A new way to map old sutures using deformed alkaline rocks and carbonatites

Kevin Burke

Department of Geosciences
University of Houston
312 Science and Research Building 1
Houston, TX 77204-5007
USA

Lewis D. Ashwal
Susan J. Webb

School of Geosciences
University of the Witwatersrand
Private Bag 3
WITS, 2050
South Africa

Abstract

Using a recent compilation of African alkaline igneous rocks and carbonatites, we show that nearly 90% (28 of 32 occurrences) of nepheline syenite gneisses and deformed carbonatites are concentrated within known or inferred Proterozoic suture zones. Given the well-established intracontinental rift setting for these rocks and the likely continental collisional setting for their subsequent deformation, we suggest that deformed alkaline rocks and carbonatites (DARCs) represent the products of two well-defined parts of the Wilson Cycle. DARCs mark the places where vanished oceans have opened and then closed. We further postulate that DARCs taken into the mantle lithosphere to ca. 100 km depths at collision could provide source material for later alkaline magmatic activity. This could account for the observation of recurrent alkaline magmatic activity over hundreds of m.y. in provinces such as that of southern Malawi.

Introduction: Elusive ancient suture zones

The record of the dissipation of the Earth's internally generated heat by plate tectonic processes over the past 4 Ga is mainly to be found in the evidence preserved within continental crust of the operation of the Wilson Cycle (Wilson, 1968, Burke and Dewey, 1974). It is critical for recognizing the past operation of the Wilson Cycle to be able to identify ancient suture zones marking the places where now vanished oceans have opened and closed. Intense collision and erosion has led to uneven preservation of indicators such as dismembered ophiolites, ultra-high pressure metamorphic rocks, igneous and metamorphic rocks with reset isotopic systems and post-collisional granites, which are the commonly accepted indicators of continental collision. In places in which sutures are cryptic (Brown and Coleman, 1972), evidence of collision may consist only of the juxtaposition of reactivated and unreactivated continental rocks. Mapping ancient sutures has proved understandably difficult and in some areas consensus about suture locations has not yet been reached.

We report here on a newly recognized indicator of continental collision. We have found that occurrences of **D**eformed **A**lkaline **R**ocks and **C**arbonatites (DARCs), mainly nepheline syenite gneiss and deformed carbonatite in Africa are concentrated in suture zones of various ages (Fig. 1). We have used the newly identified association between DARCs and suture zones in Africa to suggest locations for poorly mapped suture zones and also to confirm the locations of some suture zones that are quite well known from other evidence.

Procedure

The best defined of all associations of igneous rocks with a specific tectonic environment is the association of nepheline syenites, their volcanic equivalents and carbonatites with rifts (Bailey, 1974, 1977, 1992). Linking more abundant rock types such as basalts with particular environments is much harder, calling for subtle geochemical and isotopic interpretation (e.g., Pearce and Cann, 1973; Zindler and Hart, 1986). Woolley (2001) published a comprehensive catalog of African alkaline rocks and carbonatites that confirmed the familiar association between nepheline syenites, carbonatites and rifts. Woolley's confirmation of the association led us to wonder whether his catalogue might not also reveal a tectonic association for DARCs. Acquaintance with the Wilson cycle led us to conjecture that DARCs could be associated with the ancient collisional plate boundaries whose former existence can be discerned in suture zones. We therefore tabulated (Table 1) and plotted on a map of Africa (Fig. 1) the 32 DARCs of Woolley's catalogue. We also plotted (Fig. 1) the distribution of known suture zones that represent continental and arc-continental collisions. Our analysis was restricted to suture zones that record collisions involving at least one continent because nepheline syenites and carbonatites have, with very few exceptions, been emplaced into continental crust.

Results

Ten of the 32 DARCs (Figs. 1, 2) lie within mapped suture zones. A further 18 lie close to the western margin of the Mozambique belt in a pattern that has led us to suggest locations for hitherto elusive suture zones separating the Congo and Kalahari cratons from the Panafrican aged Mozambique Belt. The four remaining DARCs (#s 4, 7, 21 and 28 in Fig. 1 and Table 1) are not clearly linked to suture zones.

Suture Zones at the Western Margin of the Mozambique Belt

Kennedy (1965, Fig. 1) placed the western boundary of the Mozambique Belt of Holmes (1951) at the margins of the Congo and Kalahari cratons (Figs. 1, 2). Although it was soon recognized that Kennedy's craton boundaries were close to places where oceans had closed during Panafrican times (Burke and Dewey, 1972), locating southern Mozambique Belt suture zones with any exactitude has remained a challenge. In a new attempt at locating those elusive structures, we have plotted (Fig. 2) the distribution of DARCs in an area between 20ºS and the Equator that straddles the western border of the Mozambique Belt. We have used the DARC distribution within that area together with regional geological and geophysical data to tentatively suggest possible locations for suture zones. Fig. 2 shows the suture zone pattern that we have discerned.

In Fig. 2 the suture zone between the Damara-Lufilian-Zambezi Fold Belt, which separates the Kalahari and Congo cratons, carries two DARCs (#31, 32, both deformed carbonatites shown as filled squares). The Kalahari craton was completely, or almost completely surrounded by collision zones during the interval 1.3-1.0 Ga, and until better ages have been determined it remains uncertain whether the two DARCs shown in Fig. 2 were thrust onto the Kalahari craton at ca. 1 Ga or at ca. 0.5 Ga. The Panafrican suture extends eastward toward Tete (Fig. 2), where the regional strike has long been recognized to change from E-W to N-S (e.g., Evans, et al., 1999, Fig. 2). We interpret a 300 km wide cluster of 18 DARCs outcropping between 13ºS and 17ºS as recording the suturing of Mozambique Belt rocks against the Congo and Kalahari Cratons.

Southward from Tete we used a line of 6 DARCs (# 13, 22, 23, 14, 15, 25) to map the location of a Panafrican aged suture that links with two other sutures at Nsanje (Fig. 2). From Nsanje one suture continues southward and in a few km becomes completely buried under Phanerozoic cover. The other suture, which is marked by 6 DARCs (# 24, 20, 19, 18, 17, 16), extends northward in a curve for about 500 km. We have projected that suture to the NNE under Lake Malawi to pass through a group of DARCs (# 10, 8, 9, 30, 29) and to reach the Congo Craton border at 9ºS, 30ºE. From that point as far as the Equator, the margin of the Congo Craton is occupied by a cryptic suture. To complete our picture of Panafrican suturing in the region of Lake Malawi, we have drawn a suture northward from Tete through DARCs #11 and #12 to close a loop of sutures at ca. 11ºS (Fig. 2). We used regional geological and geophysical maps in addition to DARCs in plotting these sutures, but make no claims for great accuracy. Incorporating different kinds of data could lead to an improved suture pattern. We do claim that the anastomosing pattern of the sutures that we have drawn is stylistically of the kind to be expected in a continental collision zone.

At ca. 1.85 Ga, the Congo Craton incorporated what had previously been a distinct Tanzanian Craton (represented by rocks now outcropping east of Lake Tanganyika) along a Ubendian suture that Daly (1988) interpreted to have been a ca. 100 km wide strike-slip fault zone. We recognize two DARCs #29 and #28 on that boundary, which we show as a curved line on Fig. 2 that continues northward along the shore of Lake Tanganyika. Where the suture goes north of 4ºS is unknown. Nepheline syenites and carbonatites of Panafrican age, including one DARC (#4) outcrop between 1º and 2ºS in the Congo. It seems possible that these bodies may lie on a Kibaran (ca. 1.25 Ga) suture.

A Tectonic Explanation of Bailey's Observation

Bailey (1974, 1977, 1992) drew attention to the repeated emplacement over intervals of up to hundreds of m.y. of nepheline syenites and carbonatites within some relatively small regions of Africa. This relationship is best seen in Malawi (Fig. 2), where Cretaceous nepheline syenites and carbonatites were emplaced among numerous DARCs of Panafrican age (ca 550 Ma). Our recognition of the association of DARCs with suture zones leads us to a simple tectonic explanation of Bailey's observation of repeated eruptions in the same area over long intervals (Fig. 3).

The finding of " ultra-high-pressure" minerals in rocks that have been involved in continental collisions has shown that material from the Earth's surface is commonly carried to depths of 90 to 120 km in collision zones (e.g., Smith and Lappin, 1989). We suggest that nepheline syenites and carbonatites have been carried to depths of ca. 100 km in collisional zones such as that which developed in Malawi ca 550 Ma. The occurrence of DARCs at outcrop among the Malawi suture zones indicates that suitable material for emplacement within the mantle lithosphere was being subducted at the time of the Panafrican collision. If subducted nepheline syenite was incorporated into the mantle lithosphere at ca. 100 km beneath Malawi at ca. 550 Ma then that rock would have been in a position to respond to pressure relief melting when the overlying Shire rift formed in Malawi 400 m.y. later at the end of Jurassic times (ca. 140 Ma) (Woolley, 1991).

Isotopic compositions of nepheline syenites and carbonatites clearly show that they represent products of mantle-derived magmatism, although the relative roles of primary mantle melting, fractional crystallization and liquid immiscibility are currently debated (e.g., Hall, 1996). For carbonatites, there is abundant evidence from experimental petrology that carbonatitic melts would form from mantle peridotite in the presence of carbonate minerals, at solidus temperatures considerably below those that would yield basalt (e.g., Lee and Wyllie, 2000). Similarly, experiments to 35 kbar in the quartz-albite-nepheline system (Boettcher and Wyllie, 1969) indicated that nepheline-normative melts would remain undersaturated throughout the melting interval, unless substantial aqueous fluid was present, which seems unlikely. Available data, therefore, allow the possibility that the parental magmas of DARCs were derived from previously formed alkaline igneous rocks that were taken down via subduction to ca. 100 km depths. For carbonatites, Sr, Pb and to a lesser degree Nd isotopic signatures show temporal evolution compatible with the idea of DARCs as sources. Such DARCs could have been incorporated into the mantle lithosphere at times as long ago as 3.0 Ga (Bell and Tilton, 2002). As far as we know, comparable data do not yet exist for nepheline syenites.

Conclusions

We have found a high concentration of DARCs along African suture zones and few DARCS in other tectonic environments. We attribute this concentration to the emplacement in intra-continental rifts of alkaline rocks and carbonatites, and their later deformation during continent-continent and arc-continent collisions. Concentration of subducted nepheline syenite and carbonatite in mantle lithosphere as a result of collision generates a reservoir of source rocks for alkaline magmas and carbonatites, and a plausible explanation for Bailey's observation that magmatic activity in alkaline rock provinces within continents has recurred episodically over periods of hundreds of m.y.

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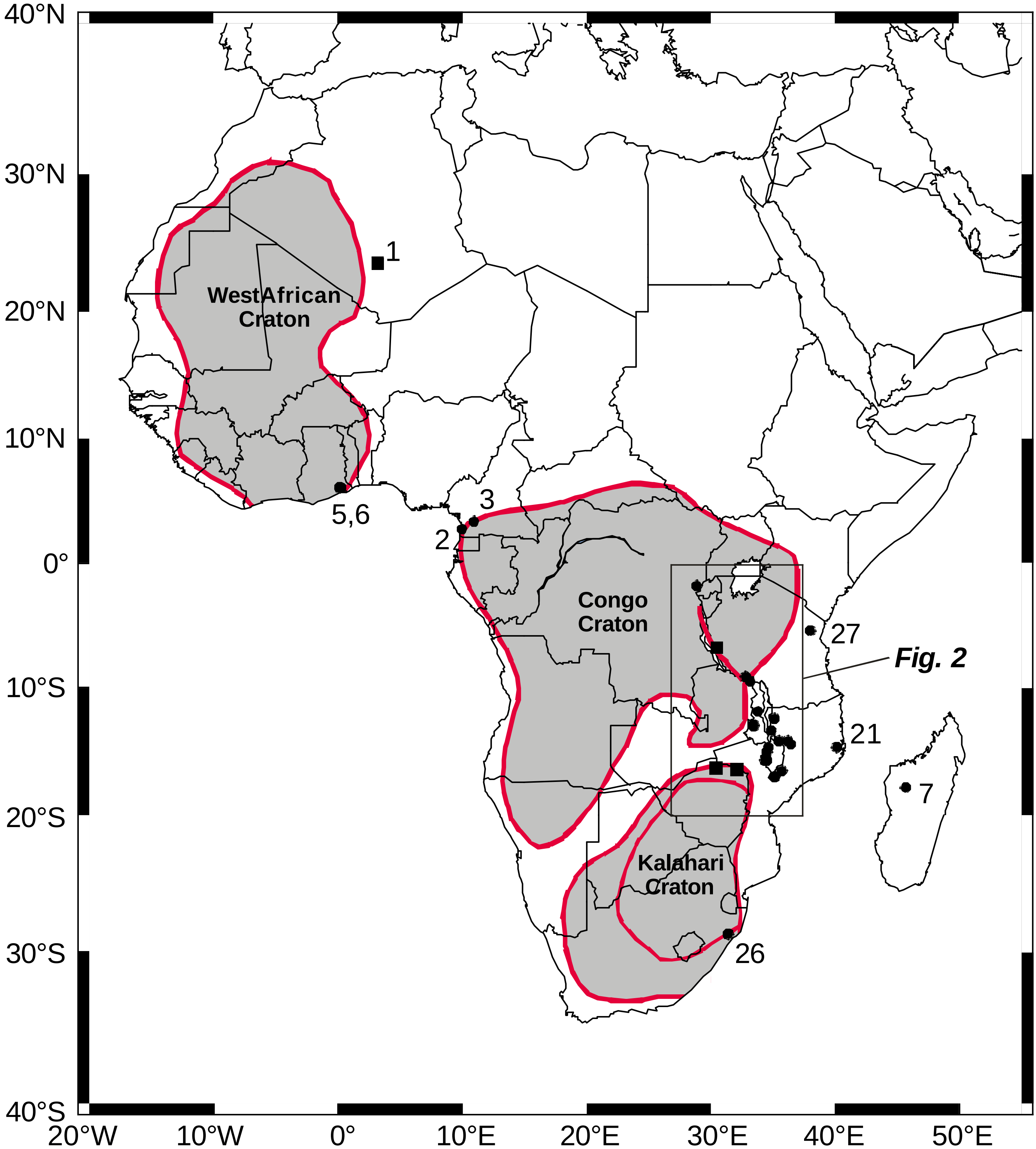
Figure Captions

Fig. 1. Map of Africa showing cratons (Kennedy, 1965) bounded by sutures that mark sites of ocean closure during Panafrican time (Burke and Dewey, 1972). Locations of the 32 Deformed Alkaline Rocks and Carbonatites (DARCs) taken from the Woolley (2001) catalogue are shown as filled symbols (circle = nepheline syenite gneiss; square = deformed carbonatite, numbers as in Table 1). The line carrying 2 DARCs inside the Congo Craton shows where the Tanzanian Craton was incorporated into the Congo Craton in Ubendian time (ca. 1.85 Ga). The line inside the Kalahari Craton marks the 1.2 Ga Natal-Namaqualand suture zone and its postulated continuation. DARC locations indicated but not numbered within the inset area of Fig. 2.

Fig. 2. Alkaline rocks, carbonatites, cratons, Panafrican-aged fold belts and suture zones in SE Africa. Circles = nepheline syenites; squares = carbonatites; open symbols = Mesozoic occurrences; filled symbols = Panafrican occurrences. Only DARCs are numbered. Dashed lines indicate the regional strike of Panafrican-aged rocks in the Damara-Lufilian-Zambezi (DLZB) and Mozambique (MB) Fold Belts. Phanerozoic sedimentary rocks south of Nsanje are shown with stippled pattern. Sutures (lines with cross marks) indicate the locations of ocean closure during Panafrican times. Suture pattern in the area around Lake Malawi is based on the distribution of DARCs, regional geology and geophysics. Line passing through DARCs #28 and #29, and along the eastern shore of Lake Tanganyika is a Ubendian suture (? indicates uncertainty about its continuation). Panafrican nepheline syenites and DARC #4 in NW corner are possibly on a Kibaran suture.

Fig. 3. Repeated episodes of alkaline intracontinental magmatism- an example from Malawi. (A) Nepheline syenites and carbonatites (black filled circles) were emplaced into an intracontinental rift at ca. 1 Ga. (B) Those rocks were later preserved at a rifted continental margin. (C) During Panafrican collision, the alkaline rocks from the rifted margin developed gneissic fabrics, becoming nepheline syenite gneisses and deformed carbonatites (DARCs). (D) During a long period of lithospheric stability, DARCs remained preserved both in the crust and in the mantle lithosphere at depths of ca. 100 km. (E) At the beginning of Cretaceous time, a renewed episode of rifting led to adiabatic decompression melting of DARCs in the mantle lithosphere, producing a new generation of nepheline syenites and carbonatites.



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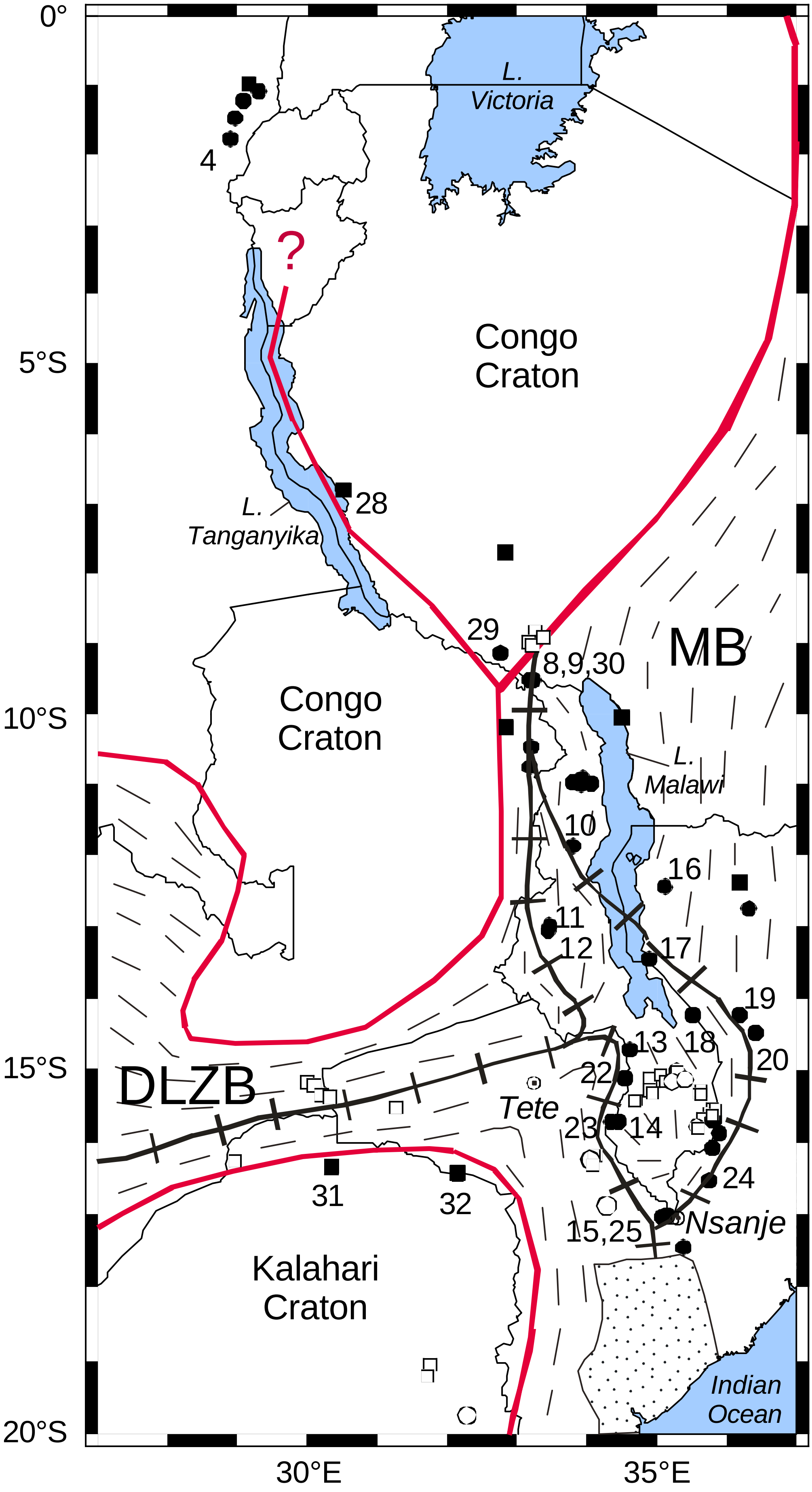
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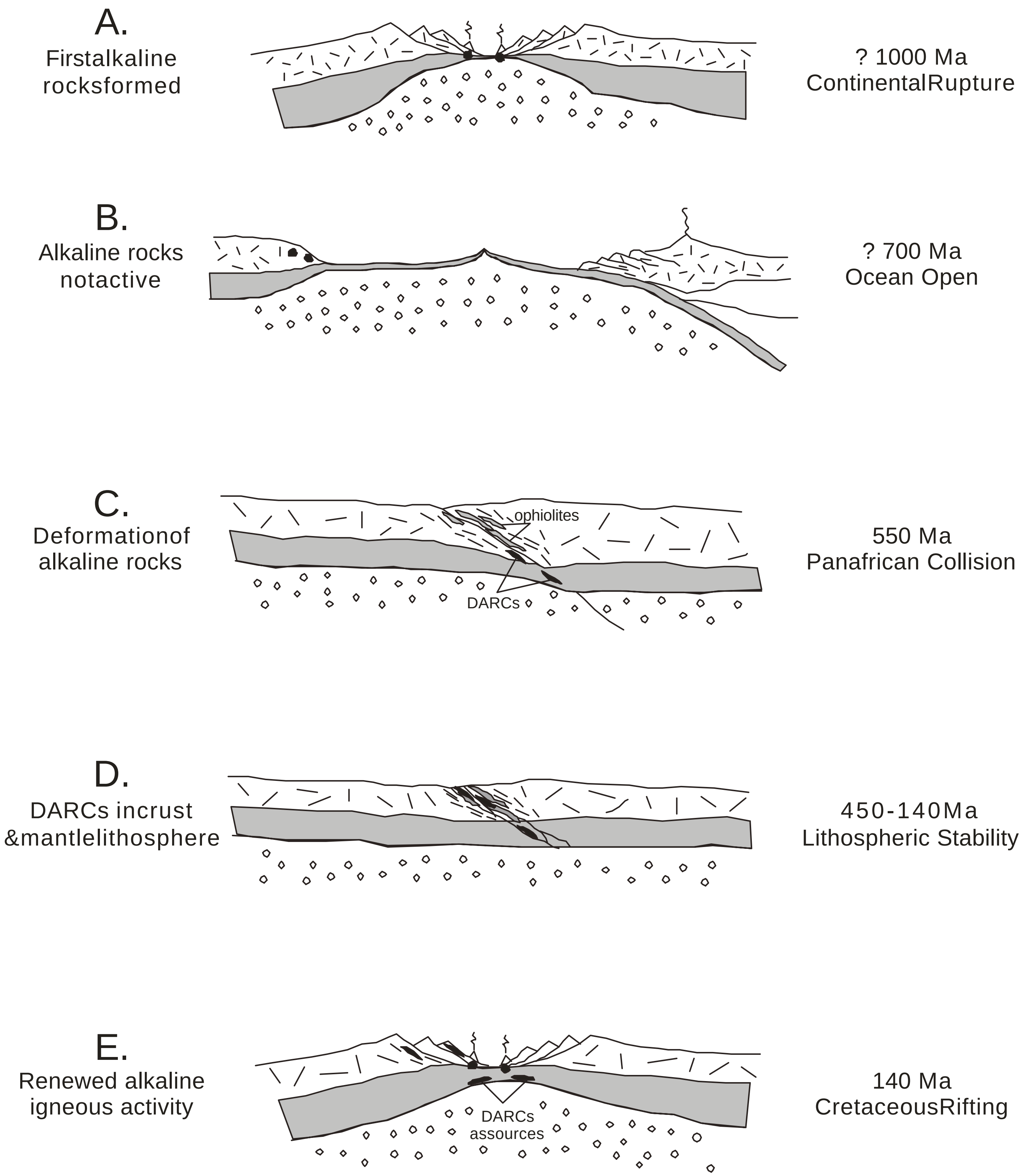
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TABLE 1. OCCURRENCES OF DEFORMED ALKALINE ROCKS AND CARBONATITES IN AFRICA

No.	Locality	Lat	Long	Rock Types*	Age# Primary (Ma)	Age# Reactivation (Ma)	Suture Name	Suture Age (Ma)	Key Reference
	<u>Algeria</u>								
1	In'ouzzal	23 37' N	03 13' E	c	2090 [3] 1994 ± 20 [3]	255 ± 8 [4] 564± 64 [4]	W. African Craton	550	Ouzegane et al. (1988)
	<u>Cameroon</u>								
2	Nkonglong	02 46' N	10 01' E	n	2890 ± 45 [2]	529 ± 15 [1]	Congo Craton	550	Kornprobst et al. (1976)
3	Lolodorf	03 23' N	10 58' E	n	N.D.§	N.D.§			Kornprobst et al. (1976)
	<u>Congo (DRC)</u>								
4	Numbi	01 46' S	28 54' E	n	830 ± 51 [2]	648 ± 17 [2]	Kibaran?	1100	Kampunzu et al. (1988)
	<u>Ghana</u>								
5	Somanya, Kpong & Pore	06 09' N	00 08' E	n	N.D.§	N.D.§	W. African Craton	550	Holm (1974)
6	Dufo to Jirawde	06 07' N	00 11' E	n	N.D.§	N.D.§			Allen and Charsley (1968)
	<u>Madagascar</u>								
7	Makaraingobe	17 52' S	45 40' E	n	N.D.§	N.D.§	Unknown	?	Welter (1964)
	<u>Malawi</u>								
8	Ilomba	09 31' S	33 11' E	n	N.D.§	508 ± 12 [1] 490 ± 12 [1] 685 ± 62 [2]			Woolley et al. (1996)
9	Ulindi	09 31' S	33 14' E	n	N.D.§	686 ± 62 [2]			Eby et al. (1998)
10	Chikangawa	11 52' S	33 48' E	n	N.D.§	410 ± 16 [1] 650 ± 40 [2]			Gaskell (1973)
11	Chipala and Chipala East	12 59' S	33 28' E	n	N.D.§	N.D.§			Eby et al. (1998)
12	Kasungu	13 03' S	33 27' E	n	N.D.§	N.D.§			Eby et al. (1998)
13	Ncheu	14 43' S	34 37' E	n	N.D.§	N.D.§			Walshaw (1965)
14	Tambani	15 43' S	34 27' E	n	N.D.§	587 ± 72 [3] 542 [3]			Bloomfield (1968)
15	Nsanje Area	17 01' S	35 09' E	n	N.D.§	N.D.§	Mozambique Belt	550	Allen and Charsley (1968)
	<u>Mozambique</u>								
16	Unnamed	12 26' S	35 07' E	n	N.D.§	N.D.§			Instituto Nacional de Geologia (1987)
17	Meponda	13 27' S	34 54' E	n	755 ± 115 [2]	538 [3]			Lulin et al. (1985)
18	Unnamed	14 14' S	35 31' E	n	N.D.§	N.D.§			Instituto Nacional de Geologia (1987)
19	Unnamed	14 14' S	36 11' E	n	N.D.§	N.D.§			Instituto Nacional de Geologia (1987)
20	Unnamed	14 29' S	36 25' E	n	N.D.§	N.D.§			Instituto Nacional de Geologia (1987)
21	Unnamed	14 45' S	40 08' E	n	N.D.§	N.D.§			Instituto Nacional de Geologia (1987)
22	Unnamed	15 07' S	34 33' E	n	N.D.§	N.D.§			Instituto Nacional de Geologia (1987)
23	Unnamed	15 43' S	34 21' E	n	N.D.§	N.D.§			Instituto Nacional de Geologia (1987)
24	Chiperone and Derre	16 32' S	35 45' E	n,g	N.D.§	N.D.§			Cilek (1989)
25	Lulwe	17 02' S	35 05' E	n	N.D.§	N.D.§			Instituto Nacional de Geologia (1987)
	<u>South Africa</u>								
26	Bull's Run	28 45' S	31 26' E	n,c	1140 ± 35 [3] 1100 ± 40 [3]	900 [1]	Namaqua-Natal Belt	1100	Scogings and Forster (1989)
	<u>Tanzania</u>								
27	Lungolo	05 27' S	38 02' E	n	N.D.§	N.D.§	Usagaran?	?	Kempe (1968)
28	Sangu-Ikola	06 48' S	30 31' E	c	N.D.§	N.D.§	Ubendian	1800	van Straaten (1989)
29	Mbozi	09 08' S	32 46' E	n	N.D.§	743 ± 30 [1] 745 ± 45 [1]	Ubendian	1800	Basu and Ikingura (1984)
30	Nachendezwaya	09 30' S	33 12' E	c	655 [3]	N.D.§	Mozambique Belt	550	Nelson et al. (1988)
	<u>Zimbabwe</u>								
31	Dande-Doma	16 20' S	30 21' E	c	N.D.§	N.D.§	Kalahari Craton	1000?	Barber (1991)
32	Kapfrugwa	16 28' S	32 09' E	c	N.D.§	N.D.§		550?	Barton et al. (1991)

Note: Data taken from Woolley (2001).

* c = carbonatite, n = nepheline syeite, g = peralkaline granite.

[1] K-Ar, [2] Rb-Sr, [3] U-Pb, [4] apatite fission track.

§N.D. = not determined.