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Late Pan-African tectonics marking the transition from subduction-related calc-alkaline magmatism to within-plate alkaline granitoids (Adrar des Iforas, Mali)

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Abstract

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The Pan-African Trans-Saharan belt, resulting from oceanic closure and oblique collision between the West-African Craton and the Tuareg–Nigerian shields around 600 Ma ago, displays in the Iforas a rapid switch from subduction and collision related calc-alkaline magmatism to typical A-type granitoids (560–540 Ma). The transition is clearly seen in associated spectacular acid dyke swarms, early calc-alkaline E–W trending sets being cut by alkaline N–S trending arrays. Isotopic evidence shows that the change in chemistry involves a different more primitive mantle source. Structural observations indicate that the transition from calc-alkaline to alkaline magmatism is related to reversals in the stress field during and after collision. In the model proposed, the first major reversal from D_2 with σ_1 ca. 135°N–110°N to D_3 with σ_1 ca. 50°N–60°N is thought to have been responsible for the slicing of the subducted plate thereby allowing the rise to shallow depth beneath the continental lithosphere, of asthenospheric mantle believed to be the source of the alkaline magmatism. The tapping of this new source occurred between D_3 and D_4 events contemporaneous with a rotation of the maximum compressive stress back from 60°N to 105°N.

Introduction

The Adrar des Iforas (Mali, Fig. 1) belongs to the Pan-African Trans-Saharan belt (Cahen et al., 1984). It is interpreted in terms of a Wilson cycle and a collision between the stable 2 Ga old West African Craton and the Tuareg shield (Black et al., 1979; Caby et al., 1981). The subduction and the collision were accompanied by calc-alkaline magmatism which shows a large range of chemical variation and is comparable to calc-alkaline suites of modern continental margins (Bertrand et al., 1984a; Liégeois and Black, 1984). A very large composite calc-alkaline batholith was emplaced during the collision on the western border of the reactivated continent and is bracketed between 615 and 570 Ma (Bertrand and Davison, 1981; Liégeois and Black, 1984).

Subsequently, alkaline dykes, lavas (Nigritien: Karpoff, 1958) and ring complexes intruded the central part of the Adrar des Iforas (Ba, 1982; Ba et al., 1985). Liégeois and Black (1984, 1986) have

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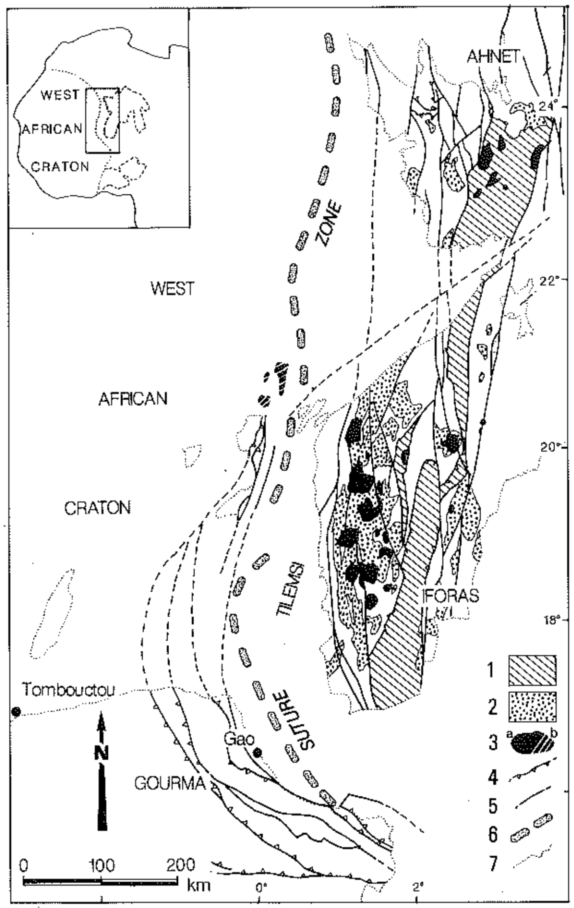

Fig. 1. Structural map of The Adrar des Iforas–Ahnet area after Fabre et al. (1982). *1* = Eburnean allochthonous or autochthonous basement, *2* = composite calc-alkaline batholith and late-tectonic granitoids, *3*a = oversaturated alkaline ring-complexes and lavas, *3*b = undersaturated alkaline ring-complexes and carbonatites, *4* = thrusts, *5* = faults, *6* = suture zone as suggested by high positive gravimetric anomalies (Bayer and Lesquer, 1978), *7* = Phanerozoic sedimentary cover. Only the alkaline rocks which are situated to the east of the suture zone are late Pan-African in age (Liégeois and Black, 1984). The undersaturated alkaline rocks situated to the west of the suture are Permian in age (Liégeois et al., 1983; Sauvage and Savard, 1985).

shown that the switch from calc-alkaline to alkaline magmatism involved a change in mantle source and occurred in a short interval of time (less than 10 Ma) around 560 Ma ago. Although alkaline magmatism is typically anorogenic and similar to the Palaeozoic and Mesozoic alkaline Younger Granite provinces of Niger and Nigeria, it is clear that the post-tectonic alkaline magmatism in the Adrar des Iforas has some genetic link with the collisional event. Such an evolution in magmatic sequences is in fact not uncommon and recently has been described in many collisional terrains, e.g., in the Pan-African of Saudi-Arabia (Duyvermann et al., 1982; Harris, 1982), during the Permian in Corsica (Bonin, 1980), and in the Tertiary–Quaternary volcanism of the Turkish–Soviet Armenia–West Iranian Alpine segment (Innocenti et al., 1982).

Our aim in this paper, which is centred on the Adrar des Iforas where the geodynamic setting at the close of the Pan-African is now thought to be well established, is to trace chronologically the tectonic and magmatic events accompanying the change from an active continental margin to a within-plate environment marked by the appearance of alkaline magmatism (A-type granitoids).

Geological setting

The Pan-African mobile belt of the Adrar des Iforas can be subdivided into three domains which are from west to east (Fig. 1):

(1) the accretion domain of Tilemsi valley including the suture zone and the island arc (Caby, 1978);

(2) the central Iforas domain which is characterized by a multi-stage tectonic and magmatic Pan-African evolution involving the 2 Ga old Eburnean basement;

(3) the eastern domain where structural and geochronological data are scarce; it is separated from the central domain by the Adrar Fault (Fig. 2) which has suffered a complex Pan-African history (Boullier et al., 1978; Caby et al., 1985) and has been intermittently active throughout the Phanerozoic.

Here attention will be focused on the central Iforas domain where the studied magmatic transition is confined.

Tectonic evolution of the central Iforas domain

A succession of four main tectonic events has been recognized by Boullier et al. (1978), Wright (1979), Boullier (1979, 1982) and Davison (1980):

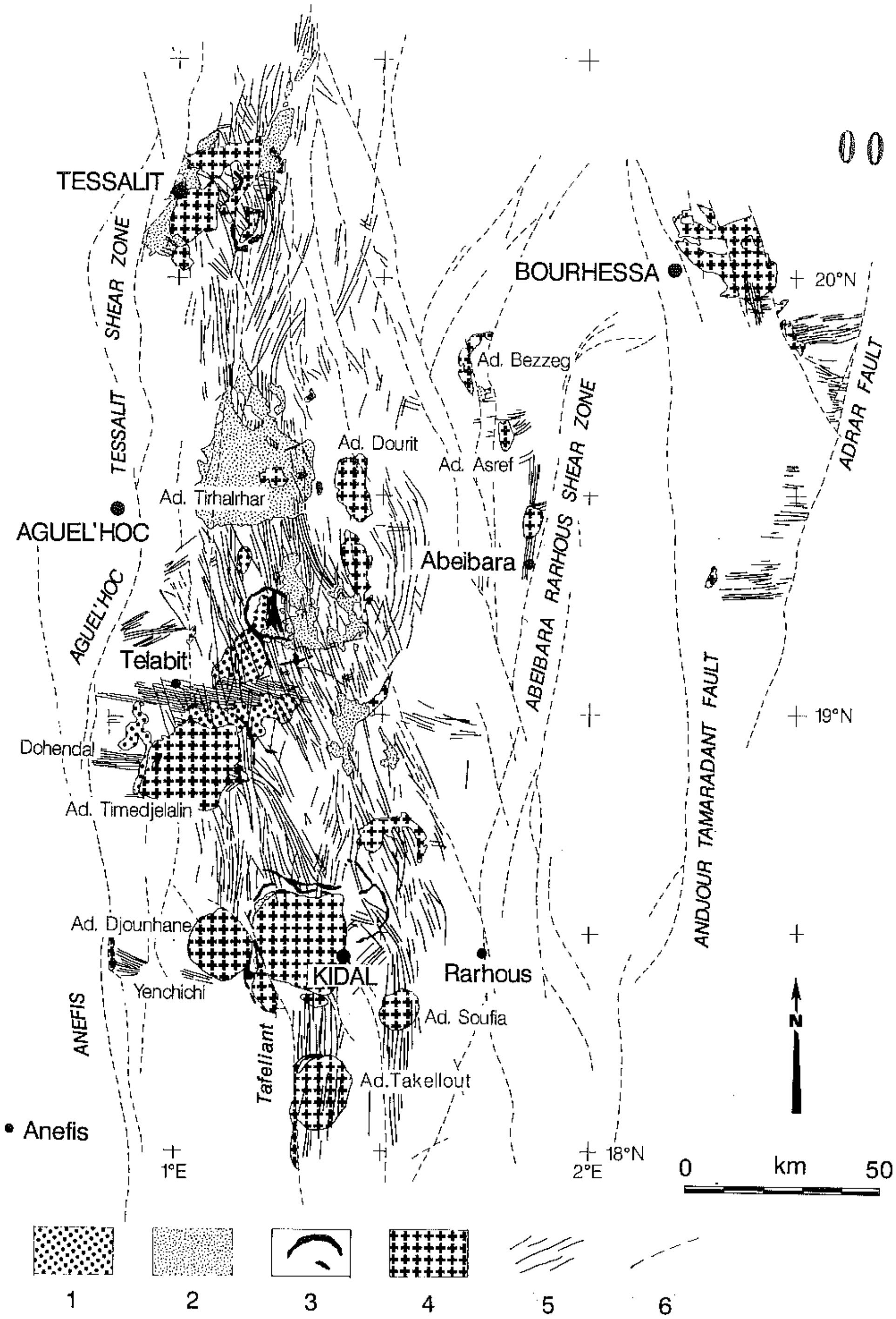

Fig. 2. Geological map of the alkaline province of the Adrar des Iforas after Fabre et al. (1982). *1* = alkaline granite of Tarhmert, *2* = rhyolites, *3* = ring dykes, *4* = = alkaline ring complexes, *5* = dykes, *6* = faults.

(1) The first D_1 event corresponds to a roughly S–N nappe emplacement involving the 2 Ga old Eburnean basement (nappe of the Iforas granulitic unit). It is not well dated but seems to have no clear relationships with the E–W 600 Ma old collision.

(2) The second D_2 event is 135°N varying in time to a 90°N compressional event which is

clearly related to the collision and took place around 600 Ma (Bertrand and Davison, 1981; Bertrand et al., 1984b). The constrictive deformation accompanied by a sinistral N–S strike-slip movement in the Tafeliant Group, a volcanosedimentary sequence outcropping as a N–S strip between Djounhane and Takellout ring-complexes (Fig. 2), might correspond to the first stage of this D_2 event with a SE–NW shortening (Ball and Caby, 1984), and is dated between 615 Ma (U/Pb on zircons: Ducrot et al., 1979) and 595 Ma (Rb/Sr whole-rock isochrons: Liégeois and Black, 1984) results obtained from the late-tectonic Adma granodioritic pluton.

(3) The third D_3 event is characterized by N–S to 20°N dextral strike-slip shear-zones and faults (Boullier, 1986) one of which has been dated between 566 and 535 Ma (Lancelot et al., 1983). A roughly 50°N to 60°N shortening direction can be attributed to this deformation. It seems likely that this new stress field produced dextral movement along preexisting vertical planes of weakness orientated N–S such as the Tessalit–Aguel'hoc–Anefis shear-zone which acted sinistrally during the D_2 event, but this remains to be confirmed by field observations. A study of the microstructures associated with the Abeibara–Rarhous D_3 shear-zone indicates that the shortening direction rotated again towards an E–W direction at the end of the D_3 deformation event (Boullier, 1986).

(4) A last brittle tectonic event D_4 was described by Ball (1980); it corresponds to a system of conjugate faults (sinistral 150°N, dextral 60°N) that Ball (1980) attributed to the last stage of the collision between the West African Craton and the Pan-African mobile belt. It has been dated in the Yenchichi area around 545 Ma (Liégeois and Black, 1984).

To summarize, an observational and structural analysis of the deformation features in the central Iforas domain shows that the shortening direction rotated from a S–N direction (D_1) to a 135°N–90°N direction (D_2), then to a 50–60°N to 90°N direction (D_3) and finally to a 105°N direction (D_4). Consequently, the Pan-African Trans-Saharan belt cannot be explained by a simple frontal collision but must involve a direction of movement oblique to the margin of the West African Craton (Wright, 1979; Davison, 1980; Boullier, 1982; Ball and Caby, 1984). Although aware of the complexities inherent to plate tectonics (Dewey, 1982), tentatively, we suggest that the sudden reversal in the stress field marked by the D_3 event may be attributable to the shape of the West-African craton, the Ghana–Benin promontory acting as a rigid block during the closing stages of crustal shortening in the Iforas embayment (Black et al., 1980).

Magmatic evolution of the central Iforas domain

The geochemistry (major and trace elements) of the Pan-African magmatism was studied by Bertrand et al. (1984a, 1984b) and Leterrier and Bertrand (1985) for the eastern part of the central Iforas domain and by Liégeois and Black (1984, 1986) for the western part (batholith). Four trends were distinguished: the pre-tectonic D_1 basic and ultrabasic rocks show tholeiitic affinities, the pre-tectonic D_2 granitoids display a low-K calc-alkaline trend, the late- to post-tectonic D_2 granitoids are on a high-K calc-alkaline trend and the late post-tectonic granites are alkaline (Liégeois and Black, 1986).

Bertrand and Davison (1981) distinguished two stages with respect to the major tectonic imprint of the D_2 event. Some late calc-alkaline granitoids of the eastern part of the batholith are also post-tectonic D_3 since they cross-cut the D_3 Abeibara–Rahrous shear-zone (Tin Ouli granite, Fig. 6). The last manifestation of the calc-alkaline magmatism is represented by the E–W dyke-swarms (Fig. 2), some of which still show some transitional characteristics towards an alkaline affinity, and by some high-level plutons (Liégeois and Black, 1984, 1986).

The oldest alkaline body recorded in the central Iforas domain is the Tarhmert granite (Figs. 2 and 8) which precedes immediately the unroofing of the batholith (Liégeois and Black, 1984). It is cross-cut by the N–S dyke swarms and by the alkaline and peralkaline ring-complexes.

Magma sources

The nature of the magma sources has been discussed in some detail by Liégeois and Black

(1984, 1986). To summarize, all the calc-alkaline granitoids have $^{87}Sr/^{86}Sr$ initial ratios between 0.7035 and 0.7050 and alkaline granites between 0.7050 and 0.7060. These values preclude a significant upper crustal participation. The three other classical reservoirs (lower crust, depleted upper mantle, and more primitive mantle) can be identified in the Adrar des Iforas. The Iforas granulitic unit made of Archean material can be taken as representative of the lower crust. Its mean $^{87}Sr/^{86}Sr$ ratio at 600 Ma is ca. 0.7095.

This implies that the lower crust can be taken as a contaminant but not as the source of Iforas granitoids. Depleted mantle (plus oceanic-crust participation) and primitive mantle isotopic compositions can be inferred respectively from the Iforas island-arc close to the suture with the West African Craton (0.7025–0.7030), and from the Permian Tadhak undersaturated complex (100 km to the west of the Adrar des Iforas on the West African Craton), for which a pure OIB-type mantle origin has been shown ($^{87}Sr/^{86}Sr$ calculated for 600 Ma: 0.7043, Liégeois et al., 1983; Weis et al., 1986). These results are summarized on the $^{87}Sr/^{86}Sr$ evolution diagram (Fig. 4).

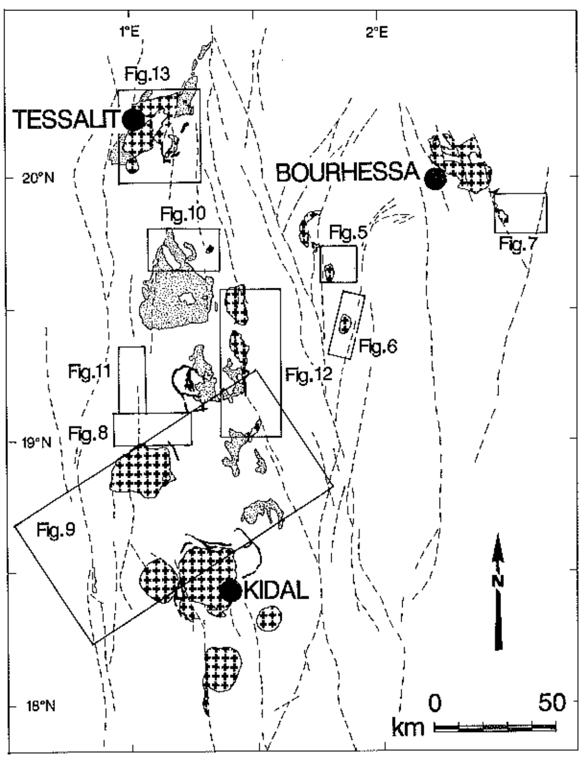

Fig. 3. Localization map of the illustrations. Same symbols as in Fig. 2.

The cordilleran calc-alkaline granitoids are interpreted as derived from depleted upper mantle modified by subducted oceanic crust fluids (typical island-arc source) and slightly contaminated by the lower continental crust. The same source, but from a greater depth, is inferred for the late- and post-tectonic high-K calc-alkaline granitoids which is consistent with the fact that the collision was an oblique "docking" convergence rather than a Himalayan-type confrontation as is likely in the southern part of the belt in Benin. A more primitive source (Tadhak source) is proposed for the post-tectonic alkaline magmas to take into account their more radiogenic initial Sr and Pb ratios.

The E–W dyke swarms

The E–W dyke swarms are mostly emplaced on one side of some large, N–S, previously active, shear-zones or faults, which represent some very large vertical discontinuities in the continental crust: the Anefis–Aguel'hoc–Tessalit shear-zone, the Abeibara–Rahrous shear-zone or the Adrar Fault (see Fig. 2). They are vertical and generally perpendicular to the regional N–S foliation. Their regularity and parallelism (inside one swarm) are only perturbed in the vicinity of some contemporaneous plutons where the stress field related to the granite was superimposed on the regional field and deviated the stress trajectories as demonstrated theoretically by Odé (1957)—the dyke swarm related to the Adrar Adrar late calc-alkaline granite (Fig. 5) is such an example. The dyke swarm is cross-cut by the later alkaline Adrar Asref pluton. On the Fig. 5 as on the following figures, each dyke visible on a serial photographs is shown on the sketch.

The E–W dyke swarms are clearly later than D_3: this fact is demonstrated some 15 km north of Abeibara village where an E–W dyke swarm (maybe related to the post-D_3 calc-alkaline Tin Ouli granite) cross-cut the S_3 schistosity (Fig. 6); the E–W dykes are curved; this fact indicates either that some sinistral shear has occurred after the main dextral D_3 event along the 20°N S_3

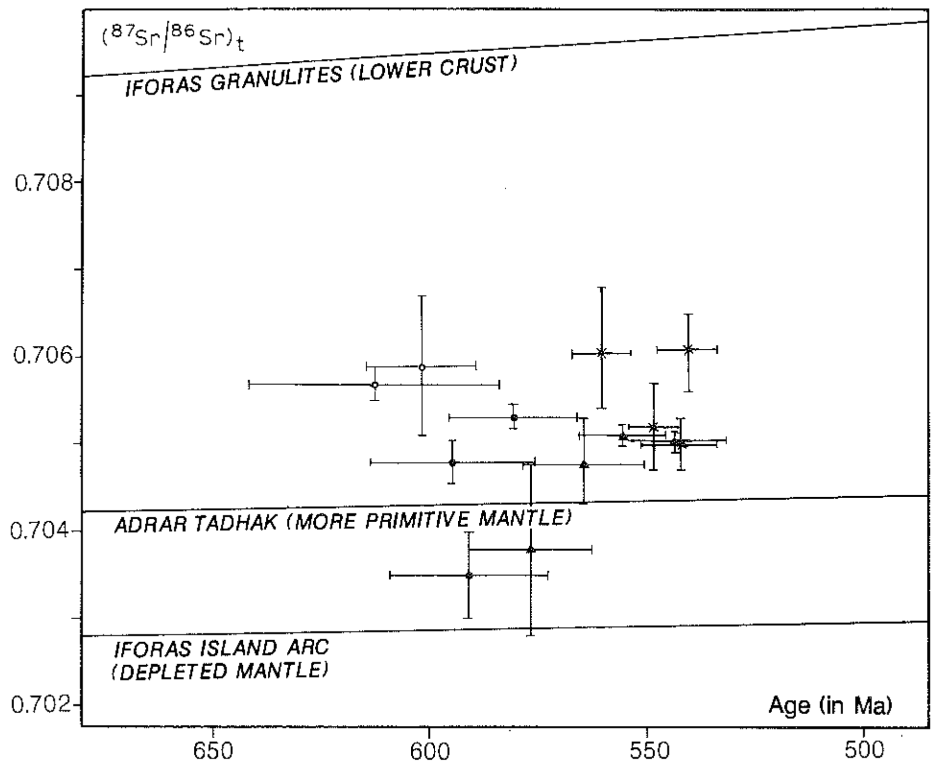

Fig. 4. Initial $^{87}Sr/^{86}Sr$ ratios of the different plutons versus time. Empty circles: pre-D_2 plutons (rehomogeneization values); filled circles: late-tectonic plutons; triangles: post-tectonic E–W calc-alkaline dykes and plutons; crosses: post-tectonic N–S alkaline dykes and plutons. The upper mantle, the more primitive and the lower crust evolution curves are respectively based on the Iforas palaeo-island arc, on the Permian Tadhak alkaline pluton and on the IGU (Iforas granulitic unit).

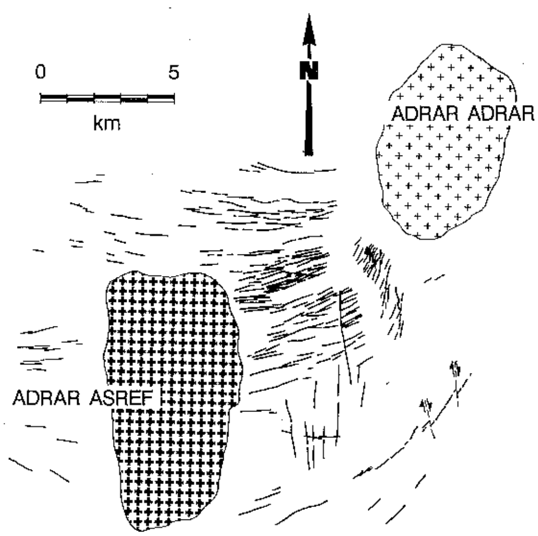

Fig. 5. Relationships between the post-tectonic D_3 calc-alkaline granite of Adrar Adrar (light crosses), the dyke swarm and the alkaline pluton of Adrar Asref (heavy crosses).

schistosity, or that the regional stress field has been perturbed around the Tin Ouli pluton. Note that the E–W dykes are cut by a N–S dyke swarm and by an alkaline plutonic body, and that 35°N dextral faults displace the N–S dykes.

In the Tahaldjé E–W dyke swarm (Fig. 7), it is obvious that at least some dextral movement occurred along the N–S vertical foliation *during* the emplacement of the dykes, as some of them are displaced whereas others are not. All the dykes are subsequently sinistrally displaced. It seems that the regional foliation might act like transform fault during the emplacement of the dykes. This phenomenon has been observed in the Telabit E–W swarm where a N–S dyke segment is filled with a magmatic breccia and links two E–W segments of the same dyke.

In the spectacularly dense Telabit swarm (Fig. 8) the extension related to the dyke emplacement has been estimated at 80% on aerial photographs

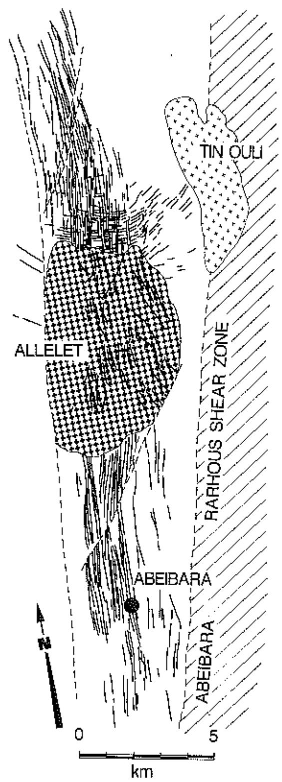

Fig. 6. Relationships between the post-tectonic D_3 calc-alkaline granite of Tin Ouli (light crosses), the E–W and N–S dyke swarms, and the Allelet alkaline pluton (heavy crosses), along the D_3 Abeibara–Rarhous shear zone.

(Ball, 1977), but this figure is unrealistic. Indeed, measurements in the field indicate a dilation of 10% which is still higher than the mean values

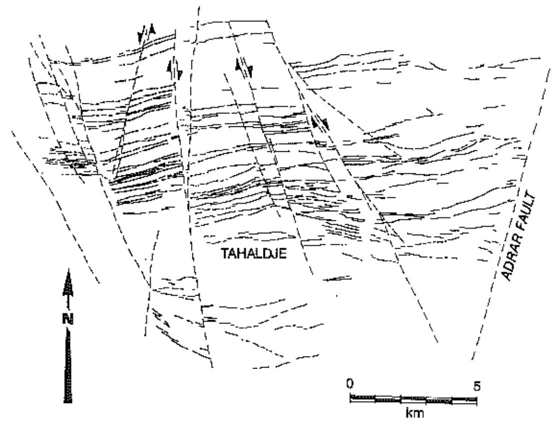

Fig. 7. The E–W Tahaldje dyke swarm. Note that some dextral strike-slip faults displace almost all the dykes except the northern ones, suggesting contemporaneity of the emplacement of the dykes and movement along the faults.

obtained by Walker (1974), Gudmundsson (1983) and Helgason and Zentilli (1985) in the rift zone in Iceland. The E–W dykes are displaced by sinistral 160°N faults (D_4 event). The micro-adamellites and micro-diorites of the Telabit swarm have clear calc-alkaline affinities, but, in contrast, the microgranites and felsites of the younger Dohendal swarm (Fig. 2) announce an alkaline affinity (Liégeois and Black, 1984). Thus a transition occurred during the emplacement of the E–W dykes.

By comparison with Engelder's study (1982) on regional joints, the E–W dykes are interpreted as

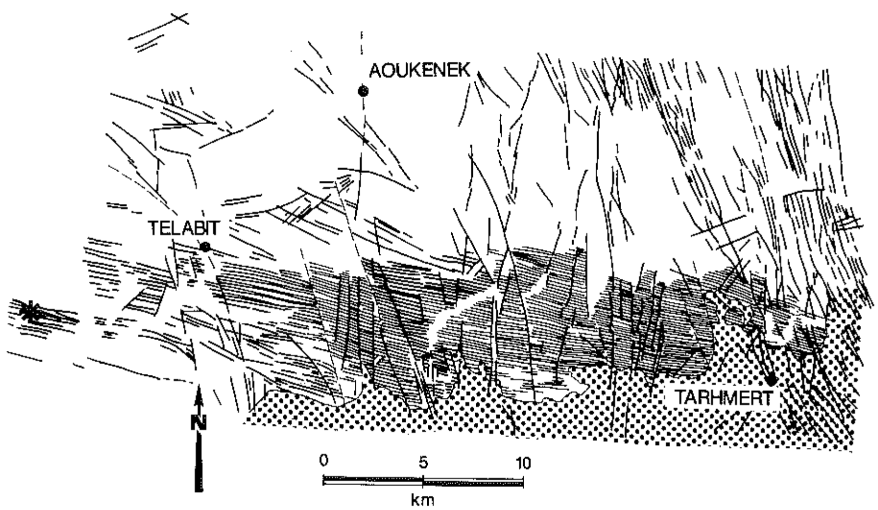

Fig. 8. Map of the Telabit area showing the E–W calc-alkaline dyke swarm which predates the Tarhmert alkaline granite (dots) which is itself cross-cut by the 150°N alkaline dykes. Star localizes the magmatic breccia cited in the text.

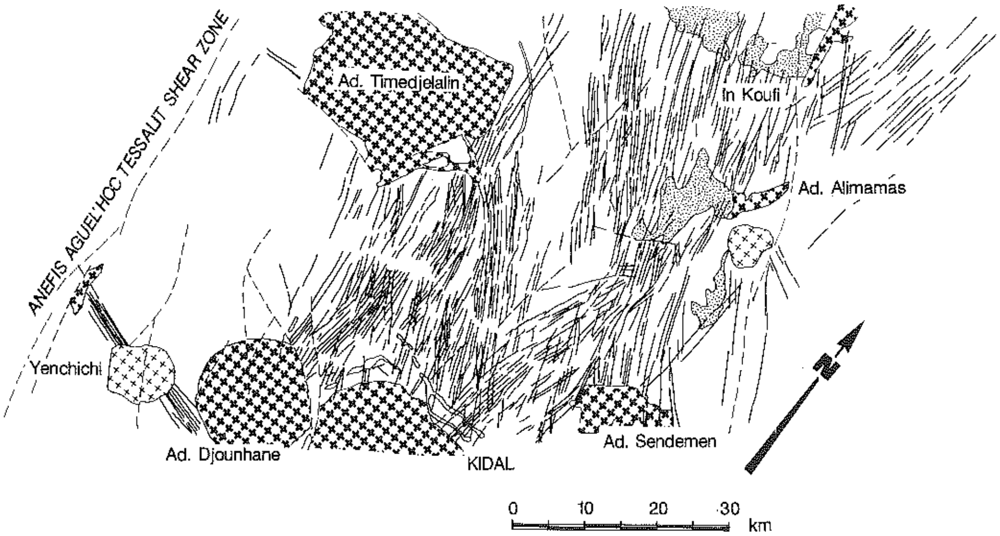

Fig. 9. Map of the Kidal area, drawn after the Schuttle Imaging Radar-A (N.A.S.A.). Note the two directions of the submeridian dyke swarms which are deflected towards the Timedjelalin alkaline ring-complex (heavy crosses). The ring dykes of the Kidal pluton are cut by the N–S and 150°N dykes. The Yenchichi calk-alkaline (light crosses) granite is affected by 150°N sinistral strike-slip fault (D_4) which has been dated around 545 Ma (Liégeois and Black, 1984). This pluton postdates the 100°N Yenchichi dyke swarm. The rhyolitic alkaline lavas are represented by dots.

mode-I cracks propagated in a state of stress where the least principal stress (σ_3) is horizontal N–S and the (σ_1, σ_2) plane is vertical E–W. Following Engelder (1982), the loading path leading to mode-I propagation of cracks may include the removal of overburden, cooling and an increase of

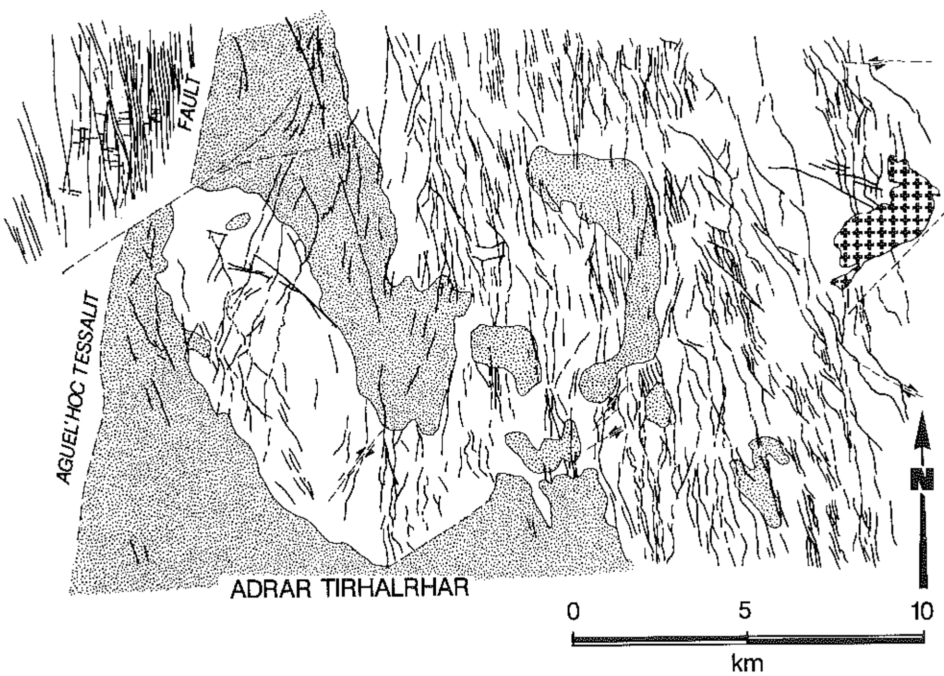

Fig. 10. Map of the northern part of the Tirhalrhar rhyolitic plateau showing that only a few dykes cross-cut the lavas (dots) and could be considered as the feeder dykes. Most of them are overlain by the lava flows. A small alkaline pluton (heavy crosses) cross-cuts all the dykes.

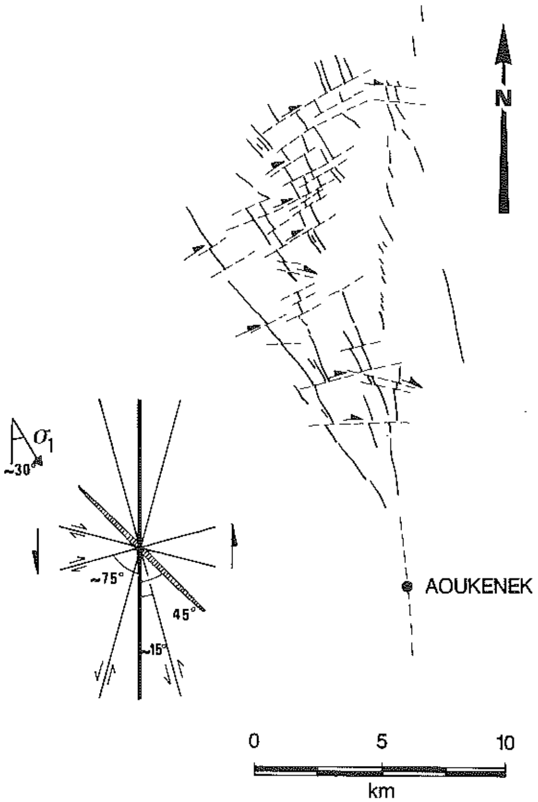

Fig. 11. Schematic map of the area north of Aoukenek. A fault (discontinuous line) is prolonged by "en échelon" 155°N dykes. The 75°N and 100°N faults are interpreted as second-order faults related to a N–S sinistral shearing, and contemporaneous with the emplacement of the dykes.

radius of curvature of a basin. The Adrar des Iforas corresponds at least to the first and second conditions as unroofing began during or just after the E–W dykes, leading to cooling of the crust.

The N–S dyke swarms

In contrast to the more localized E–W dyke sets, the N–S swarms are intruded along the entire length of the batholith in a belt measuring 250 × 50 km and form one of the most spectacular arrays of acid alkaline dykes known in the world. They cross-cut the E–W dyke swarms and the Tahrmert granite (Figs. 8 and 9), but in the majority of cases are truncated by the alkaline ring-complexes and plutons. The injection of the N–S dykes continued intermittently between the emplacement of early plutonic phases in individual complexes (Takellout, Kidal, Tessalit). Only the late Adrar Timedjelalin and Adrar Djounhane complexes are uncut by the N–S dykes.

The N–S dykes are composed of several generations of rhyolites, quartz–feldspar porphyries, granophyres and quartz microsyenites and as in the case of the alkaline plutonic complexes, both metaluminous and peralkaline varieties are present. Some rhyolites and quartz-porphyries are probably the feeder dykes of the rhyolitic flows and ignimbrites (Tirhalrhar) which overlie the unroofed batholith. Both along the northern (Fig. 10) and southern margins of the Tirhalrhar plateau one can observe dykes which either cross-cut or are overlain by lava flows.

Locally, some N–S sinistral strike-slip movements seem to guide the intrusion of the 155°N dykes (for example in the western part of the batholith, Fig. 11): a N–S fault is extended by 155°N dykes (tension gashes) and to the west, long 155°N dykes are cut by 75°N and 100°N dextral faults; the dykes are contemporaneous with these faults, as some are displaced and others not. For this reason and because of the geometry of the dykes and faults, the latter can be interpreted as second-order faults related to the major N–S sinistral fault. In this case, the structure indicates that σ_1 is horizontal 150°N and σ_3 horizontal 60°N. This stress tensor could also be responsible for some N–S sinistral movement displacing the E–W dykes of Abeibara and Taraldjé (Figs. 6 and 7).

The orientation of the dykes is much more irregular than in the earlier E–W family. They are rarely strictly N–S and oscillate between 150°N and 30°N. Two types of deviation are displayed: the first consists of arcuate swarms with a large radius of curvature (50 km or more) and the second is represented by curved tails with small radii of curvature (around 15 km) which are clearly associated with the ring complexes (Timedjelalin, Tessalit, Kidal). Figure 12 represents an example of the first type. It should be noted that the arcuate swarm cross-cuts an earlier family of 155°N dykes (south of the Tirhalrhar plateau) and are intruded in 10°N fractures that previously acted as sinistral strike-slip faults (as shown in the detailed map). The N–S to 15°N dykes constitute

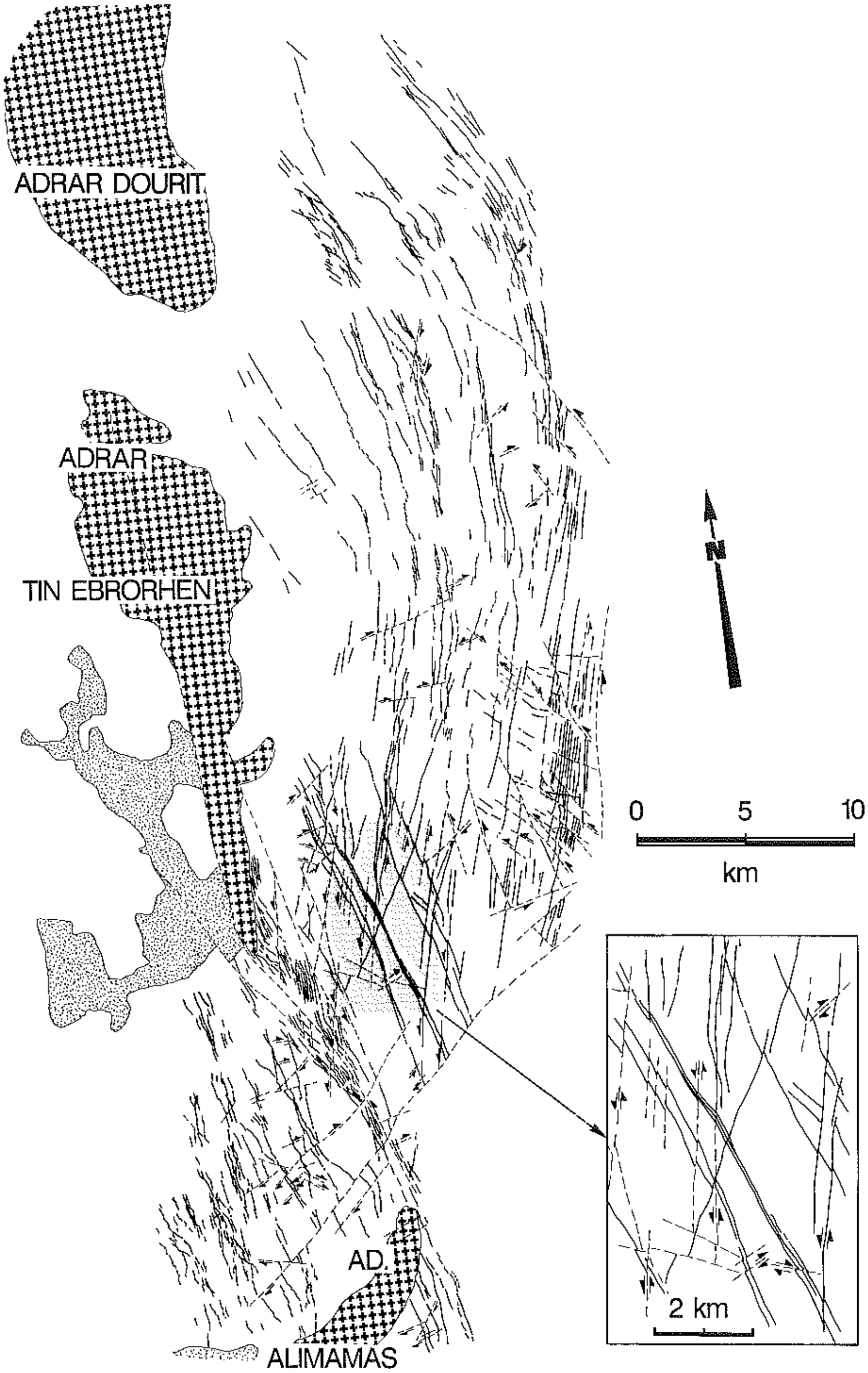

Fig. 12. Map of the curved dyke swarm of the Tin Ebrorhen area in the central part of the alkaline province (see Fig. 3 for localization). As shown in the detailed map, the 155°N dykes are cross-cut by sinistral strike-slip faults. Then, N–S to 15°N dykes postdate the first generation of dykes and are sometimes intruded in the previously active N–S faults. Note the arcuate shape of the swarm and the discontinuous character of the dykes in the swarm. The curvature of the swarm is accentuated near the Adrar Dourit alkaline pluton (heavy crosses). Fine dots: rhyolitic lavas.

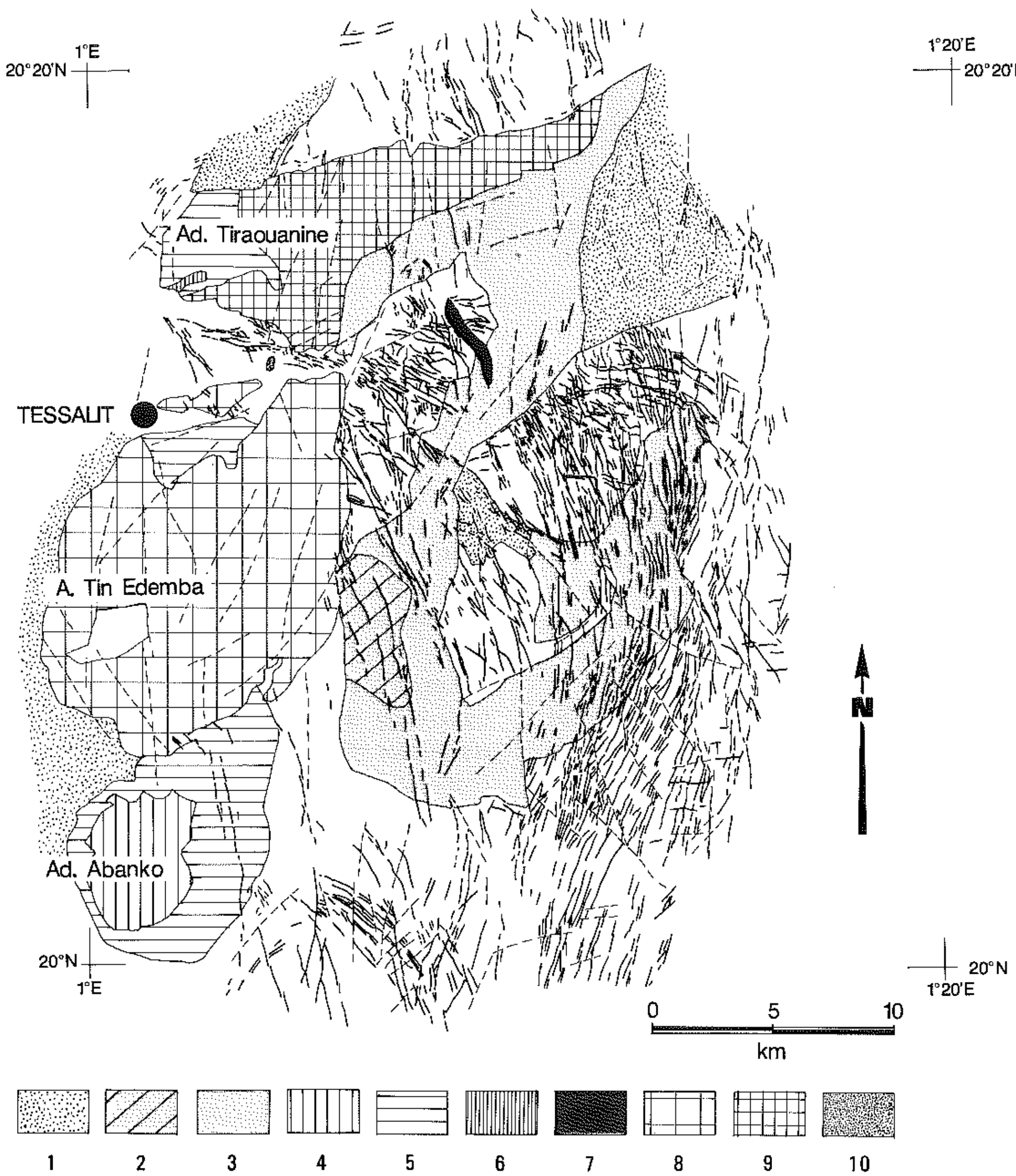

Fig. 13. Geological map of the Tessalit alkaline ring complex (geological contours by R. Black, R. Savard, J.F. Sauvage and D. Diombana, dykes and fractures from photo-interpretation by M. Sauvage). *1* = rhyolites, *2* = microgranitic enclaves, *3* = Perthitic amphibole–biotite–granite, *4* = two feldspar–biotite–amphibole–granite, *5* = two feldspar–biotite–granite, *6* = fine-grained biotite–granite, *7* = quartz–microsyenite, *8* = coarse-grained hyperalkaline granite, *9* = medium-grained hyperalkaline granite, *10* = fine-grained hyperalkaline granite. Note that the dykes postdate some parts of the ring-complex but are cut by other parts. Two families of dykes could be distinguished, one with a large radius of curvature (around 50 km) and the other with a small radius of curvature (around 15 km) which turned towards the peralkaline pluton. This complex is highly fractured and only some of the fractures are represented here.

an apparently continuous dyke swarm which swings towards a 150°N direction, some dykes turning suddenly towards the Adrar Dourit alkaline granite pluton (second type of deviation). One should remark that conjugate 60°N and 150°N faults (D_4 event) displace the dykes.

The Tessalit massif (Fig. 13) is a good example of the strong relationships existing between the alkaline ring complexes and the N–S dyke swarms. Actually, it can be seen that the perthite–granite is cross-cut by numerous N–S dykes which are in turn truncated by the peralkaline granites (Fig. 13). The presence of three curved tails of dykes seems to indicate the existence of three magmatic centres. This complex is highly fractured and many contacts are faulted; for clarity, only a few fractures have been drawn on the map. However, detailed observation of the aerial photographs shows that the conjugate fault system (40–50°N and 130°N) post-dates all the dykes and granites.

To summarize, the N–S dyke swarms preceded and were partly contemporaneous with the emplacement of the alkaline ring-complexes. It is reasonable therefore to believe that magma chambers at varying depths could have perturbed the regional stress trajectories and thus the strike of the dykes (see Roberts, 1970). The slightly arcuate swarms seem to coincide with the large gravimetric anomalies described by Ly (1979) and Ly et al. (1984) and which were attributed to the presence at depth (over 12 km) of dense intrusive basic bodies related to the alkaline magmatism. The second type of deviation (curved tails) is probably due to the ring-complexes themselves or to underlying intermediate magma chambers (Ly et al., 1984).

The general geometry of the dykes indicates that they are cut by the D_4 event as shown by Ball (1980) and that a mean N–S direction may be attributed to the maximum compressive stress (σ_1) during the emplacement of the arcuate N–S arrays of dykes. However, a detailed study in future should bring more information: for example, the chronology of the different arcuate N–S dyke swarms, the length, the width and the direction of filling of the dykes could indicate the succession in time and space of the different ring complexes and the depth of the magma chambers.

Conclusions

The Pan-African Trans-Saharan belt in the Iforas shows a rapid transition from subduction and collision-related calc-alkaline magmatism to typical A-type granitoids (Ba et al., 1985). The low-K calc-alkaline pre-tectonic tonalites related to the cordillera were followed by high-K calc-alkaline late- to post-tectonic granitoids which marked the last collisional event and lasted for some tens of million years (615–570 Ma) after oceanic closure. Geochemical and isotopic studies have shown that the sudden appearance of alkaline magmatism around 560 Ma involves the tapping of a different more primitive mantle source and must therefore be related to a significant structural event (Liégeois and Black, 1984, 1986). Structural studies show that the initiation of alkaline magmatism postdates the last ductile Pan-African D_3 deformation and predates or is just slightly younger than the D_4 conjugate wrench-fault system dated around 545 Ma (Liégeois and Black, 1984). During the emplacement of the dyke swarms the tensile stress must have been horizontal with the (σ_1, σ_2) plane vertical. As some of the swarms are centred on plutonic complexes, temporary inversions between σ_1 and σ_2 probably occurred, determined by pressure conditions in underlying magma chambers. The alkaline ring-complexes were emplaced after unroofing of the batholith beneath a thick volcanic cover of fissural origin by a process of subterranean cauldron subsidence and major stoping (Ba et al., 1985). The injection of N–S dykes continued between early phases of plutonic emplacement.

Alkaline magmatism appeared during the transition between D_3 and D_4 which are very close in time. This transition reflects a complete reversal in the direction of the maximum compressive stress (60°N to 105°N). We suspect that such reversals can have profound disruptive effects without necessarily producing large strike-slip movements (harpoon effect: Black et al., 1985). In the Adrar des Iforas it enabled the tapping of a new mantle source. Alkaline magmatism was contemporaneous with rapid uplift and erosion of the belt which marked the end of the orogeny. Although at this time the crust may have been relatively thick, particularly when taking into account the importance of crustal accretion in this segment of the Pan-African belt, the thermal pattern must have been such that the lithosphere was thin. Liégeois and Black (1984, 1986) proposed a model in which the asthenospheric more-primitive mantle, originally underlying the subducted plate, rose to shallow depth beneath the continental lithosphere after the rupture of the cold plunging plate. With this model in mind the D_3 event which itself marked a complete reversal in the stress field with respect to D_2 may well have caused slicing of the subducted plate thus enabling the emplacement at a high level of asthenospheric mantle.

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