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Tadhak alkaline ring-complex (Mali): existence of U-Pb isochrons and "Dupal" signature 270 Ma ago

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The Tadhak alkaline ring-complex of Permian age provides two whole rock U-Pb isochrons giving concordant ages in agreement within relative errors with the Rb-Sr isochron age: ^{235}U-^{207}Pb isochron: 271 ± 32 Ma (MSWD = 0.3); ^{238}U-^{206}Pb isochron: 254 ± 18 Ma (MSWD = 7.8), both on 8 whole-rock samples. The existence of these isochrons indicates that in favorable conditions U (and Pb) can be immobile. This can be due either to the lack of hard oxidizing conditions and/or to the location of U, in very low concentrations, in weathering-resistant minerals. The initial ratios ($^{206}Pb/^{204}Pb$ = 18.714 ± 70 and $^{207}Pb/^{204}Pb$ = 15.589 ± 16), corrected for their Permian age, lie in the range observed for oceanic island basalts or continental alkali basalts and indicate an origin in a similar mantle, without any significant crustal contamination. This was also suggested by the initial $^{87}Sr/^{86}Sr$ ratio of 0.70457 ± 4. Moreover, these Sr and Pb isotopic characteristics belong to the field of the so-called "Dupal" anomaly and indicate that it existed already 270 Ma ago. This study shows the potential interest of isotopic investigations of within-plate alkaline ring-complexes to characterize subcontinental mantle compositions, particularly in the past.

1. Geological background

The Tadhak *undersaturated* province in Mali is composed of several plutonic ring-complexes, smaller volcano-plutonic complexes and carbonatites [1]. It is associated with the Tessofi graben which reflects an episode of Permian rifting along the Pan-African suture [2] resulting from the collision 600 Ma ago between the West African craton and the Tuareg shield (Fig. 1) [3,4]. On the other hand, the Iforas silica *oversaturated* alkaline province of ring-complexes, 100 km to the east of the Tadhak area, has a completely distinct and older (560–540 Ma) history and follows immediately an important calc-alkaline magmatism related to a subduction and collision episode east of the suture in the Tuareg shield [5,6]. By contrast, the Tadhak province is located on the eastern edge of the West African craton stabilized in the Eburnean (2000 Ma ago) with no pre-Permian sedimentary cover in this area (Fig. 2) [7].

Petrographically [2,7], the Tadhak complex is composed of four main units. These are concentrically disposed (Fig. 2) and consist of: (1) an outer fine-grained nepheline syenite with steeply inward-dipping flow structures; (2) a leucocratic nepheline syenite; (3) a lenticular unit of nepheline melteigite grading to a nepheline ijolite, with enclaves of pyroxenites displaying cumulate textures. Glimmerite is also present; (4) an inner foyaitic nepheline syenite. These units are cut by numerous foyaite and tinguaite dykes while the complex is cut by a small satellite ring-complex in the east.

The geological setting of the Tadhak complex, whose lithology and Permian age contrast markedly with the 2000 Ma old basement (Eburnean gneisses and granitoids [7]) represents a very good situation to try to assess the nature of the source of this undersaturated magma. Indeed, although a mantle origin is consistent with previ-

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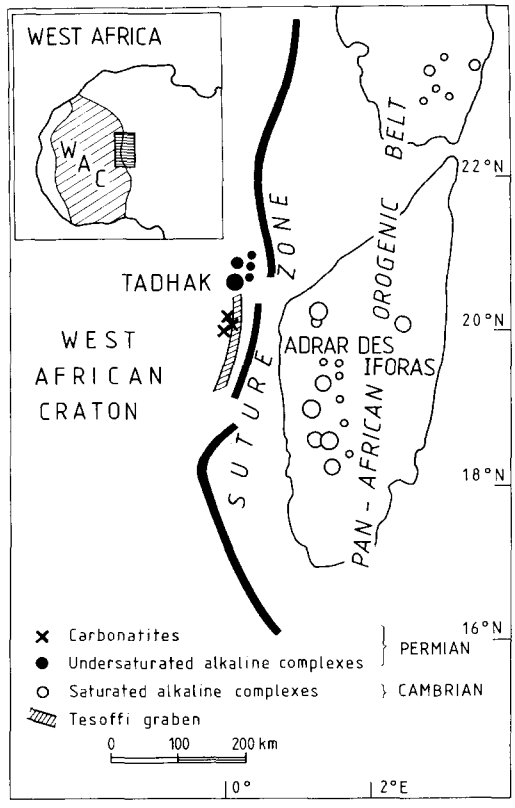

Fig. 1. General sketch map showing the two palaeo-continents (Eburnean West African craton and Pan-African belt of Iforas-Ahnet) separated by the suture zone resulting from their collision 600 Ma ago.

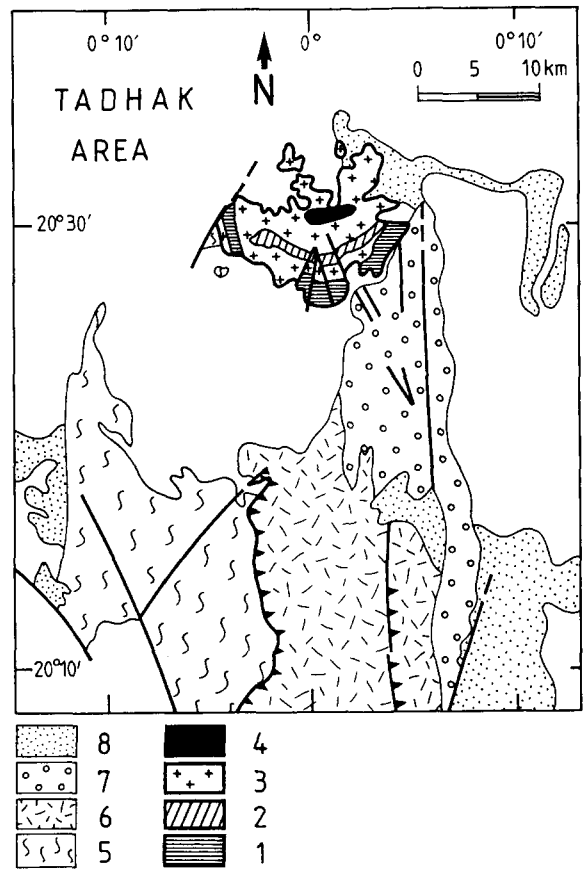

Fig. 2. Geological map of the Tadhak alkaline ring-complex area after Fabre et al. [7]. (a) *Tadhak ring-complex*; *1* = nephelinic syenite with fluidal structures; *2* = hololeucocratic nephelinic syenite; *3* = foyaitic nephelinic syenite; *4* = pyroxenolite inclusion-bearing ijolite. (b) *Neighbouring rocks*: *5* = Eburnean gneisses; *6* = Pan-African nappes (Proterozoic quartzites and Pan-African volcanosedimentary sequence); *7* = Permian Tesoffi graben; *8* = Mesozoic shales and sandstones. Absence of ornamentation represents Quaternary materials.

ously determined $^{87}Sr/^{86}Sr$ initial ratio (0.70457 $\pm$ 4 [2]), this latter value does not preclude the possibility that the magma had interacted with a Rb depleted lower crust. Therefore, Pb isotopes have been determined to assess this possibility and to compare the Tadhak source with present-day mantle sources, especially the suboceanic ones, which have been recently extensively studied and are much better characterized [18–21].

2. Results and U-Pb isochrons

Eight samples, covering the different petrographic types, have been analysed for whole-rock Pb isotopes compositions as well as U and Pb concentrations. The data are reported in Table 1 and Fig. 3a, b. The range of isotopic variations is very wide: indeed, the $^{206}Pb/^{204}Pb$ ratios vary from 18.757 for sample T16, a foyaite dyke, to 26.460 for sample T35, a pyroxenolite of the ring No. 2; the $^{207}Pb/^{204}Pb$ ratios vary from 15.584 to 16.024 and the $^{208}Pb/^{204}Pb$ from 39.072 to 64.453. The concentrations of both Pb and U show also very big variations, from 0.66 to 40.0 ppm and from 0.026 to 49.4 ppm respectively.

The U-Pb data define well fitted U-Pb isochrons which moreover yield ages in agreement or near agreement with the age determined by the Rb-Sr method. The different ages obtained are: Rb-Sr system: 272 $\pm$ 7 Ma [2]; $^{235}U/^{207}Pb$ system: 271 $\pm$ 32 Ma (MSWD = 0.3 for 8 WR, Fig. 3b); $^{238}U/^{206}Pb$ system: 254 $\pm$ 18 Ma (MSWD =

TABLE 1

Pb isotopic compositions and U and Pb concentrations in the Tadhak samples

Sample	$^{208}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{206}Pb/^{204}Pb$	Pb	U	$^{238}U/^{204}Pb$	$^{235}U/^{204}Pb$
T16	39.072	15.584	18.757	5.3	0.026	0.314	0.00228
T29	39.827	15.607	19.161	4.54	0.99	14.1	0.103
T35	64.453	16.024	26.460	0.66	1.35	198	1.44
T42	40.711	15.670	19.809	4.02	1.72	28	0.206
T48	41.380	15.779	22.249	40.0	49.4	86	0.62
T66	39.394	15.633	19.377	8.4	2.08	16.1	0.117
T76	39.824	15.635	19.533	5.6	1.59	18.7	0.136
T83	41.729	15.699	20.677	7.3	5.0	47.5	0.347
T84	39.817	15.659	19.535				

The isotopic composition and the concentration (isotope dilution) analyses were carried out on a Finnigan MAT 260 and TH5 mass spectrometers respectively. Errors on the $^{235}U/^{204}Pb$ and $^{238}U/^{204}Pb$ ratios are 2% while the between-run precision is better than 0.1% for $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ ratios (except for sample T35, T42 and T83 where it is 0.15%) and better than 0.15% for the $^{208}Pb/^{204}Pb$ ratios. Repeated analyses of the NBS981 Pb standard [9] give a mean mass discrimination factor of $-0.1 \pm 0.04\%$ (25 analyses) per a.m.u.
$^{235}U = 0.98485 \times 10^{-9}\ y^{-1}$ and $^{238}U = 0.155125 \times 10^{-9}\ y^{-1}$ [8].
For a detailed description of the chemical procedure see [10].

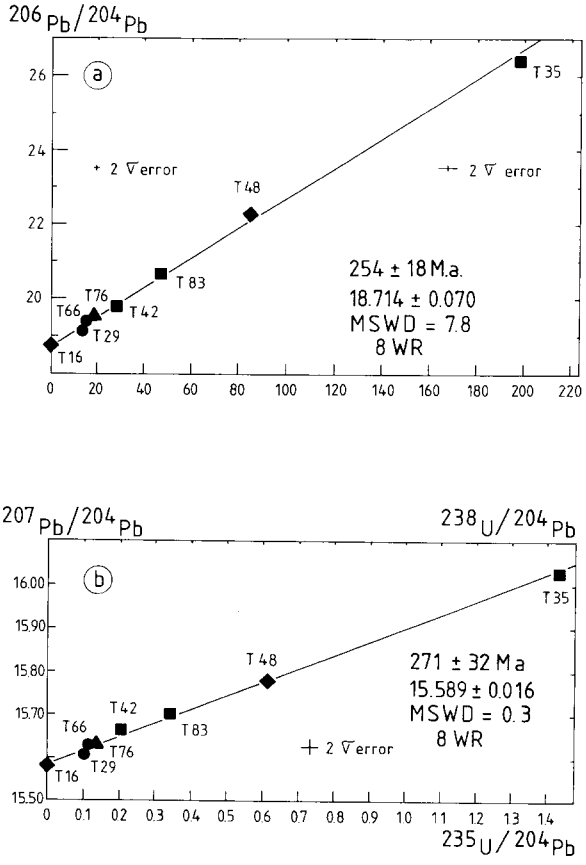

Fig. 3. (a) ^{238}U-^{206}Pb and (b) ^{235}U-^{207}Pb isochron diagrams for Tadhak ring-complex. ● = unit 1; ■ = unit 2; ▲ = unit 3; ◆ = late dykes.

7.3 for 8 WR, Fig. 3a). These ages and 2σ errors were calculated following the Williamson method [11]. The errors of the $^{238}U/^{206}Pb$ system were multiplied by VMSWD to take into account its higher MSWD value, which must only reflect slight and recent perturbations as the ^{235}U-^{207}Pb system does not appear to be affected. The omission for the fitting of the U-Pb isochrons of sample T35, with a very high U/Pb ratio, has no influence either on the ages or on the initial ratios defined by these isochrons. The great scatter of the U/Pb ratios reflects in fact large relative variations, at low concentration levels, of both U and Pb. Considering now the Pb-Pb system, the slope of the best-fit line on the nine samples corresponds to an age of 414^{+280}_{-304} Ma (MSWD = 0.5). The large errors reflect the small spread of $^{207}Pb/^{204}Pb$ ratios in relatively young rocks and account for the poor reliability of this age. However, within error limits, this age is in agreement with the age determined by the other systems. This confirms the poor applicability of the Pb-Pb method for Phanerozoic rocks.

Although the ^{232}Th-^{208}Pb system has yielded good isochrons from rocks as old and older than 2000 Ma [12–14], it is unusual for the U-Pb systems to provide convincing results because of the uranium mobility of U in surface or subsurface conditions [12]. With the exception of very few cases where U-Pb isochrons of two or three

points on old carbonate rocks were obtained [15], it has usually been possible to define U-Pb isochrons only by omitting discrepant samples on the basis of Pb-Pb or other geochronological data [16,17]. In contrast to these studies, the existence of U-Pb isochrons in the Tadhak complex requires an unusual immobility of U (and Pb) for the post-emplacement history of this complex.

Two complementary and additional factors could account for the exceptional case of the Tadhak: (1) the absence of strong oxidizing conditions due to arid climatic conditions and/or sediment protection; and (2) the very low U concentrations (< 2 ppm for the majority of the samples), probably located in weathering-resistant minerals.

3. Initial ratios—inferences concerning the subcontinental mantle

U-Pb isochrons also provide precise Pb initial ratios and these will greatly help to define the source characteristics of the Permian igneous province. Usually, these ratios have to be defined by indirect and less reliable methods, such as the analysis of comagmatic U-poor phases (K-feldspar for instance), whereas here they have been obtained directly.

The respective values for the $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ ratios for the Permian time of crystallization are: 18.714 ± 0.070 and 15.589 ± 0.016. To allow a comparison of these ratios with those of recent mantle derived rocks, we have calculated the change due to in situ U decay in the source from Permian (270 Ma) to present. Considering μ values for the source between 7 and 9 (broad range of mantle values), the correction affects only slightly the ratios (the relative changes are 0.299–0.385 for the $^{206}Pb/^{204}Pb$ ratio and 0.015–0.020 for the $^{207}Pb/^{204}Pb$ ratio). Even considering a higher μ value, as 14, which corresponds to sample T29 (the plutonic sample which has the lowest μ value), the increase is only 0.604 and 0.031 for the $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ ratios respectively. This maximum change is shown by the arrow in Fig. 4a. In the same way, the maximum correction for ^{87}Rb decay in the source has been based on sample T29 (Fig. 4b). The comparison of the Tadhak data with those from recent mantle-derived rocks is shown on the same figures.

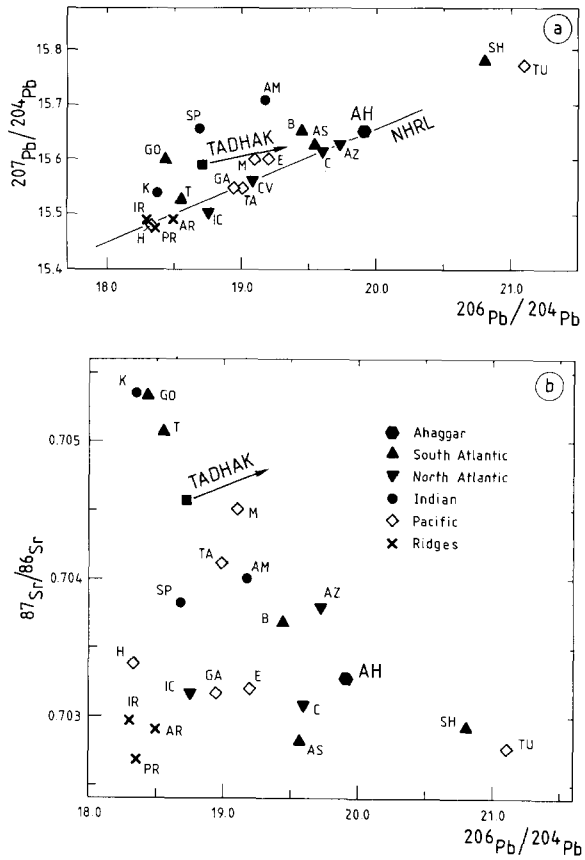

Fig. 4. Comparison with MORB and OIB data [19–21] and with continental alkali basalts from the Ahaggar volcanic suite [26]. The Tadhak initial ratio (270 Ma ago) is shown by a black square while the arrow represents the correction for in situ U decay in the source magma considered as a maximum for the Permian age (see text for explanation). *NHRL*: northern hemisphere reference line [21]. *AH*: Ahaggar; *AM*: Amsterdam; *AS*: Ascension; *AZ*: Azores; *B*: Bouvet; *C*: Canaries; *CV*: Cape Verde; *E*: Easter Island; *GA*: Galapagos; *GO*: Gough; *H*: Hawaii; *IC*: Iceland; *K*: Kerguelen; *M*: Marquesas; *SH*: St. Helena; *SP*: St. Paul; *T*: Tristan da Cunha; *TA*: Tahiti; *TU*: Tubuai. Ridges: *AR*: Atlantic; *IR*: Indian; *PR*: Pacific. (a) $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ diagram. (b) $^{87}Sr/^{86}Sr$ versus $^{206}Pb/^{204}Pb$ diagram.

The Tadhak initial Pb and Sr ratios fall in the field of modern oceanic island basalts (OIB) [20,21]. More precisely, the Tadhak Pb isotopic compositions lie above the NHRL (northern hemisphere reference line [21]) and typically within the field of South Atlantic and South Indian islands. There are two ways to account for the Pb and Sr ratios: either the primary magma had originated in a mantle with North Atlantic OIB characteristics and has been contaminated by up-

per crust or, these compositions are pristine and reflect the mantle source. In both cases, there are implications for the mantle structure under the continents.

First of all, let us stress that any significant contamination by the West African craton (2000 Ma old) would have had important effects on Pb ratios, particularly on $^{207}Pb/^{204}Pb$ ratios which are very sensitive to old continental crust contamination (the only terrestrial reservoir showing large $^{207}Pb/^{204}Pb$ variations). This would be particularly evident in the case of the Tadhak rocks which have relatively low lead contents. The radiogenic composition of the Tadhak Pb isotopes excludes a lower crust contamination. Only an upper crust derived material could be an adequate contaminant for the Pb and Sr isotopes but appears unlikely for three reasons: firstly, the Tadhak rocks are undersaturated (from 45 to 55% SiO_2, H. Bertrand, personal communication), which prohibits an important contamination by silicic crust; secondly, the emplacement of this kind of complex is usually very rapid [22], which is not favourable to important interaction with country rocks during ascent; thirdly, basement gneissic inclusions are very rare. The oversaturated alkaline province of Iforas is partly represented by high-level ring-complexes which have intruded the Trans-Saharan Pan-African belt just after the orogen [5,6] i.e. in a hot and wet environment. Nevertheless, Weis et al. [23] can conclude on an oxygen isotopes basis, that upper crustal contamination is limited to ring contact zones. It is then not surprising that in an old, cold and dry basement, the undersaturated Adrar Tadhak has not suffered any contamination by upper crust [24].

Moreover, the Tadhak isotopic compositions are situated in the same relative position with regard to the different islands in both Pb-Pb and Pb-Sr diagrams (Fig. 4): between Kerguelen, Tristan and Gough islands on the one hand and Bouvet, Ascension, Canaries, Azores and St. Helena islands on the other. An upper crust contamination of an Atlantic MORB would have little chance to produce this concordance.

The absence of crustal contamination implies that the Tadhak Pb and Sr isotopic characteristics are representative of its mantle source region. Although currently situated in the northern hemisphere (20°30′N), these characteristics are entirely comparable to those observed for rocks derived from the southern hemisphere-type mantle, the so-called "Dupal" mantle [21,25]. This is the main difference with the recent Ahaggar alkali basalts which have a North Atlantic mantle signature [26] (Fig. 4). However, taking into account palaeomagnetic reconstructions of Pangea for Permian times [27–30] (Fig. 5), we can see that the Tadhak area was situated at a latitude of about 15°S, undoubtly in the southern hemisphere. In fact, West Africa has jumped the Dupal boundary between Permian and Quaternary.

We conclude then from our data that:

—the mantle which is the source of alkaline magmas, no matter their outcropping environment, has the same geochemical characteristics, particularly a similar range of heterogeneities, under the continents as under the ocean basins. This supports the view of previous workers on continental mantle derived alkaline rocks [26,31,32].

—the Dupal anomaly has existed at least for 270 Ma and is apparently anchored in the southern hemisphere. It is then clearly not related to plate motion.

This last point implies that the lithosphere cannot be the source of alkaline magmas. Fitton and

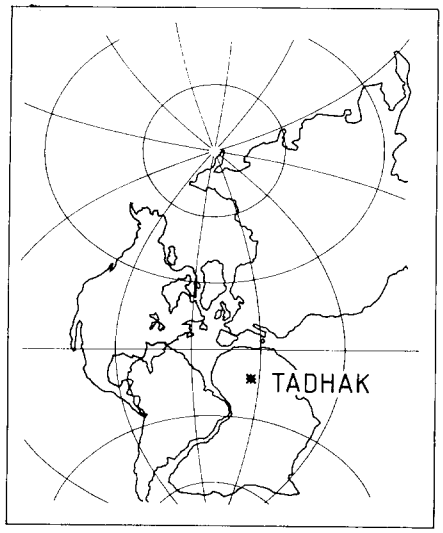

Fig. 5. Proposed reconstruction for Pangaea in the Permian times by Westphal [30]. It is a Transverse Mercator Projection. Parallels and meridians are drawn every 30°. The Tadhak Province is clearly located in the southern hemisphere at this epoch.

Dunlop [33] arrive at the same conclusion on the basis of their study of the alkaline volcanoes forming the Cameroon line which runs from the African continent into the Atlantic Ocean. Indeed, there is no change, either in geochemical or in isotopic signatures of these volcanic rocks, when crossing the limit between these two environments. On the other hand, the structure of the lithosphere and reactivation of lithospheric faults determine the loci of alkaline magmatism [34,35]. The Tadhak province is located along the Pan-African palaeo-suture between the West African craton and the Tuareg shield and its age corresponds to an important rifting episode within the Gondwana and European plates (Oslo, North Sea, Midland valley of Scotland). This implies that the source is not much deeper than the base of the lithosphere, i.e. the asthenosphere, as already proposed for the 550 Ma old Iforas alkaline rocks [6,36]. As the asthenosphere can also be an intermediate reservoir, even if a long-lived one, this inference is not in conflict with a deeper mantle primary origin for OIB-type magmas as implied by several models including recycling of oceanic crust and sediments or continental lithosphere at great depth [37–40]. We want to stress that these deep mantle manifestations cannot be tapped without lithospheric sollicitation [34] and therefore that the asthenosphere must be an important reservoir for alkaline magmas.

4. Conclusions

This isotopic study shows that alkaline ring-complexes may yield important information on the nature of the subcontinental mantle, for which at the moment there are few published data. In the present case we find interesting that mantle material with similar geochemical characteristics sampled today by the South Atlantic volcanoes ("Dupal" mantle) was already available beneath West Africa in Permian times when the latter was located in the southern hemisphere. Although within-plate alkaline complexes may occur either in continental or oceanic environments as in the case of Kerguelen archipelago [41], they seem to constitute a single family with a common mantle origin, minor variations being due to heterogeneity in the asthenosphere, major variants reflecting mainly different proportions of crustal participation [22]: the continental Tadhak complex may be considered as a typical pure mantle product, in contrast to the Nigerian Younger Granite Province [42] which displays important crustal interaction. In view of the wide range in age of alkaline ring-complexes, from 2000 Ma [43,44] to recent [45], further detailed isotopic investigations of well selected examples should throw light on variations of mantle composition with time.

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References

1 J.F. Sauvage and R. Savard, Les complexes alcalins sous-saturés à carbonatites de la région d'In Imanal (Sahara malien): une présentation, J. Afr. Earth Sci. 3, 143–150, 1985.

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

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

4 R. Caby, J.M.L. Bertrand and R. Black, Pan-African ocean closure and continental collision in the Hoggar-Iforas segment, central Sahara, in: Precambrian Plate Tectonics, A. Kröner, ed., pp. 407–434, Elsevier, Amsterdam, 1981.

5 J.P. Liégeois and R. Black, Pétrographie et géochronologie Rb-Sr de la transition calco-alcaline–alcaline fini-pan-africaine dans l'Adrar des Iforas (Mali): accrétion crustale au Précambrien supérieur, In: Géologie Africaine—African Geology, J. Klerkx and J. Michot, eds., pp. 115–145, Tervuren, 1984.

6 J.P. Liégeois and R. Black, Alkaline magmatism subsequent to collision in the Pan-African belt of the Adrar des Iforas (Mali), in: Alkaline Rocks, J. Fitton and J. Upton, eds., Geol. Soc. London, Spec. Vol., in press, 1986.

7 J. Fabre, H. Ba, R. Black, R. Caby, M. Leblanc and A. Lesquer, Notice explicative de la carte géologique de l'Adrar des Iforas, 85 pp., Dir. Nat. Géol. Mines, Bamako, 1982.

8 A.H. Jaffey, K.F. Flynn, L.E. Glendenin, W.C. Bentley and A.M. Essling, Precision measurement of half-lives and specific activities of ^{235}U and ^{238}U, Phys. Rev. C4, 1889–1906, 1971.

9 E.J. Catanzaro, T.J. Murphy, W.R. Shields and E.L. Garner, Absolute isotopic abundance ratios of commun, equal-atom

and radiogenic lead standards, J. Res. Natl. Bur. Stand. 72a, 261, 1968.
10 D. Weis, Composition isotopique du plomb total de roches: méthodologie, Bull. Soc. Chim. Belg. 90, 1127–1140, 1981.
11 J.H. Williamson, Least-square fitting of a straight line, Can. J. Phys. 46, 1845–1847, 1968.
12 J.N. Rosholt, R.E. Zartman and I.T. Nkomo, Lead isotope systematics and uranium depletion in the Granite mountains, Wyoming, Geol. Soc. Am. Bull. 84, 989–1002, 1973.
13 L.P. Black and J.R. Richards, Rock lead isotopes in northeast Queensland, J. Geol. Soc. Aust. 19, 321–330, 1972.
14 I.T. Nkomo and J.N. Rosholt, A lead-isotope age and U-Pb discordance of Precambrian gneisses from Granite Mountains, Wyoming, U.S. Geol. Surv. Prof. Pap. 800, C169–177, 1972.
15 E.K. Gerling and A.D. Iskandorova, Isotopic composition of lead from carbonate rocks of different ages. Dokl. Akad. Nauk USSR, 170, 905–907, 1966.
16 C.W. Montgomery and P.M. Hurley, Total rock U-Pb and Rb-Sr systematics in the Imataca Series, Guyana shield, Venezuela, Earth Planet. Sci. Lett. 39, 281–290, 1978.
17 G. Manhès, J.F. Minster and C.J. Allègre, Comparative uranium-thorium-lead and rubidium-strontium study of the Saint Sévérin amphoterite: consequence for the early solar system chronology, Earth Planet. Sci. Lett. 39, 14–24, 1978.
18 M. Tatsumoto, Isotopic composition of lead in oceanic basalts and its implication to mantle evolution, Earth Planet. Sci. Lett. 38, 63–87, 1978.
19 S.S. Sun, Lead isotopes study of young volcanic rocks from mid-ocean ridges, ocean islands and island arcs, Philos. Trans. R. Soc. London, Ser. A 297, 409–445, 1980.
20 A. Zindler, E. Jagoutz and S. Goldstein, Nd-Sr and Pb isotopic systematics in the three component mantle: a new perspective, Nature 298, 519–523, 1982.
21 S.R. Hart, A large-scale isotope anomaly in the Southern hemisphere mantle, Nature 309, 753–757, 1984.
22 B. Bonin, Les granites des complexes annulaires. Manuels et Méthodes, 4, 183 pp., BRGM, 1982.
23 D. Weis, J.P. Liégeois and M. Javoy, The Timedjelalen alkaline ring-complex and related N-S dyke swarms (Adrar des Iforas, Mali). A Pb-Sr-O study, Chem. Geol., in press, 1986.
24 B. Bonin and A. Giret, Clinopyroxene compositional trends in oversaturated and undersaturated alkaline ring-complexes, J. Afr. Earth Sci. pp. 175–183, 1985.
25 B. Dupré and C.J. Allègre, Pb-Sr-Nd isotopic correlation and the chemistry of the North Atlantic ocean, Nature 303, 142–146, 1983.
26 C.J. Allègre, B. Dupré, B. Lambret and P. Richard, The subcontinental versus suboceanic debate, I. Pb-Nd-Sr isotopes in primary alkali basalts from a shield area: the Ahaggar volcanic suite, Earth Planet. Sci. Lett. 52, 85–92, 1981.
27 A.G. Smith, A.M. Hurley and J.C. Bridan, Phanerozoic Palaeocontinental World Maps, 102 pp., Cambridge University Press, Cambridge, 1981.
28 E. Irving, Drift of the major continental blocks since the Devonian, Nature 270, 304–309, 1977.
29 P. Morel and E. Irving, Tentative paleocontinental maps for the early Phanerozoic and Proterozoic, J. Geol. 86, 535–561, 1978.
30 M. Westphal, Configuration of the magnetic field and reconstruction of Pangaea in the Permian period, Nature 267, 136–137, 1977.
31 J.D. Kramers, C.B. Smith, N.P. Lock, R.S. Harmon and F.R. Boyd, Can kimberlites be generated from an ordinary mantle? Nature 291, 53–56, 1981.
32 D. Weis and D. Demaiffe, A depleted mantle source for kimberlites from Zaïre: Nd, Sr and Pb isotopic evidence, Earth Planet. Sci. Lett. 73, 269–277, 1985.
33 J.G. Fitton and H.M. Dunlop, The Cameroon line, West Africa, and its bearing on the origin of oceanic and continental alkali basalts, Earth Planet. Sci. Lett. 72, 23–38, 1985.
34 R. Black, J. Lameyre and B. Bonin, The structural setting of alkaline complexes, J. Afr. Earth Sci., 3, 5–16, 1985.
35 L.R. Sykes, Intraplate seismicity reactivation of pre-existing zones of weakness, alkaline magmatism and other tectonism post-dating continental fragmentation, Rev. Geophys. Space Phys. 16, 621–688, 1978.
36 J.P. Liégeois, J.M. Bertrand and R. Black, The Pan-African calc-alkaline composite batholith of the Adrar des Iforas (Mali): a review, in: African Geology Review, J. Kinnaird and P. Bowden, eds., J. Wiley, in press.
37 A.W. Hofmann and W.M. White, The role of subducted oceanic crust in mantle evolution, Carn. Inst. Washington Yearb. 79, 477–483, 1980.
38 W.M. White and A.W. Hofmann, Sr and Nd isotope geochemistry of oceanic basalts and mantle evolution, Nature 296, 821–825, 1982.
39 A.E. Ringwood, Mantle dynamics and basalt petrogenesis, Tectonophysics 112, 17–34, 1985.
40 C.J. Allègre and D.L. Turcotte, Geodynamic mixing in the mesosphere boundary layer and the origin of oceanic islands, Geophys. Res. Lett. 12, 207–210, 1985.
41 A. Giret, Le plutonisme océanique intraplaque. Exemple des îles Kerguelen, C.N.F.R.A. 54, 300 pp., 1983.
42 O. Van Breemen, J. Hutchinson and P. Bowden, Age and origin of the Nigerian Mesozoic granites: a Rb-Sr isotopic study, Contrib. Mineral. Petrol. 50, 157–172, 1975.
43 A. Holmes and L. Cahen, Géochronologie africaine 1956. Résultats acquis au ler juillet 1956, Mem. Acad. R. Sci. Colon., 1, 169 pp., 1957.
44 J. Lameyre and M. Lasserre, Etude géochronologique des syénites alcalines et néphéliniques du massif annulaire de Hassi el Fogra (Mauritanie du Nord), C.R. Acad. Sci. Paris 265, 733–736, 1967.
45 J. Lameyre, A. Marot, S. Zimini, J.M. Cantagrel, L. Dosso and P. Vidal, Chronological evolution of the Kerguelen Islands syenite-granite ring-complex, Nature 263, 306–307, 1976.