes, and to collect palaeomagnetic data on contemporaneous complexes lying on different plates in order to improve our scanty knowledge on past plate motions.

REFERENCES

Almeida, F. F. M. and Black, R. 1968. Geological comparison of north-eastern South America and western Africa. *An. Acad. Bras. Cienc.* (Suppl.), 317–319.

Asmus, H. E. and Ponte, F. C. 1973. The Brazilian marginal basins. In: *The Ocean Basins and Margins, Vol. 1, The South Atlantic* (Edited by Nairn, E. M. and Stehli, F. G.), pp. 87–133. Plenum Press, New York.

Ba, H., Black, R., Benziane, B., Diombana, D., Hascoët-Fender, J., Bonin, B., Fabre, J. and Liegeois J.-P. 1985. La province des complexes annulaires alcalins sursaturés de l'Adrar des Iforas, Mali. *J. Afr. Earth Sci.* **3**, 123–142.

Bailey, D. K. 1964. Crustal warping. A possible tectonic control of alkaline magmatism. *J. geophys. Res.* **69**, 1103–1111.

Barberi, F., Bonatti, E., Marinelli, G. and Varet, J. 1974. Transverse tectonics during the split of a continent: data from the Afar rift. *Tectonophysics* **23**, 17–29.

Barker, D. S. 1969. North American feldspathoidal rocks in space and time. *Bull. geol. Soc. Am.* **80**, 2369–2372.

Barker, D. S. 1974. Alkaline rocks of North America. In: *The Alkaline Rocks* (Edited by Sørensen, H.), pp. 160–171. John Wiley, London.

Benkhelil, J. 1982. Benue Trough and Benue Chain. *Geol. Mag.* **119**, 155–168.

Black, R. 1963. Note sur les complexes annulaires de Tchouni-Zarniski et de Gouré (Niger). *Bull. Bur. Rech. geol. Minière* **1**, 31–45.

Black, R. 1965. Sur la signification pétrogénétique de la découverte d'anorthosites associées aux complexes annulaires sub-volcaniques du Niger. *C. r. Acad. Sci., Paris* **260**, 5829–5832.

Black, R. 1976. The Afar: example of an atlantic-type continental margin in the making. *An. Acad. Bras. Cienc.* (Suppl.) **48**, 27–36.

Black, R. 1980. Precambrian of West-Africa. *Episodes* **4**, 3–8.

Black, R. 1984. The Pan-African event in the geological framework of Africa. *Pangea* **2**, 8–16.

Black, R. and Girod, M. 1970. Late Palaeozoic to Recent igneous activity in the West Africa and its relationship to basement structure. In: *African Magmatism and Tectonics* (Edited by Clifford, T. N. and Gass, I. G.), pp. 185–210. Oliver and Boyd, Edinburgh.

Black, R., Ba, H., Ball, E., Bertrand, J. M. L., Boullier, A. M., Caby, R., Davison, I., Fabre, J., Leblanc, M. and Wright, L. I. 1979a. Outline of the Pan-African geology of Adrar des Iforas (Republic of Mali). *Geol. Rundsch.* **68**, 543–564.

Black, R., Caby, R., Moussine-Pouchkine, A., Bayer, R., Bertrand, J. M. L., Boullier, A. M., Fabre, J. and Lesquer, A. 1979b. Evidence for late Precambrian plate tectonics in West Africa. *Nature, Lond.* **278**, 223–227.

Black, R., Jaujou, M. and Pellaton, C. 1967. Notice explicative de la carte géologique de l'Aïr à l'échelle 1/500000. *Dir. Mines Géol. Niger.*

Black, R., Morton, W. H., Rex, D. C. and Shackleton, R. M. 1972a. Sur la découverte en Afar (Ethiopie) d'un granite hyperalcalin miocène: le massif de Limmo. *C. R. Acad. Sci., Paris* **274**, 1453–1456.

Black, R., Morton, W. H. and Varet, J. 1972b. New data on Afar Tectonics (Ethiopia) *Nature Phys. Sci.* **240**, 170–173.

Blaxland, A. B., Van Breemen, O., Emeleus, C. H. and Anderson, J. G. 1978. Age and origin of the major syenites centers in the Gardar province of south Greenland: Rb–Sr studies. *Bull. geol. Soc. Am.* **89**, 231–244.

Bloomfield, K. 1965. The geology of the Zomba area. *Bull. geol. Surv. Malawi* **16**. 193 p.

Boissonnas, J. 1973. Les granites à structure concentrique et quelques autres granites tardifs de la chaine pan-africaine en Ahaggar. *Thèse de Doct. d'Etat*, Université Pierre et Marie Curie, Paris.

Bonin, B. 1980. Les complexes acides alcalins continentaux: l'exemple de la Corse. *Thèse de Doct. d'Etat*, Université Pierre et Marie Curie, Paris, 756 pp.

Bonin, B. 1982. Les granites des complexes annulaires. *Bur. Rech. géol. Minière, Manuels et Methodes* **4**.

Bonin, B., Vialette, Y. and Lameyre, J. 1972. Géochronologie et signification du complexe granitique annulaire de Tolla-Cauro (Corse). *C. R. somm. Soc. géol. Fr.* **2**, 52–54.

Bowden, P. and Turner, D. C. 1974. Peralkaline and associated ring-complexes in the Nigeria–Niger Province, West Africa. In: *The Alkaline Rocks* (Edited by Sorensen, H.), pp. 330–351. John Wiley, London.

Bowden, P., Van Breemen, O., Hutchison, J. and Turner, D. C. 1976. Palaeozoic and Mesozoic age trends for some ring complexes in Nigeria and Niger. *Nature, Lond.* **259**, 297–299.

Briden, J. C. and Gass, I. G. 1974. Plate movement and continental magmatism. *Nature, Lond.* **248**, 650–653.

Briden, J. C., Henthorn, D. I. and Rex, D. C. 1972. Paleomagnetic and radiometric evidence for the age of the Freetown igneous complex. *Earth Planet. Sci. Lett.* **12**, 385–391.

Burke, K. and Dewey, J. F. 1973. Plume generated triple junctions: Key indications in applying plate tectonics to old rocks. *J. Geol.* **81**, 406–433.

Butakova, E. L. 1974. Regional distribution and tectonic relations of the alkaline rocks in Siberia. In: *The Alkaline Rocks* (Edited by Sørensen, H.), pp. 172–189. John Wiley, London.

Caby, R., Bertrand, J. M. L. and Black, R. 1981. Pan-African ocean closure and continental collision in the Hoggar–Iforas segment, Central Sahara. In: *Precambrian Plate Tectonics* (Edited by Kröner, A.), pp. 407–451. Elsevier, Amsterdam.

Cahen, L. and Snelling, N. J. 1984. *The Geochronology and Evolution of Africa.* Oxford University Press, Oxford, 550 pp.

Chapman, C. A. 1968. A comparison of the Maine crustal plutons and the magmatic complexes of New-Hampshire. In: *Studies of Appalachian Geology: Northern and Southern Maritime* (Edited by E-An Zen *et al.*), pp. 385–398.

Clifford, T. N. 1966. Tectono-metallogenic units and metallogenic provinces of Africa. *Earth Planet. Sci. Lett.* **1**, 421.

Cook, K. L. 1969. Active rift system in the Basin and Range province. *Tectonophysics* **8**, 469–511.

Cox, K. G., Johnston, R. L., Monkman, L. J., Stillman, G. S., Vail, J. R. and Wood, D. N. 1965. The geology of the Nuanetsi igneous province. *Phil. Trans. R. Soc.* **257A**, 71–218.

Dewey, J. F. 1982. Plate tectonics and the evolution of the British Isles. *J. geol. Soc. Lond.* **139**, 371–412.

Dixey, F., Campbell Smith, W. and Bisset, J. B. 1955. The Chilwa series of southern Nyasaland. *Bull. geol. Surv. Nyasaland* **5**.

Doigt, R. and Barton, J. M. 1968. Ages of Carbonatites and other alkaline rocks in Quebec. *Can. J. Earth Sci.* **5**, 1401–1407.

Embleton, J. C. B., Hughes, D. J., Klemnic, P. M., Poole, S. and Vail, J. R. 1982. A new approach to the stratigraphy and tectonic evolution of the Red Sea Hills, Soudan. *Precambrian Res.* **16**, 19.

Ervin, G. P. and McGinnis, L. D. 1975. Reelfost rift: reactivated precursor to the Mississippi embayment. *Bull. geol. Soc. Am.* **86**, 1287–1995.

Fabre, J., Ba, H., Black, R., Caby, R., Leblanc, M. and Lesquer, A. 1982. La chaîne pan-africaine, son avant-pays et la zone de suture au Mali. Notice explicative de la carte géologique et gravimétrique de l'Adrar des Iforas au 1/500000. *Dir. Nat. Geol. Mines, Bamako*, 85 pp.

Foland, K. A. and Fall, H. 1977. Ages of the White Mountain intrusives—New Hampshire, Vermont and Maine. USA. *Am. J. Sci.* **77**, 888–904.

Foland, K. A. and Henderson, C. M. P. 1979. Application of age and the isotope data to the petrogenesis of the Marangudzi ring complexes. *Earth Planet. Sci. Lett.* **29**, 291–301.

Gass, I. G., Chapman, D. S., Pollack, H. N. and Thorpe, R. S. 1978. Geological and geophysical parameters of mid-plate vulcanism. *Phil. Trans. R. Soc. Lond.* **288A**, 581–597.

Gerasimovski, I., Volkov, V. P., Kogarko, L. N. and Polyakov, A. I. 1974. Kola Peninsula. In: *The Alkaline Rocks* (Edited by Sørensen, H.). pp. 206–220. John Wiley, London.

Giret, A. and Lameyre, J. 1985. Inverted alkaline–tholeiitic sequences related to lithospheric thickness in the evolution of continental rifts and oceanic islands. *J. Afr. Earth Sci.* **3**, 261–268.

Gold, D. P. 1967. Alkaline ultrabasic rocks in the Montreal area, Quebec. In: *Ultrabasic and Related Rocks* (Edited by Willye, P. J.), pp. 288–502. John Wiley, New York.

Gough, D. I., Brock, A., Jones, D. L. and Opdyke, N. D. 1964. The paleomagnetism of the ring-complexes at Marangudzi and of the Mateke Hills. *J. geophys. Res.* **69**, 2499–2507.

de Gruyter, P. and Vogel, T. A. 1981. A model of the origin of the alkaline complexes of Egypt. *Nature, Lond.* **291**, 571–574.

Harris, N. B. H. 1982. The petrogenesis of alkaline intrusives Africa and their implications for within-plate magmatism. *Tectonophysics* **83**, 243–258.

Hossain, M. T. and Turaki, U. M. 1983. Bibliography on the Younger Granite ring complexes and tin mineralization with emphasis on Nigeria. *J. Afr. Earth Sci.* **1**, 73–81.

Innes, M. J. S. 1960. Gravity and isostasy in N Ontario and Manitoba. *Publ. Dom. Obs. Ottawa* **21**, 263–338.

Jacobson, R. R. E., MacLeod, W. N. and Black, R. 1958. Ring-complexes in the Younger Granite province of northern Nigeria. *Mem. geol. Soc. Lond.* **1**, 72 pp.

Karche, J. P. and Vachette, M. 1978. Age et migration de l'activité magmatique dans les complexes paléozoïques du Niger, conséquences. *Bull. Soc. géol. Fr.* **20**, 941–953.

Klerkx, J. 1979. Tectono-metamorphic evolution of the Precambrian basement of the Uweinat region (S.E. Libya) *Résumés 10th Colloquium Géol. Afr. Montpellier*, 5A.

Lameyre, J. and Bonin, B. 1978. Réflexions sur la position et l'origine des complexes magmatiques anorogéniques. *Bull. Soc. géol. Fr.* **20**, 45–59.

Lameyre, J. and Bowden, P. 1982. Plutonic rock types series: discrimination of various granitoid series and related rocks. *J. Volcan. geother. Res.* **14**, 169–186.

Lameyre, J., Black, R., Bonin, B. and Giret, A. 1984. Les provinces de l'Est américain et de l'Ouest africain et des Kerguelen. Indications d'un contrôle tectonique du magmatisme intraplaque et des processus associés. *Bull. Soc. géol. Nord Fr.* **103**, 101–114.

Lameyre, J. and Lasserre, M. 1967. Etude géochronologique des syénites alcalines et népheliniques du massif annulaire de Hassi el Fogra (Mauritanie du Nord). *C. r. Acad. Sci., Paris* **265**, 733–736.

Lasserre, M. 1978. Mise au point sur les granitoïdes dits "ultimes" du Cameroun. Gisements, pétrologie et géochronologie. *Bull. Bur. Rech. géol. minières* **4**, 143–159.

Lazarenkov, V. G. 1976. Alkaline lamprophyres from Los Massif (Guinée). *Geol. Geofis.* **197**, 120–127.

Leger, J.-M. 1985. Géologie et evolution magmatique du complexe plutonique d'Iskou (Aïr, Niger). *J. Afr. Earth Sci.* **3**, 89–96.

Liégeois, J. P. and Black, R. 1983. Preliminary results on the geology and geochemistry of the late Pan-African composite batholith of western Iforas (Mali). *Abstracts 12th Colloquium Afr. Geol.*, 62.

Liégeois, J. P. and Black, R. 1984. Pétrographie et géochronologie Rb–Sr de la transition fini-panafricaine dans l'Adrar des Iforas (Mali): accretion crustale au Précambrien supérieur. *Volume en Hommage à L. Cahen* (Edited by Klerkx, J. and Michot, J.). Tervuren (In press).

Liégeois, J. P., Bertrand, H., Black, R., Caby, R. and Fabre, J. 1983. Permian alkaline undersaturated and carbonatite province and rifting along the West African craton. *Nature, Lond.* **305**, 42–43.

McConnell, R. B. 1972. Geological development of the rift system of eastern Africa. *Bull. geol. Soc. Am.* **83**, 2549–2572.

Marsh, J. S. 1973. Relationships between transform directions and alkaline igneous rock lineaments in Africa and South America. *Earth Planet Sci. Lett.* **18**, 317–323.

Marsh, J. S. 1975. The Luderitz alkaline province, south west Africa. Descriptive petrology of the Granitberg foyaite complex. *Trans. geol. Soc. S. Africa* **78**, 215–224.

Mascle, J. 1976. Le Golfe de Guinée (Atlantique Sud): un exemple d'évolution de marge atlantique en cisaillement. *Mem. Soc. géol. Fr.* **128**, 1–104.

Mathias, M. 1974. Alkaline rocks of southern Africa. In: *The Alkaline Rocks* (Edited by Sørensen, H.), pp. 189–202. John Wiley, London.

Mattauer, M., Proust, F. and Tapponnier, P. 1972. Major strike-slip fault of late Hercynian age in Morocco. *Nature, Lond.* **237**, 160–162.

Mignon, R. 1970. Etude géologique et prospection du Damagaram Mounio et du Sud Maradi. *Rapp. Bur. Rech. géol. Minière, Dir. Mines Géol., Niamey*.

Moreau, C. 1982. Les complexes annulaires anorogéniques à suite anorthosique de l'Air Central et septentrional (Niger). *Thèse de Doct. d'Etat*, University Nancy I.

Morgan, W. J. 1972. Plate motions and deep mantle convection. *Mem. geol. Soc. Am.* **132**, 7–22.

Philpotts, A. R. 1974. The Montegerian province. In: *The Alkaline Rocks* (Edited by Sørensen, H.), pp. 293–310. John Wiley, London.

Rahaman, M. A., Bennet, J. B., Van Breemen, O. and Bowden, P. 1984. Detailed age study of the migration of Younger Granite ring complexes in northern Nigeria. *J. Geol.* **92**, 173–184.

Rankin, D. W. 1976. Appalachian salients and recesses: Late Precambrian continental break up and the opening of the Iapetus ocean. *J. geophys. Res.* **81**, 5605–5619.

Reyre, D. 1983. Quelques idées d'ensemble concernant les bassins sédimentaires de l'Afrique Atlantique. In: *Bassins sédimentaires en Afrique. Trav. Lab. Sci. Terre, Saint-Jerôme, Marseille* **A15**, 31–32.

Rock, N. M. S. 1982. The late Cretaceous alkaline igneous province in the Iberian Peninsula and its tectonic significance. *Lithos* **15**, 111–131.

Rodriguez, B. 1972. Major tectonic alignments of Alkaline complexes in Angola. In: *African Geology Ibadan, 1970* (Edited by Dessauvagie, T. F. J. and Whitman, T. F. J.), 149–153. University Press, Ibadan.

Sauvage, J.-F. and Savard, R. 1985. Les complexes alcalins sous-saturés à carbonatites de la région d'In Imanal (Sahara malien): une présentation. *J. Afr. Earth Sci.* **3**, 143–149.

Serencsits, C. M., Faul, H., Foland, K. A., El Ramly, M. F. and Hussein, A. A. 1979. Alkaline ring complexes in Egypt: their ages and relationship to tectonic development of the Red Sea. *Ann. geol. Surv. Egypt* **9**, 102–116.

Sibuet, J. C. and Mascle, J. 1978. Plate kinimatic implications of alkaline Equatorial fracture zone trends. *J. geophys. Res.* **83**, 3401–3421.

Sørensen, H. 1974. *The Alkaline Rocks*. John Wiley, London, 662 pp.

Streckeisen, A. L. 1976. To each plutonic rock its proper name. *Earth Sci. Rev.* **12**, 1–33.

Sykes, L. R. 1978. Intraplate seismicity reactivation, reactivation of pre-existing zones of weakness, alkaline magmatism and other tectonism post-dating continental fragmentation. *Rev. geophys. Space Phys.* **16**, 621–688.

Tack, L., Deutsh, S., Liegeois, J. P. and De Paepe, P. 1983. Age Nd and Sr isotopic geochemistry of the alkaline plutonic complexe of the upper Ruvubu (Burundi). *Abstracts 12th Colloquium Afr. Geol. Tervuren*, 96.

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

Umedji, A. C. and Caen-Vachette, M. 1983. Rb–Sr isochron from

Gboko and Kyuen rhyolites and its implication for the age and evolution of the Benue Trough, Nigeria. *Geol. Mag.* **20**, 529–533.
Upton, B. G. J. 1974. The alkaline province of South-West Greenland. In: *The Alkaline Rocks* (Edited by Sørensen, H.), pp. 221–237. John Wiley, London.
Vellutini, P., Bonhomme, M., Caron, J. P., Basira Kampunzu, A. and Libalat, J. 1981. Sur la signification tectonique des complexes alcalins acides du Kahuzi et du Biega (Kivu, Zaire). *C. r. Acad. Sci., Paris* **292**, 1027–1029.
Williams, H. R. and Williams, R. A. 1977. Kimberlites and plate-tectonics in West-Africa. *Nature, Lond.* **270**, 507–508.
Wimmenauer, W. 1974. The alkaline province of Central Europe and France. In: *Alkaline Rocks* (Edited by Sørensen, H.), pp. 238–270. John Wiley, London.
Wooley, A. R. and Garson, M. S. 1970. Petrochemical and tectonic relationship of the Malawi carbonatite–alkaline province and the Lupata–Lebombo volcanics. In: *African Magmatism and Tectonics* (Edited by Clifford, T. N. and Gass, I. G.), pp. 237–262. Oliver and Boyd, Edinburgh.
Wright, J. B. 1973. Continental drift, magmatic provinces and mantle. *Nature, Lond.* **244**, 565–567.