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The "Taourirt" magmatic province, a marker of the closing stage of the Pan-African orogeny in the Tuareg Shield: review of available data and Sr–Nd isotope evidence

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Abstract

The Tuareg Shield, located between the Archaean to Palaeoproterozoic Saharan metacraton and the West African craton, is composed of 23 recognized terranes that welded together during the Neoproterozoic Pan-African orogeny (750–520 Ma). Final convergence occurred mainly during the 620–580 Ma period with the emplacement of high-K calc-alkaline batholiths, but continued until 520 Ma with the emplacement of alkali-calcic and alkaline high-level complexes. The last plutons emplaced in central Hoggar at 539–523 Ma are known as the "Taourirt" province. This expression is redefined and three geographical groups are identified: the Silet-, Laouni- and Tamanrasset-Taourirts. The Silet-Taourirts are cross-cutting Pan-African island arc assemblages while the two others intrude the Archaean–Palaeoproterozoic LATEA metacraton. The Taourirts are high-level subcircular often nested alkali-calcic, sometimes alkaline, complexes. They are aligned along mega-shear zones often delimiting terranes. Mainly granitic, they comprise highly differentiated varieties such as alaskite (Silet-Taourirts) and topaz–albite leucogranite (Tamanrasset-Taourirts). Different subgroups were defined on the basis of REE patterns and major and other trace elements. The Taourirt province displays a wide transition from dominant alkali-calcic to minor alkaline granite varieties. Sr isotopes indicate that these complexes were affected by fluid circulation during the Ordovician along shear zones probably contemporaneous to the beginning of the Tassilis sandstone deposition. Nd isotope systematic indicates a major interaction with the upper crust during the emplacement of highly differentiated melts, particularly in samples showing seagull wing-shaped REE patterns. On the other hand, all Taourirt plutons are strongly contaminated by the lower crust: ε_{Nd} vary from −2 to −8 and T_{DM} from 1200 to 1700 Ma. This implies the presence of an old crust at depth, also below the Silet-Taourirts, which are emplaced within Pan-African island arc assemblages. A model is proposed for the genesis of the Taourirt province where reworking of the mega-shear zones, which dissected the LATEA metacraton, provoked a linear delamination of the lithospheric mantle, asthenosphere uprise and partial melting of the lower crust (or strong interaction with), giving rise to a mixed source.

Keywords: Granite; Taourirt; Pan-African; Hoggar; Tuareg Shield

1. Introduction

The end of a major orogenic episode is often marked by a sequence of post-collisional, or post-orogenic, magmatic events, displaying successively: (i) K-rich suites, that can comprise shoshonitic to ultrapotassic compositions; (ii) less potassic alkali-calcic (as defined by Peacock, 1931) or alkaline series, with metaluminous, slightly peraluminous and peralkaline end-members (for reviews, Liégeois, 1998). The sequence is observed in Proterozoic and in Phanerozoic orogenic belts during their subsequent consolidation. It seems to have been active at least since 2.6 Ga, i.e. as early as the Late Archæan (Bonin et al., 1998).

The Tuareg Shield (Fig. 1) resulted, during the Pan-African orogeny (850–520 Ma), from the welding of ophiolite-bearing juvenile terranes along or onto

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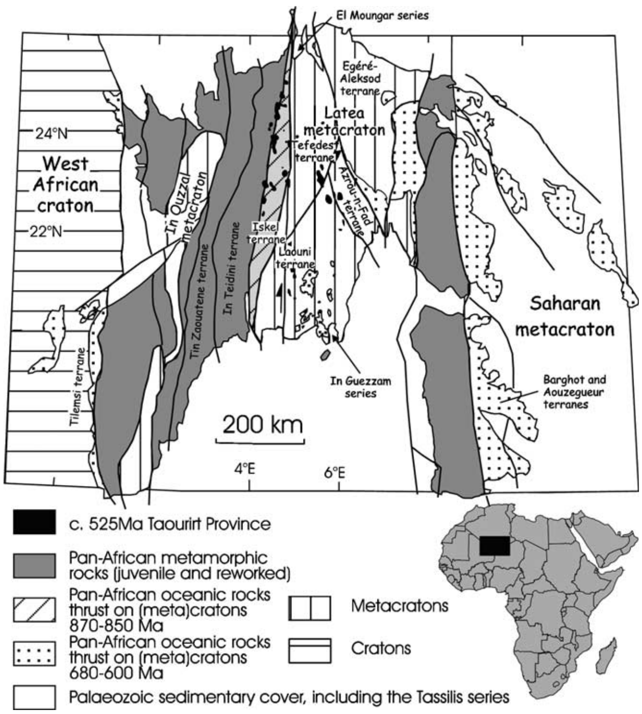

Fig. 1. Terrane map of the Tuareg Shield. From Black et al. (1994), Liégeois et al. (2003, this issue) for the LATEA metacraton and Boissonnas (1974) for the localization of the Taourirt plutons.

reworked older terranes, pinched in between two major Archaean–Palaeoproterozoic cratons, the West African craton and the Saharan metacraton (Boullier, 1991; Black et al., 1994), respectively to the west and to the east. At the very end of the Pan-African orogenic episode, after a major event of intrusion of high-K calc-alkaline batholiths, the Tuareg Shield was subjected to post-collisional/post-orogenic alkali-calcic and alkaline magmatic events during a 70 Ma-long protracted event when considering the whole shield (550 000 km^2). These events occurred from 592 Ma (Hadj-Kaddour et al., 1998) through 560–540 Ma (Liégeois and Black, 1987; Liégeois et al., 1996) to 523 Ma (Paquette et al., 1998). The latest magmatic event in the Tuareg Shield is located in Central Hoggar and is named the "Taourirt" Province (Boissonnas, 1974; Fig. 1). It took place during the 539–523 Ma age interval (Cheilletz et al., 1992; Paquette et al., 1998).

In general, the last post-collision magmatic event is represented by either alkali-calcic or alkaline rocks, which seem to be mutually exclusive, suggesting that they could be issued from different sources and/or originate through different evolutionary processes. The Taourirt Province in Central Hoggar is, to the current knowledge, the only area where both alkali-calcic and alkaline rock types were emplaced simultaneously within the same subvolcanic nested complexes. The aims of this paper are: (i) to review available geological, petrological, mineralogical and geochronological evidence; (ii) to discuss new Sr–Nd isotope data relevant to the alkali-calcic rocks and new Sr isotope data relevant to alkaline rocks allowing to constrain their origin and significance and; (iii) to provide clues for the understanding of the closing stage of the magmatic events in the Tuareg Pan-African belt. In addition, a goal of this article is to review the current knowledge of the Taourirt province to stimulate future research.

2. Geological, petrological and geochronological review of the Taourirt province

The Tuareg Shield is composed of 23 terranes (Black et al., 1994) that collided, welded and moved along subvertical shear zones to be finally squeezed between the West African craton to the west and the Saharan metacraton to the east (Fig. 1). The geological evolution varies from one terrane to another, including Archaean and Palaeoproterozoic blocks variably reworked during the Pan-African, e.g. In Ouzzal and LATEA metacratons. A metacraton is a craton partially remobilized during an orogeny, keeping large parts of its cratonic characters but not all (see Abdelsalam et al. (2002) and Liégeois et al. (2003), this issue for details). Other terranes are formed by Neoproterozoic oceanic or continental active margins welded with (e.g. In Teidini terrane) or thrust (e.g. Barghot and Aouzegueur terranes; Liégeois et al., 1994; Fig. 1) on cratons or metacratons. This amalgamation occurred mainly between 620 and 580 Ma (Caby et al., 1985; Bertrand et al., 1986; Liégeois et al., 1987, 1994). More limited episodes occurred earlier at 870–850 Ma (Caby et al., 1982) and at 730–680 Ma (Caby and Andreopoulos-Renaud, 1987; Caby et al., 1989; Liégeois et al., 1994, Liégeois et al., 2003, this issue). Events younger than 580 Ma are represented by high-level alkali-calcic to peralkaline plutons among which the Taourirt province in Central Hoggar (Figs. 1 and 2) is the most important and the youngest. After the emplacement of the Taourirt plutons, the whole province was eroded and covered by the Palaeozoic Tassilis sandstones.

2.1. What is a "Taourirt" pluton?

According to the original definition, all the roughly circular (Fig. 3A) igneous complexes intruding the Tuareg Shield formations and characterized by a sugar-loaf shape topographic feature (Fig. 3B) were named "Taourirt", the local Tuareg word "Taourirt" defining such an isolated mountain clearly visible in the distance. Later on, the term was used only for the younger nested complexes emplaced in Central Hoggar (Boissonnas, 1974). Indeed, they are the only plutons that cut the dyke swarms subsequent to the main Pan-African

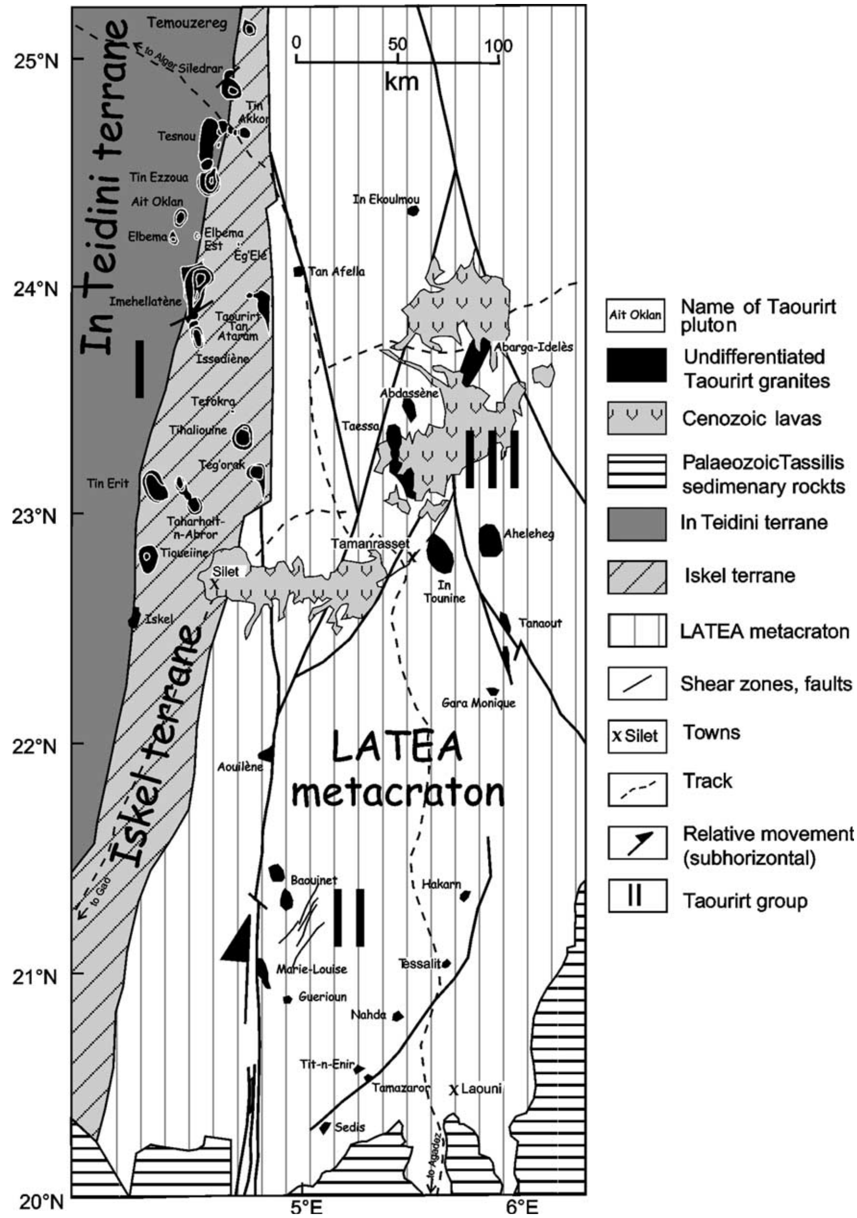

Fig. 2. Sketch map of the Central Hoggar, with localization of the Taourirt plutons (Boissonnas, 1974), with the three proposed groups: I: Silet-Taourirts; II: Laouni-Taourirts; III: Tamanrasset-Taourirts.

magmatic activity in Hoggar, indicating a distinct late event. This author distinguished the Taourirt plutons from: (i) the west, intruded into greenschist to amphibolite facies volcano-sedimentary sequences (the "Fossé pharusien" defined by Lelubre (1952) currently forming the Iskel and In Teidini terranes; Figs. 1 and 2); (ii) the east, emplaced into high-grade gneisses in Central Hoggar (currently the LATEA metacraton; Figs. 1 and 2). Although these two groups display differences (shape, mineralizations, magmatic processes), Boissonnas (1974) considered that the "Taourirt" name should be applied to both groups as they are subcontemporaneous, belonging to the same geodynamic "window", in addition to the fact that for Tuareg people the two areas comprise very well-known Taourirt mountains. Later, based on the differences noted above, Cheilletz et al. (1992) recommended to abandon the name "Taourirt" to avoid ambiguity, while Azzouni-Sekkal and Boissonnas (1993) proposed to limit its use to the late plutons from the west, intruded into the "Pharusian" (In Teidini and Iskel terranes).

In this paper, we propose to go back to the initial view of Boissonnas (1974), considering that all these plutons intruded during the same period (539–523 Ma; post-batholitic dykes, pre-sedimentary cover) in response to the same global event and that the well-known expression "Taourirt" is useful to name such an event, even if polymorph or maybe because it is polymorph. To

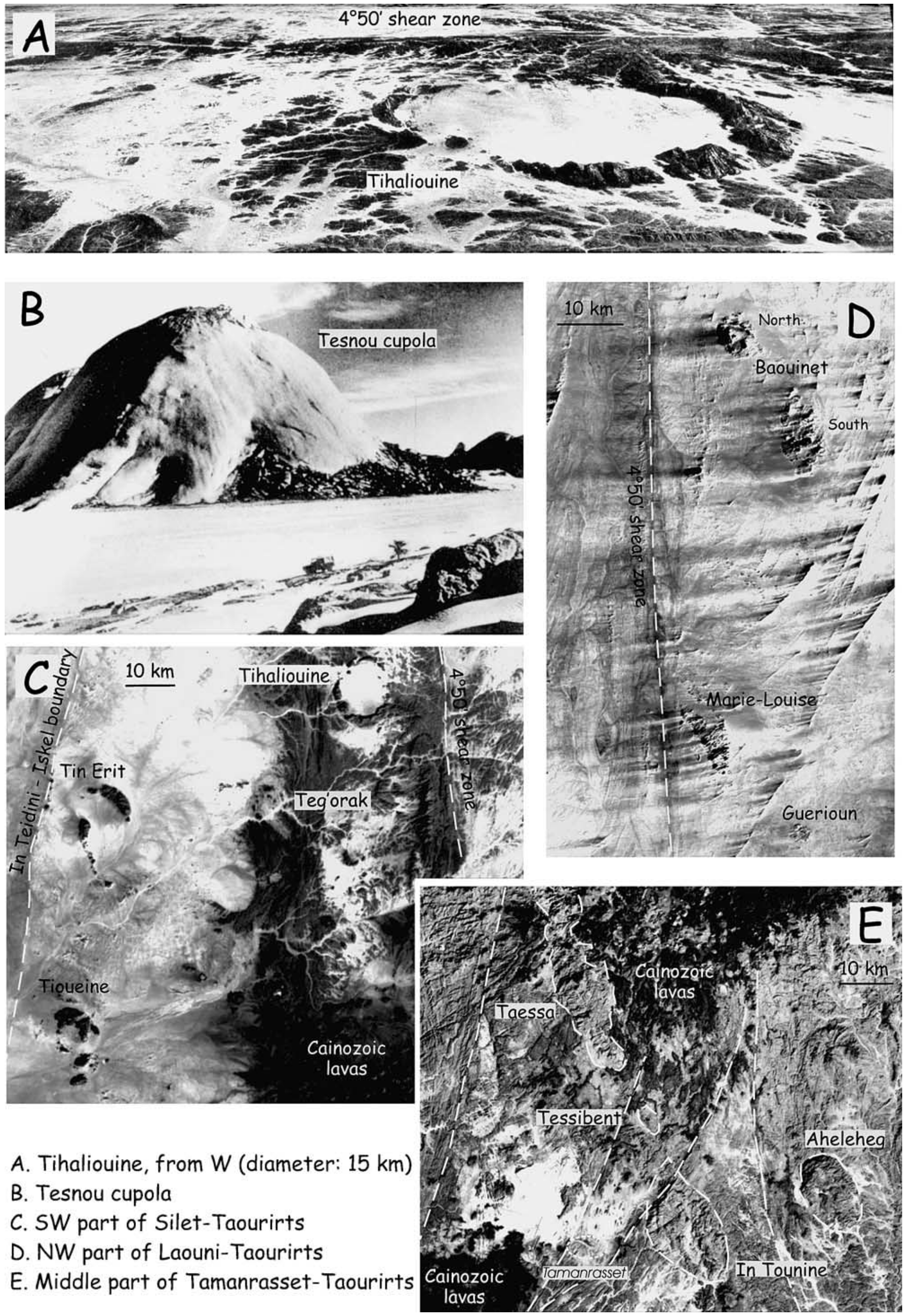

Fig. 3. A: Aerial photograph, taken from west, of the Tihaliouine Silet-Taourirt (diameter: 15 km) (Boissonnas, 1974), close to the 4°50′ mega-shear zone, separating the Iskel terrane from the LATEA metacraton. B: Cupola on the west of Tesnou complex, typical of the Taourirt sugar-loaf morphology. There is no link between this morphology and the internal structure of the coarse-grained monzogranite (Boissonnas, 1974). C–E: Satellite photographs (Orthorectified Landsat Thematic Mapper Mosaics as compressed color imagery in MrSID™ file format from Lizardtech); C: south-western part of the Silet-Taourirts with the Tihaliouine, Teg'Orak, Tin Erit and Tiouieine complexes; D: north-western part of the Laouni-Taourirts with the Baouinet North and South, Marie-Louise and Guerioun complexes; E: middle part of the Tamanrasset-Taourirts with the Taessa, In Tounine and Aheleheg complexes. The darker zones are Cainozoic lavas.

take into account the observed differences, we add here a geographical determinant (the name of the nearby town), dividing the Taourirt province in three main groups (Fig. 2): I: Silet-Taourirt, II: Laouni-Taourirt, III: Tamanrasset-Taourirt. For an easy use, these names will be used as nouns.

The Silet-Taourirts are intrusive into the Neoproterozoic In Teidini and Iskel terranes west of the 4°50′ shear zone (Fig. 3C) and correspond to the restricted definition of the Taourirts following Azzouni-Sekkal and Boissonnas (1974). The Laouni-Taourirts (Fig. 3D) comprise several small plutons intrusive into the LATEA metacraton, as it is the case for the Tamanrasset-Taourirts (Fig. 3E), the latter being larger and associated with albite–topaz leucogranites (Cheilletz et al., 1992).

2.2. The Taourirt igneous province: general features

The geology and petrology of the Taourirt igneous province are described in detail by Boissonnas (1974); Azzouni-Sekkal (1989); Azzouni-Sekkal and Boissonnas (1993) and Cheilletz et al. (1992). A series of unpublished theses are dealing with the Taourirt province and will be cited hereafter.

The *Silet-Taourirts* cross-cut the ≈850 Ma Iskel terrane (formerly called Pharusian I) and the ≈650 Ma In Teidini terrane (formerly called Pharusian II) and are aligned along the mega-shear zones bordering the Iskel terrane (Fig. 2). The Iskel and In Teidini terranes comprise Neoproterozoic metavolcano-sedimentary sequences attributed to island arc assemblages (of different ages) but displaying some differences such as being more detritic in the In Teidini terrane. The Iskel terrane is the only terrane in the Tuareg Shield to comprise granodioritic plutons dated at 870–850 Ma (Caby et al., 1982) whereas the high-K calc-alkaline plutons intruding In Teidini at around 600 Ma belong to a widespread family in the Tuareg Shield. These two terranes are limited by a mega-shear zone (formerly "Pharusian unconformity") along which eclogite lenses are intercalated (Bertrand et al., 1986). No pre-Neoproterozoic rocks are known within these two terranes. The Silet-Taourirts comprises a cluster of about 20 granitic subcircular zoned plutons with a mean diameter of 10–15 km forming an elongated (280 × 70 km) north–south-trending igneous alignment bracketed roughly between longitude 4 °E and 5 °E and latitude 22°50′ and 25°10′ (Figs. 1 and 2). Some are multi-pulse nested complexes, among which Ait Oklan (2 units; Belaïdi-Zinet, 1999; Fig. 4A) with two satellites, Tesnou (11 units; Djouadi, 1994; Belaïdi-Zinet, 1999; Fig. 4B), Imehellatene–Issediene (8 units associated with intermediate bodies), Tin Erit (3 felsic units associated with ultramafic to mafic cumulative bodies; Bechiri-Benmerzoug, 1998), Taharhait-Nabror (3 or 4 units), Tihaliouine (3 units), Teg'Orak (at least 4 units; Ferrag, 1997; Fig. 4C), Abankor-Timgaouine (Zaimen, 1994) and Tioueine (3 units; Azzouni-Sekkal and Boissonnas, 1987; Djouadi, 1994). Consistent low-field anisotropy of magnetic susceptibility (AMS) fabrics, essentially the magnetic lineation, in the apparently undeformed Tesnou and Tioueine complexes substantiate a weak magmatic-state deformation attributed to north–south dextral shearing of low strain magnitude ($\gamma < 1.5$), associated with clockwise bulk rotation during emplacement (Djouadi et al., 1997). In other complexes, the effect of the mega-shear zone is obvious (e.g. Teg'Orak complex; Fig. 4C).

The *Laouni-Taourirts* and the *Tamanrasset-Taourirts* are intrusive within the LATEA metacraton. The latter comprises four terranes (Laouni, Azrou-n-Fad, Tefedest, Egere-Aleksod, giving rise to the LATEA acronym, Fig. 1) that are made of an Eburnian granulite and amphibolite facies basement (Bertrand et al., 1986) with the presence of Archaean lithologies to the north of Egere-Aleksod (Latouche and Vidal, 1974; Peucat et al., 2003, this issue). Low-grade Neoproterozoic sedimentary rocks represent less than 10% of the surface of LATEA and are all bounded by tectonic contacts (Bertrand and Caby, 1978). One of these has been dated at ≈686 Ma and corresponds to an island arc assemblage thrust onto LATEA (Tin Begane area, north of Askarn in Fig. 2; Liégeois et al., 2003, this issue). Pan-African granitoids are abundant to the south and the west. Collisional to post-collisional movements converted the LATEA craton into a metacraton and truncated it into the four present terranes (for details, see Liégeois et al., 2003, this issue). The *Laouni-Taourirts* are undeformed and comprise the two complexes Baouinet North and Baouinet South (Figs. 3D and 4D), emplaced within the Laouni terrane east of the 4°50′ E shear zone (Fig. 3D; Zaimen, 1994). The relation with the nearby Laouni post-collisional mafic-ultramafic layered complexes (Cottin et al., 1998) is not known. The *Tamanrasset-Taourirts* include large massifs such as In Tounine, Aheleheg or Taessa (Figs. 2 and 3E) or smaller one such as Tessibent (Fig. 3E) but also very small massifs made up of albite–topaz mineralized granites (Cheilletz et al., 1992; Ahmed-Said et al., 1995; Chalal and Marignac, 1997; Kesraoui and Nedjari, 2002) corresponding to the most evolved end-members of the Taourirt suite that were emplaced close to the boundary between Laouni and Azrou-n-Fad terranes (Fig. 1).

A few late complexes within the northern Tefedest and Egere-Aleksod terranes (Fig. 1) are also described by Boissonnas (1974), but are not considered as belonging to the Taourirt series (e.g. the Tisselliline complex; Liégeois et al., 2003, this issue).

2.3. Age constraints on the Taourirt province

A lower limit is given by the dyke swarms cutting the calk-alkaline batholiths but which are cut by the Taourirt plutons (Boissonnas, 1974; Fig. 4D). Although undated, these dyke swarms put a clear break between the batholiths and the Taourirts. In the western Tuareg Shield, such dyke swarms are contemporaneous with

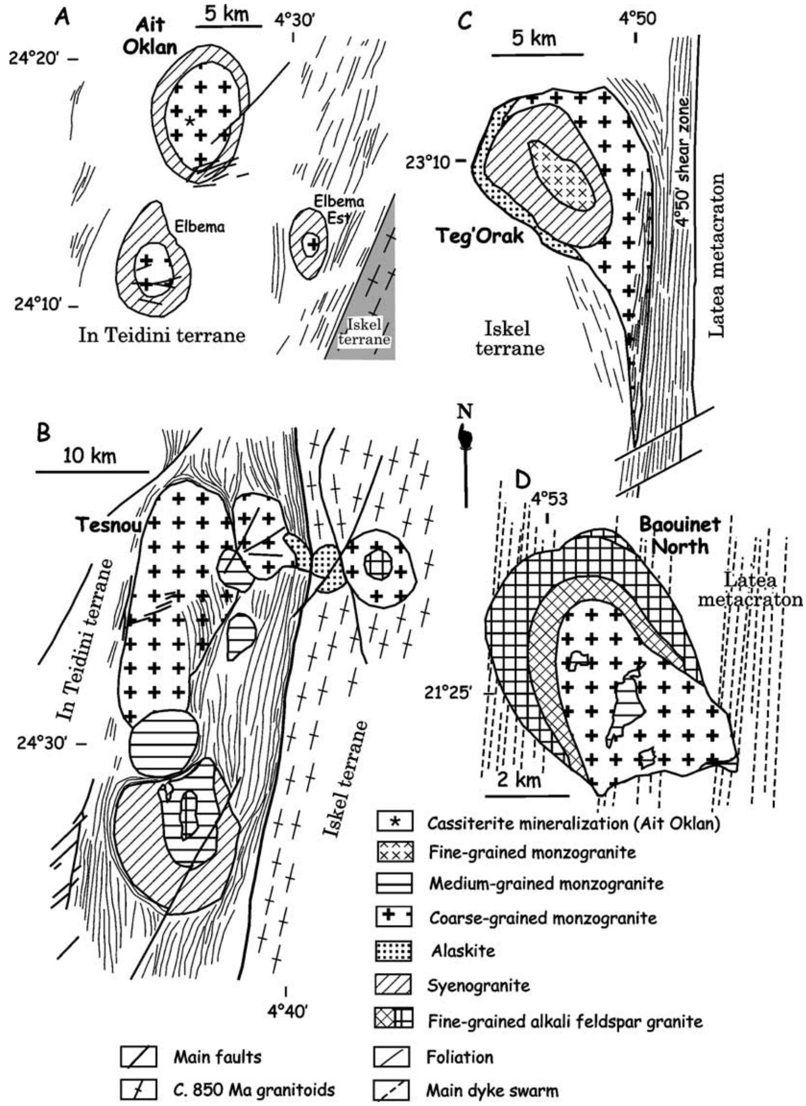

Fig. 4. Geological sketch map of some Taourirt plutons and structures in the country-rocks (simplified from Boissonnas, 1974). A: Ait Oklan and the two Ebelma complexes within the In Teidini terrane, along the boundary with the Iskel terrane; B: the large nested Tesnou complex intruded along and across the boundary between the In Teidini and Iskel terranes. Part of the basement structure turns around the complex; C: Teg'Orak complex intruded within the Iskel terrane along the 4°50′ mega-shear zone bounding to the west the LATEA metacraton; this complex is spectacularly affected by the mega-shear zone, indicating a dextral movement during the emplacement of the intrusive body; D: Baouinet North complex intruded within the LATEA metacraton, cross-cutting one of the dyke swarms that in turn are cutting the main Pan-African batholiths.

molasse deposits, which are very rich in rhyolitic pebbles (up to 50%) and have been shown to be contemporaneous with rhyolitic plateau lavas and slightly older than late alkaline–peralkaline ring complexes (e.g. Caby and Moussu, 1967; Liégeois et al., 1987; Fabre et al., 1988). In Central Hoggar, such deposits are rarer and occur near the boundary of the shield. This is the case of the conglomeratic-arkosic succession of El Moungar to the north (Beuf et al., 1971; Fig. 1) and of In Guezzam to the south (Djellit et al., 2002; Fig. 1). These local sedimentary sequences are associated with late movements along shear zones and are associated with the end of the erosion of the shield (Beuf et al., 1971). The In Guezzam molassic group comprises volcanic units (rhyolite, ignimbrite, tuff; Djellit et al., 2002) suggesting a similar relation with the Taourirts in Western Hoggar between molasses and ring complexes: this would imply that these molassic units would be older.

The upper limit is given by the Tassilis sandstones, whose first fossiliferous detrital layers, indicating the onset of marine platform sedimentation, are from the Tremadoc (500–485 Ma; Fabre, 1988). They were mostly deposited within a fluvial braided system with palaeocurrents from south to north across the Tuareg Shield, which did not play any topographic role, being entirely pediplaned at the time (Beuf et al., 1971).

Concerning radiometric ages on Taourirt plutons, old whole-rock Rb–Sr determinations yielded low-precision

(±40 Ma) Neoproterozoic dates: 595 Ma for Iskel and 572 Ma for Tioueine (data and discussion in Cahen et al., 1984). Recent determinations by different radiometric methods point to Lower Cambrian ages for the Taourirts. In the Tamanrasset-Taourirts, near the boundary between the Laouni and Azrou-n-Fad terranes, the In Tounine and Aheledj plutons (Figs. 2 and 3) yielded ages of 539–525 Ma by K–Ar and ^{40}Ar–^{39}Ar mica (Cheilletz et al., 1992). In the Silet-Taourirts, the Tioueine complex yielded an age of 523 ± 1 Ma by U–Pb zircon (Paquette et al., 1998). The Tioueine complex includes true alkaline granites, suggesting it belongs to the end of the Taourirt event. The 539–523 Ma age range is then a reasonable estimate for the Taourirt event. Considering the higher precision of the U–Pb zircon age, we will adopt in this paper the age of 525 Ma for calculating Sr and Nd initial isotopic ratios.

2.4. Petrological and REE features of the Taourirt province

The Taourirt suite is dominantly granitic, with scarce mafic to intermediate rocks. The most discriminating feature between the different Taourirt groups is the rare earth element (REE) patterns. Major and other trace elements will be used afterwards to precise the nature of the series as a whole. Geochemical data are mainly unpublished (Azzouni-Sekkal, 1989; Zaimen, 1994; Ferrag, 1997; Bechiri-Benmerzoug, 1998) and can be obtained from the authors. Other data are from Cheilletz et al. (1992).

Four major felsic rock types have been defined in the Silet-Taourirts (Azzouni-Sekkal and Boissonnas, 1974): GI biotite-amphibole monzogranite, GIIa ± amphibole-biotite monzogranite and syenogranite, GIIb alaskite (leucocratic alkali feldspar granite), GIII alkali feldspar syenite and alkali feldspar granite. Azzouni-Sekkal and Bonin (1998) provide a complete summary of the petrology of the Silet-Taourirts.

The Silet-Taourirt GI monzogranite occurs in a small number of complexes, mainly to the south of this Taourirt subgroup. REE contents average 200 ppm, with patterns yielding moderate fractionation, slight LREE enrichment and weak negative Eu anomalies (Fig. 5A).

The Silet-Taourirt GIIa monzogranite and syenogranite are exposed in almost all investigated complexes. The rock-forming mineralogy is the same as within GI monzogranite, with K-feldspar being more abundant than plagioclase and amphibole rarer. The accessory paragenesis is similar, with addition of thorite + fergusonite + monazite + xenotime (Azzouni-Sekkal and Bonin, 1998). REE contents average 250 ppm, with less fractionated patterns and more pronounced negative Eu anomalies (Fig. 5B).

The Silet-Taourirt GIIb alaskite (alkali feldspar granite) is the most evolved type of the suite, characterized by pure albite and Li-bearing mica (protolithionite to zinnwaldite). High SiO2 contents are in contrast with extremely low Ti, Mg, Ca and P contents. REE patterns (Fig. 5C) show little or no fractionation and deep negative Eu anomalies. This corresponds to tetrad effects on La–Ce–Pr–Nd and Gd–Tb–Dy–Ho suites of lanthanide elements (Bau, 1996) resulting in gull wing-shaped patterns with downward concavity. With the lowest abundances of Sr, Ba, LREE, Zr and the highest abundances of Rb, U, Th, Nb, Y, MREE, HREE, alaskite exhibits the features defining the low-P subtype of topaz granite (Taylor, 1992). GIIb alaskite can indeed be correlated with the small topaz-bearing granite plutons from the Tamanrasset-Taourirts (Cheilletz et al., 1992; see below).

The Silet-Taourirt GIII association is exposed within a small number of complexes. Mesoperthitic alkali feldspar is the main mineral. The group comprises metaluminous to peralkaline syenite and granite. REE contents are higher in syenite (1100 ppm) than in granite (200–400 ppm). Fractionated and gull wing-shaped REE patterns display LREE enrichment, pronounced negative Eu anomalies, no tetrad effects and upward concavity (Fig. 5D). Ba and Sr contents are intermediate between values recorded in post-orogenic and early anorogenic alkaline granitoids (Bonin, 1990).

The Laouni-Taourirts are composed of coarse-grained monzogranite and hypersolvus alkali feldspar granite, both rock types looking similar to the GIIa and GIII Silet-Taourirts. Geochemical data are only available from the North and South Baouinet plutons (Figs. 2, 3, 4D), which display regular seagull wing-shaped REE patterns (Fig. 5E). REE patterns are flat between 30 and 80 times chondrites with deep negative Eu anomaly. They can be compared to some samples of the Silet-Taourirt GIIb group (Fig. 5D).

The Tamanrasset-Taourirts are mainly composed of coarse-grained porphyritic biotite granite, but also of finer-grained or more isogranular varieties with the same mineralogy. The Tamanrasset-Taourirts are characterized by the presence of small peculiar units such as the biotite-cordierite granite and the biotite-muscovite granites in the In Tounine complex (Boissonnas, 1974), the porphyritic microgranite and the albite–topaz leucogranite in small stocks (Cheilletz et al., 1992). The mineralogy of the albite–topaz leucogranite is constant: quartz, albite, K-feldspar, protolithionite or zinnvaldite, topaz and locally fluorite and columbite-tantalite (Cheilletz et al., 1992; Kesraoui and Nedjari, 2002). These leucogranites are spatially associated with Sn–W mineralizations (cassiterite and wolframite) in greisenized quartz dykes or in diffuse or fissured greisens (Bouabsa, 1987; Cheilletz et al., 1992). REE from In Tounine and Ahelehedj (Cheilletz et al., 1992; Fig. 5F) are similar to the Silet-Taourirt GIIa with moderate LREE-HREE fractionation and deep negative Eu

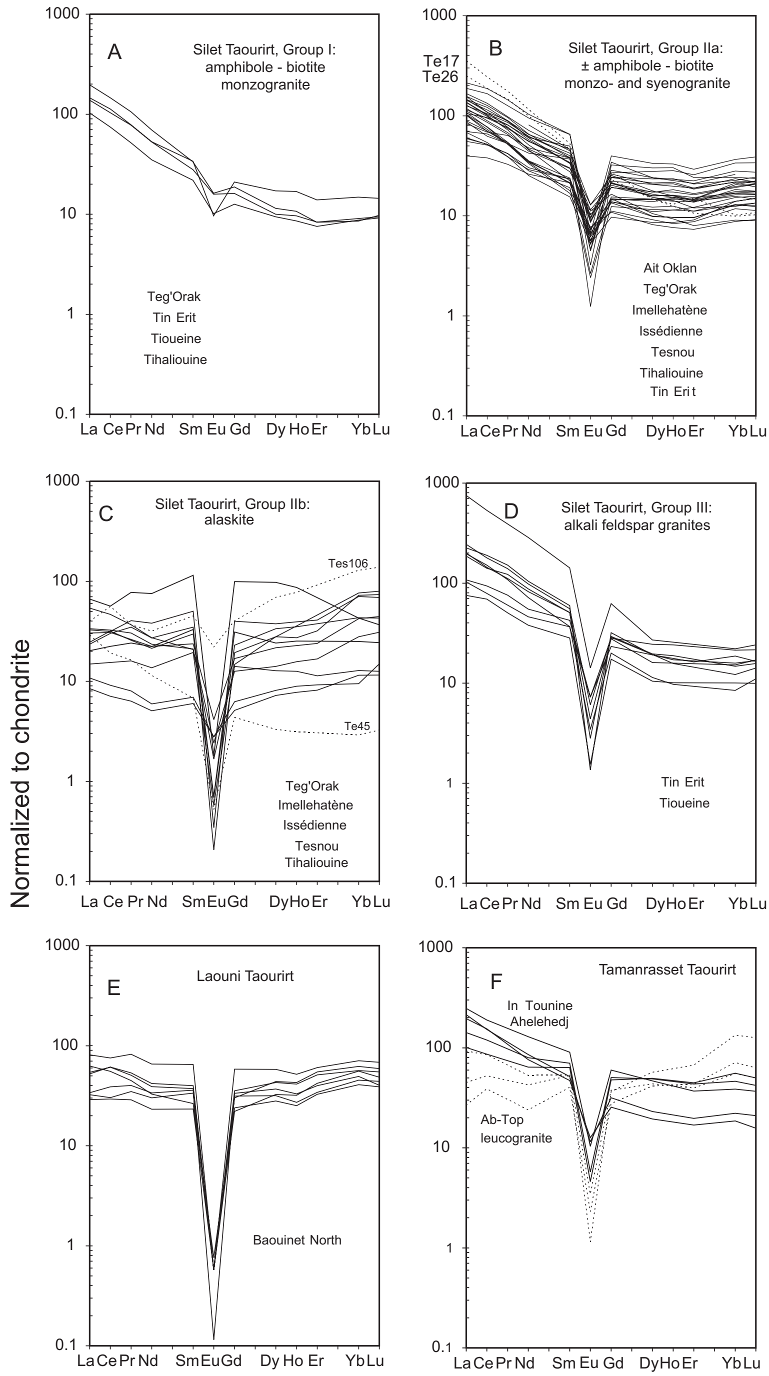

Fig. 5. Rare Earth elements (REE) patterns normalized to chondrite (Taylor and Mc Lennan, 1985): A: Silet-Taourirt, Group I amphibole-biotite monzogranite, from Teg'Orak, Tin Erit, Tioueine and Tihaliouine complexes. B: Silet-Taourirt, Group IIa ± amphibole-biotite monzo- and syenogranite, from Ait Oklan, Teg'Orak, Imehellatène, Issedienne, Tesnou, Tihaliouine and Tin Erit complexes. C: Silet-Taourirt, Group IIb alaskite, from Teg'Orak, Imehellatène, Issedienne, Tesnou and Tihaliouine complexes. D: Silet-Taourirt, Group III alkali feldspar granite, from Tin Erit and Tioueine complexes. E: Laouni-Taourirt, from Baouinet North complex. F: Tamanrasset-Taourirt, main granites, from In Tounine and Ahelehedj complexes and albite–topaze leucogranites from small plutons (data from Cheilletz et al., 1992).

anomalies. The albite–topaz leucogranites display different REE patterns (Fig. 5F; Cheilletz et al., 1992) close to the Silet-Taourirt GIIb group or to the Laouni-Taourirt Baouinet North with unfractionated REE and deep negative Eu anomaly (seagull wing-shaped).

These REE characteristics can be summarized in a diagram Eu/Eu* vs. La_N/Yb_N (Fig. 6). The Silet-Taourirt GI is concentrated in the upper right part of the diagram (moderate fractionation, weak negative Eu anomaly). The Silet-Taourirt GIIa displays a wider

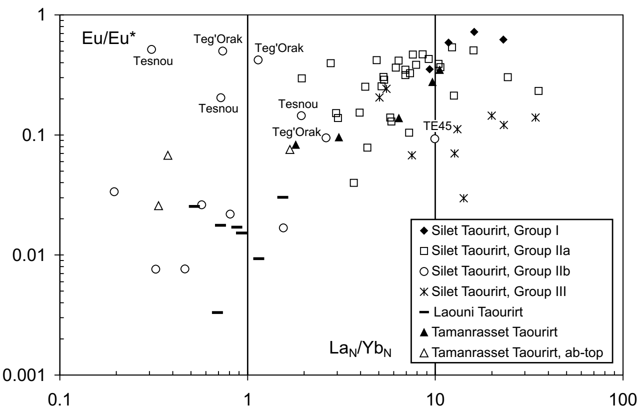

Fig. 6. La_N/Yb_N vs. Eu/Eu^* for the various Taourirt groups and subgroups. Tesnou and Teg'Orak are Silet-Taourirts.

range in fractionation and moderate to major negative Eu anomalies. The Silet-Taourirt GIII shows a similar REE fractionation as the two former groups, but a deeper negative Eu anomaly. The Silet-Taourirt GIIb is poorly fractionated with some samples having $Yb_N > La_N$ and comprises two subgroups relative to the Eu anomaly: one subgroup presents moderate negative Eu anomalies (from the Tesnou and Teg'Orak plutons; Fig. 6), while the other one shows very deep negative Eu anomalies, similar to the Laouni-Taourirt Baouinet North pluton. The Tamanrasset-Taourirt main granites are similar to the Silet-Taourirt GIIa while the Tamanrasset-Taourirt topaz leucogranites are intermediate between the two subgroups of the Silet-Taourirt GIIb alaskites.

2.5. *Major and trace element characteristics of the Taourirt province*

The Taourirt granitoids display alkali ($K_2O + Na_2O$) contents between 7 and 11 wt% (Fig. 7A). Nearly all samples are located between the lines separating the alkaline from the subalkaline series following Kuno (1966) and Irvine and Baragar (1971). This shows the intermediate character of the Taourirt province. No samples are peralkaline (Fig. 7B) and we will generally use the expression "alkali-calcic" following Peacock (1931). More specifically, the Silet-Taourirt GI and GIIa, the Laouni-Taourirt Baouinet North and the Tamanrasset-Taourirt main granites show rather constant alkali contents between 8% and 9.5%. The Silet-Taourirt GIIb and GIII have decreasing alkali content with increasing silica (11% [$K_2O + Na_2O$] at 65% SiO_2 and about 8.5% at 76%). The Tamanrasset-Taourirt topaz leucogranites lie mostly within the subalkaline field except the two silica richer samples as alkali content increases with silica. This subgroup is entirely peraluminous (Fig. 7B), in agreement with the presence of topaz. All other Taourirt groups comprise both metaluminous and peraluminous samples. Nearly all Taourirt granitoids fall in an area between $(CaO/Al_2O_3)_{mol} = 0$ and 0.25, the CaO-poorer samples being the Silet-Taourirt GIIb and GIII and the Tamanrasset-Taourirt albite–topaz leucogranites. For a province comprising mainly granitoids above 70% SiO_2, the Taourirt province shows a wide range of Ba and Sr contents (Fig. 7C), the two elements being correlated. The Silet-Taourirt GI is on the high side, the Silet-Taourirt GIIa, the Laouni-Taourirt Baouinet North and the Tamanrasset-Taourirt main granites display the widest ranges (Group IIa: from 1012 to 34 ppm Ba and from 275 ppm (outlier at 469 ppm) to 11 ppm Sr for a silica range from 69.7% to 76.3%). The other groups are much lower in both Ba and Sr with the exception of the Silet-Taourirt GIII, which is present in both poor and rich areas. The abundance of Sr is roughly correlated with the Eu/Eu^* ratio (Fig. 7D). Two main trends are displayed principally by the Silet-Taourirt GIIa and GIIb, the latter having lower Sr abundance in samples with moderate Eu negative anomaly. The Laouni-Taourirt Baouinet North is very low in Sr and Eu/Eu^*. This indicates a clear role of feldspar in the differentiation of the Taourirt granitoids.

Several observations can be made on the diagram based on major elements for distinguishing evolved calc-alkaline series from alkaline series (Fig. 7E; Sylvester, 1989). The Silet-Taourirt GI, the most primitive and the least "alkaline", plots near the triple point. The Silet-Taourirt GIIa, with its large range in Sr and Ba contents (Fig. 7C), displays a wide curved range from the calc-alkaline field to the alkaline field, most of the samples being within the common field of alkaline and highly fractionated calc-alkaline granitoids. The Silet-Taourirt GIIb, most of the Laouni-Taourirt Baouinet North and the Tamanrasset-Taourirt topaz leucogranites are within this common field. The Silet-Taourirt GIII and the Tamanrasset-Taourirt main granites lie across the boundary between this common field and the alkaline field. The last two groups appear to be the most "alkaline" Taourirts.

Comparing trace elements of different magmatic suites requires to take into account the differentiation effects. This is the role of the sliding method, which normalizes the studied rocks to the computed rock composition from a reference series that has the same silica content. This enhances differences not related to differentiation (Liégeois et al., 1998). The reference series chosen here is that from Liégeois et al. (1998), the Yenchichi-Telabit alkali-calcic series from the Adrar des Iforas, a series intermediate between the high-K calc-alkaline batholiths and the alkaline–peralkaline ring complexes and associated dykes and lavas (Liégeois et al., 1987). The synthetic diagram based on NYTS (Normalized to Yenchichi-Telabit Series) trace element values aims at separating potassic alkali-calcic series

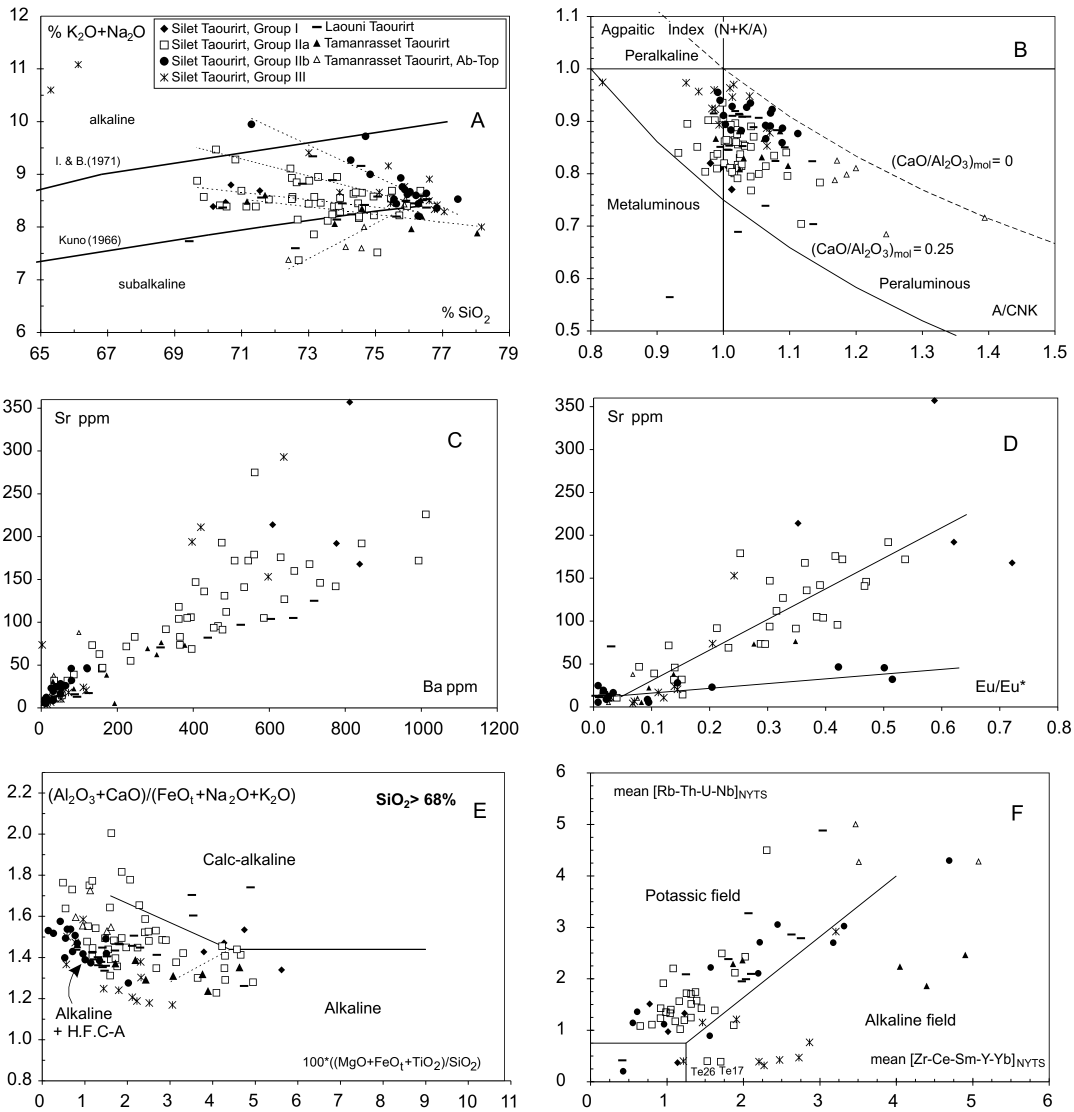

Fig. 7. Major and trace elements variations. Legend of symbols given in diagram A. A: SiO_2 vs. ($K_2O + Na_2O$). I. and B. (1971) means Irvine and Baragar (1971). The two references are given for the line dividing the alkaline from the subalkaline compositions. Dotted lines enhance trends determined by the different groups. B: A/CNK [Al_2O_3/(CaO+Na_2O+K_2O) in molar proportion] vs. agpaitic index [(Na_2O+K_2O)/Al_2O_3, in molar proportion]. C: Ba ppm vs. Sr ppm. D: Eu/Eu* vs. Sr ppm. E: $100 * ((MgO + FeO_t + TiO_2)/SiO_2)$ vs. $(Al_2O_3 + CaO)/(FeO_t + Na_2O + K_2O)$ separating calc-alkaline and alkaline granitoids with a third common field for alkaline granitoids and highly fractionated calc-alkaline (H.F. C-A) granitoids (from Sylvester, 1989). F: Diagram opposing the mean of values normalized to the Yenchichi-Telabit (NYTS) reference series (sliding normalization; Liégeois et al., 1998), see text for explanation: $(Zr–Ce–Sm–Y–Yb)_{NYTS}$ vs. $(Rb–Th–U–Nb)_{NYTS}$.

from alkaline series. In this diagram (Fig. 7F), the Silet-Taourirts GIII and the Tamanrasset-Taourirts main granites display an alkaline trend while all other Taourirts, with few exceptions, show a potassic trend, confirming the conclusions emerging from major elements (Fig. 7E). In the last two diagrams (Fig. 7D and E), some samples from the GIIa Silet-Taourirts fall within the alkaline field. The rare transition from alkali-calcic potassic granitoids to alkaline granitoids observed within the Taourirt Province justifies developing this approach by building NYTS-based spidergrams (Fig. 8). On Fig. 8, the Iforas alkaline–peralkaline Iforas province has been represented as a grey area. This diagram indicates that the Silet-Taourirt GI is very similar to the Yenchichi-Telabit alkali-calcic series (Fig. 8A). The Silet-Taourirt GIIa displays similar patterns (Fig. 8B), with the exception of samples Te17 and Te26, already outliers in Fig. 7F. Except for the Eu negative anomaly, the Silet-Taourirt GI and GIIa subgroups are indeed close, the GI samples being located at one end of the GIIa trend (Figs. 5–7). These two groups can be compared with the Iforas Yenchichi-Telabit series (Liégeois and Black, 1987; Liégeois et al., 1987). The Silet-Taourirt GIIb and the Laouni-Taourirt Baouinet subgroups can be compared each other but have no counterparts in the Adrar des Iforas or elsewhere in the Tuareg Shield,

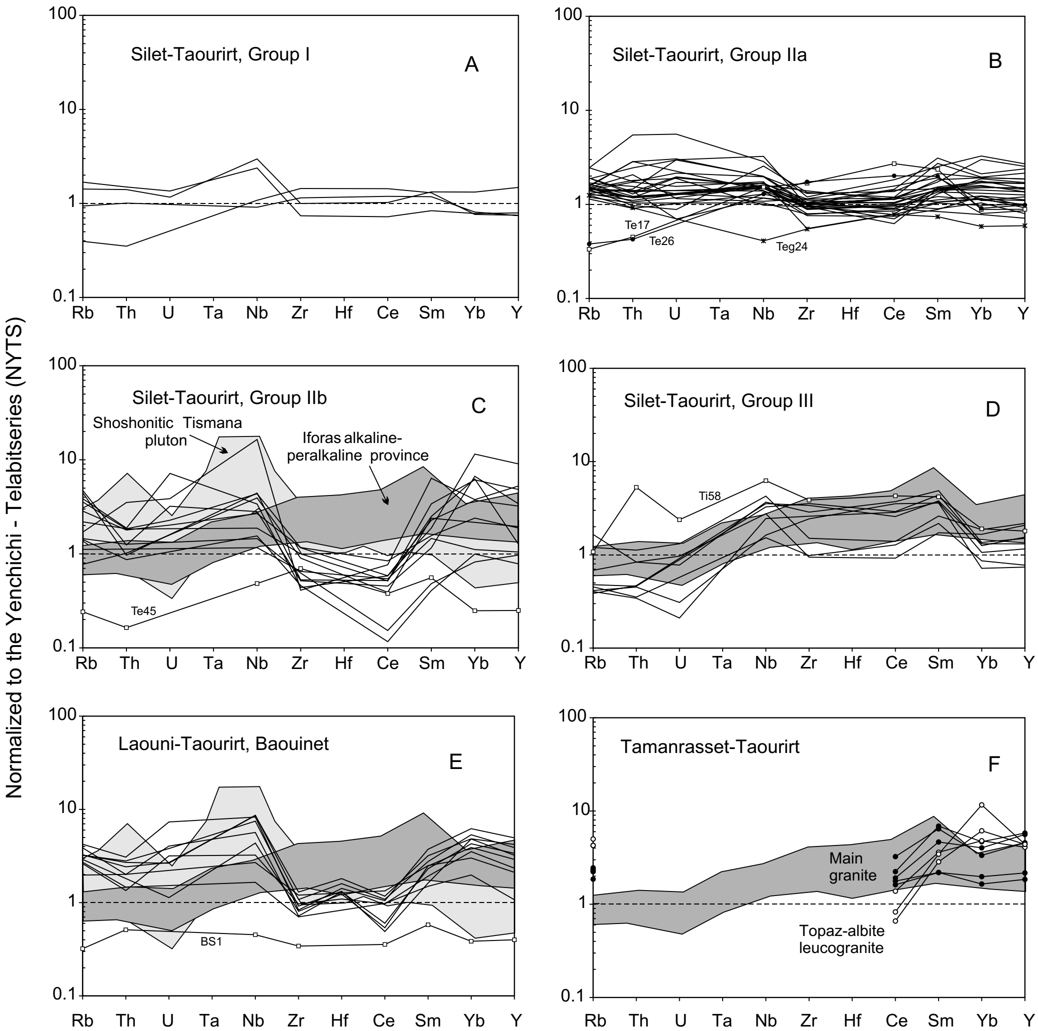

Fig. 8. Spidergrams of NYTS (Normalized to the Yenchichi-Telabit Series; sliding normalization; Liégeois et al., 1998) Taourirt samples. A: Silet-Taourirt, Group I; B: Silet-Taourirt, Group IIa; C: Silet-Taourirt, Group IIb; D: Silet-Taourirt, Group III; E: Laouni-Taourirt; F: Tamanrasset-Taourirt. The Iforas alkaline–peralkaline province is from Liégeois et al. (1998); the shoshonitic Tismana pluton is from Duchesne et al. (1998).

so far. They are more enriched in Rb, Th, U and Nb than both the Yenchichi-Telabit series and the Iforas alkaline–peralkaline province, comparable to Yenchichi-Telabit in Zr, Hf, Ce and comparable to the Iforas alkaline–peralkaline province in Yb and Y (Fig. 8C and E). They are comparable to a shoshonitic series such as the Pan-African Tismana pluton in Romania (Duchesne et al., 1998) only for the elements to the left of the diagram (Rb, Th, U, Nb). The Silet-Taourirt GIII subgroup is similar to the Iforas alkaline–peralkaline province (Fig. 8D), which is in agreement with previous observations. Available data from the Tamanrasset-Taourirts are too limited to conclude definitely (Fig. 8F); the Tamanrasset-Taourirt main granites have REE similar to the Iforas alkaline–peralkaline province but have higher Rb contents. If the Tamanrasset-Taourirt topaz leucogranites display a signature distinct from all other subgroups, they are globally not very far from the Tamanrasset-Taourirt main granites.

Additional observations can be done on MORB-normalized spidergrams (Fig. 9). The Silet-Taourirt GI subgroup (Fig. 9A) displays a classical "OIB-type" pattern with major Sr and slight Ba, P and Ti negative anomalies that could be attributed to crystal fractionation of feldspar, apatite and probably Fe–Ti oxides. The Silet-Taourirt GIIa shows accentuated GI patterns with strong negative anomalies in Sr, Ba, P and Ti, the other elements being similar. The Silet-Taourirt GIIb subgroup (Fig. 9C) shows the same negative anomalies but even stronger than in GIIa, depletion in LREE and strong enrichments in Rb and in HREE. In this diagram, the Silet-Taourirt GIII (Fig. 9D) appears close to the Group IIa, with some outliers (samples Ti8, Ti27, Ti58) and the Laouni-Taourirts are close to the Silet-Taourirt GIIb. The Tamanrasset-Taourirt main granites look like the Silet-Taourirt GIII, whereas the Tamanrasset-Taourirt topaz leucogranites patterns are close to the Silet-Taourirt GIIb subgroup.

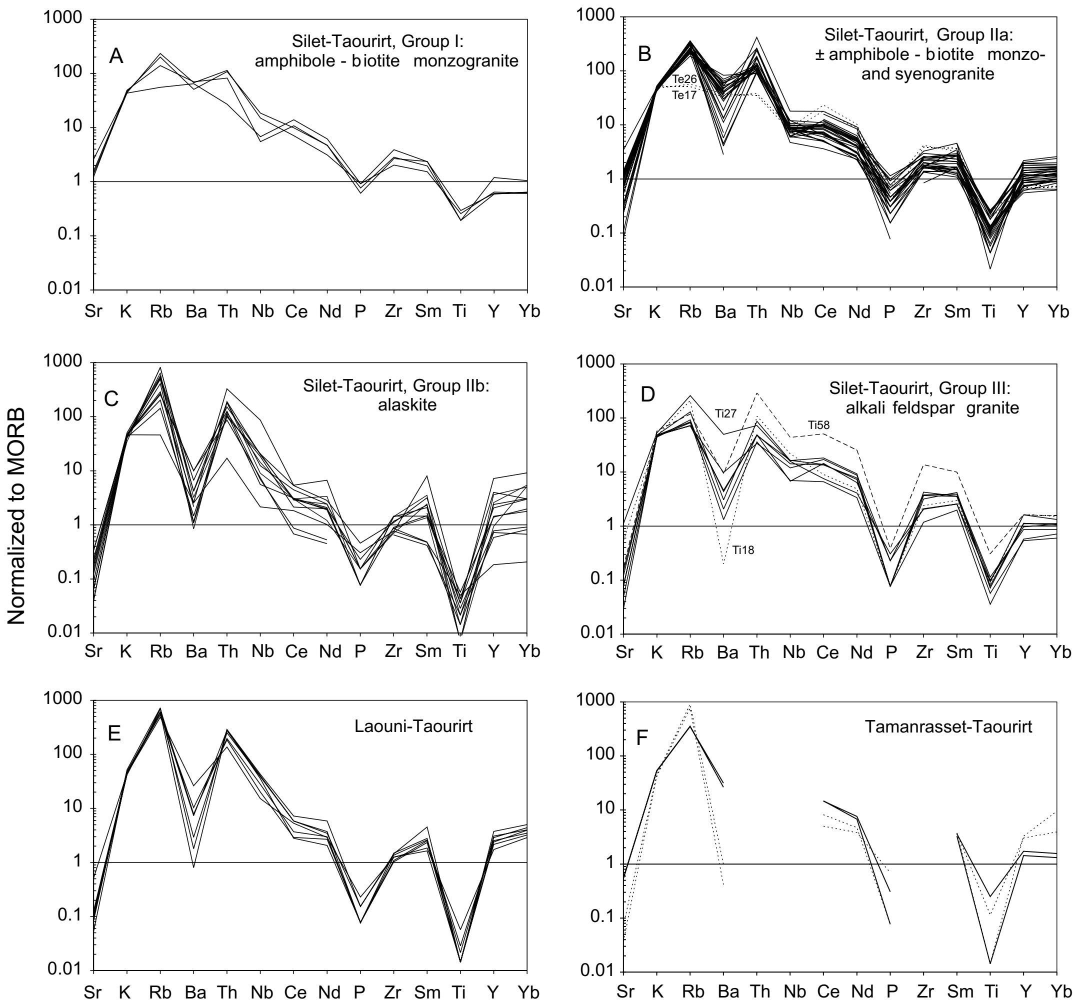

Fig. 9. Trace element spidergrams normalized to N-MORB (Pearce, 1982; Sun, 1980). A: Silet-Taourirt, Group I; B: Silet-Taourirt, Group IIa; C: Silet-Taourirt, Group IIb; D: Silet-Taourirt, Group III; E: Laouni-Taourirt; F: Tamanrasset-Taourirt.

In summary, several points can be enhanced:

- As a whole, the late granitoids in Central Hoggar share similarities that justify considering one single Taourirt igneous Province.
- The Taourirt igneous province displays an evolution from an alkali-calcic series to an alkaline series; however this province is characterized by unusually enriched strongly differentiated alkali-calcic terms.
- The early alkali-calcic series (Silet-Taourirt GI and GIIa) is similar to the Iforas Yenchichi-Telabit series that follows the main high-K calc-alkaline batholiths; the late alkaline series (Silet-Taourirt GIII) is similar to the Iforas alkaline–peralkaline series, also marking the end of the Pan-African magmatism there. The Tamanrasset-Taourirt main granites could be linked to this group.
- The evolved and enriched alkali-calcic series (Silet-Taourirt GIIb, Laouni-Taourirts, Tamanrasset-Taourirt topaz leucogranites) constitute a peculiar feature of the Taourirt province, but share enough geochemical characteristics with the other Taourirts for not hesitating to group them together.

3. Sr–Nd isotope systematics

Available isotopic data comprise Sr and Nd isotopes for Silet-Taourirts GI, GIIa and GIIb subgroups and Sr isotopes for Laouni-Taourirts and Tamanrasset-Taourirts. For the latter, data come from Cheilletz et al. (1992); for all others, they are either unpublished or come from unpublished theses and were measured in the Africa Museum in Tervuren. Sr and Nd isotope ratios are listed in Table 1 and analytical techniques are reported in Appendix A.

3.1. Rb–Sr geochronology

Ages have been calculated following Ludwig (1999) and are given at the 2σ confidence level.

Table 1
Sr and Nd isotopes results for the Taourirt province

Group	Complex	Sample	Rb	Sr	^{87}Rb/^{86}Sr	^{87}Sr/^{86}Sr	$2\sigma(10^{-6})$	Sr$_i$, 525 Ma	Sm	Nd	^{147}Sm/^{144}Nd	^{143}Nd/^{144}Nd	$2\sigma(10^{-6})$	$\varepsilon_{Nd,525\ Ma}$	T_{DM}
Silet-GI	Teg'Orak	TEG65	139	168	2.40	0.721116	±10	0.703176	6.44	37.6	0.1036	0.512031	±6	−5.60	1398
Silet-GIIa	Aït Oklan	AO5	280	89.7	9.10	0.773121	±10	0.705031	10.7	46.3	0.1400	0. 512176	±10	−5.21	1786
Silet-GIIa	Aït Oklan	AO21	221	112	5.71	0.747373	±10	0.704611	10.3	50.7	0.1231	0. 512180	±11	−4.00	1448
Silet-GIIa	Aït Oklan	AO25	251	20.0	37.3	0.965000	±14	0.685693	15.0	67.6	0.1340	0. 512251	±10	−3.35	1509
Silet-GIIa	Aït Oklan	AO26	226	45.1	14.6	0.804692	±10	0.695314	15.1	73.5	0.1240	0. 512268	±11	−2.34	1314
Silet-GIIa	Aït Oklan	AO29	282	40.2	20.6	0.850866	±8	0.696437	9.20	44.3	0.1257	0. 512330	±11	−1.25	1233
Silet-GIIa	Aït Oklan	AO31	270	15.2	53.4	1.103255	±11	0.703969	8.51	30.1	0.1712	0. 512301	±22	−4.87	–
Silet-GIIa	Teg'Orak	TEG36	245	91.3	7.80	0.758886	±9	0.700485	4.96	24.5	0.1224	0.511958	±10	−8.29	1808
Silet-GIIa	Teg'Orak	TEG18	227	142	4.64	0.737132	±8	0.702416	5.17	32.4	0.0964	0.511921	±8	−7.27	1455
Silet-GIIa	Teg'Orak	TEG19	248	95.6	7.54	0.757778	±12	0.701327	3.57	18.0	0.1203	0.512039	±14	−6.57	1634
Silet-GIIa	Teg'Orak	TEG22	254	105	7.03	0.752833	±9	0.700218	4.89	25.0	0.1182	0.511963	±12	−7.91	1720
Silet-GIIa	Teg'Orak	TEG60	187	172	3.15	0.727177	±7	0.703589	4.12	24.3	0.1025	0.511930	±17	−7.50	1522
Silet-GIIa	Teg'Orak	TEG15	225	73.5	8.91	0.765480	±14	0.698815	5.50	25.3	0.1315	0.512079	±12	−6.54	1782
Silet-GIIa	Teg'Orak	TEG20	212	146	4.21	0.734106	±9	0.702581	3.86	23.7	0.0985	0.511890	±14	−8.01	1523
Silet-GIIa	Teg'Orak	TEG32	257	127	5.88	0.746242	±9	0.702256	4.89	24.9	0.1188	0.511975	±11	−7.71	1711
Silet-GIIa	Tesnou	TES12	255	141	5.26	0.744884	±19	0.705561	7.71	42.8	0.1089	0.512070	±7	−5.20	1413
Silet-GIIa	Tesnou	TES22	241	163	4.29	0.740522	±9	0.708390	10.7	57.5	0.1120	0.512181	±9	−3.23	1290
Silet-GIIa	Tesnou	TES27	250	139	5.21	0.744479	±10	0.705482	7.89	39.9	0.1197	0.512120	±9	−4.95	1493
Silet-GIIa	Tesnou	TES100	292	152	5.59	0.748124	±7	0.706298	9.75	25.7	0.2296	0.512252	±7	−9.75	–
Silet-GIIa	Tesnou	TES97	289	29.2	29.2	0.905505	±9	0.687010	11.5	42.9	0.1621	0.512410	±10	−2.13	–
Silet-GIIb	Teg'Orak	TEG9	819	24.8	103	1.485108	±12	0.715179	8.04	19.3	0.2520	0.512563	±16	−5.18	–
Silet-GIIb	Teg'Orak	TEG12	645	6.3	378	3.513233	±21	0.682886	11.6	27.1	0.2589	0.512575	±17	−5.41	–
Silet-GIIb	Teg'Orak	TEG2	209	14.5	42.8	0.975902	±10	0.655532	4.41	20.0	0.1333	0.511991	±13	−8.38	1993
Silet-GIIb	Teg'Orak	TEG11	265	46.7	16.6	0.818075	±10	0.693862	1.60	4.24	0.2282	0.512348	±12	−7.78	–
Silet-GIIb	Teg'Orak	TEG27	257	45.7	16.4	0.815804	±9	0.692732	1.38	3.60	0.2323	0.512358	±10	−7.86	–
Silet-GIIb	Teg'Orak	TEG61[a]	203	4.3	146	1.321284	±13	0.229541	4.87	16.7	0.1764	0.512245	±10	−6.31	–
Silet-GIIb	Tesnou	TES28	475	23.8	60.3	1.151816	±15	0.700696	4.80	19.4	0.1496	0.512067	±8	−7.99	–
Silet-GIIb	Tesnou	TES106	426	20.9	61.6	1.150648	±7	0.690001	10.4	22.7	0.2780	0.512697	±8	−4.31	–
Tessalit	Baouinet	BN4	725	11.4	212	2.235812	±10	0.651162							
Tessalit	Baouinet N	BN10	617	13.4	147	1.735014	±10	0.636948							
Tessalit	Baouinet N	BN11	601	15.9	119	1.553410	±14	0.666653							
Tessalit	Baouinet N	BN18	587	7.3	282	2.843052	±15	0.735155							
Tessalit	Baouinet N	BN21	485	70.6	20.2	0.855500	±12	0.704576							
Tessalit	Baouinet N	BN24	539	17.3	96.9	1.462381	±11	0.737518							
Tessalit	Baouinet N	BN29	689	13.1	172	2.031921	±18	0.744288							
Tamanrasset	In Tounine	OT5	340	80.1	12.4	0.811190	±49	0.718303							
Tamanrasset	In Tounine	OT63	401	22.2	54.3	1.124310	±49	0.717653							
Tamanrasset	In Tounine	OT64	736	31.1	72.3	1.258150	±56	0.717183							
Tamanrasset	In Tounine	OT67	354	74.8	13.9	0.829370	±37	0.725591							
Tamanrasset	In Tounine	OT69	436	51.0	25.2	0.908410	n0	0.719589							
Tamanrasset	In Tounine	OT73	341	37.9	26.6	0.912880	±62	0.714057							
Tamanrasset	In Tounine	OT85	489	29.9	49.0	1.052210	±48	0.685916							
Tamanrasset	In Tounine	OT86	493	29.1	50.8	1.068960	±51	0.689038							

Rb, Sr, Sm and Nd in ppm; T_{DM} Nd model ages (in Ma) following Nelson and De Paolo (1985); see Appendix A for other information. Baouinet N = Baouinet North. OT samples are from Cheilletz et al. (1992).

[a] TEG61 is cataclastic and is not used in age calculation.

Sample Teg61 (Teg'Orak pluton, Silet-Taourirt GIIb) has been affected by a cataclasis of unknown age that has strongly affected its Rb–Sr isotopic system (initial $^{87}Sr/^{86}Sr$ [Sr_i] at 525 Ma = 0.22954, Table 1) and will not be considered further.

Samples from all Taourirt groups (43 whole-rocks) define an Rb–Sr errorchron 520.5 ± 8.5 Ma, Sri = 0.7030 ± 0.0059, MSWD = 12 (Fig. 10A) close to the U–Pb age of Tioueine (523 ± 1 Ma; Paquette et al., 1998). Individual plutons give similar errorchron ages within error limits, although with larger errors: 506 ± 16 Ma (Tesnou, 8 WR, MSWD = 3.4; Fig. 10B), 511 ± 39 Ma (Ait Oklan, 6 WR, MSWD = 4.4; Fig. 10C), 519 ± 18 Ma (Teg'Orak, 14 WR, MSWD = 4.8; Fig. 10D), 524 ± 43 Ma (Baouinet North, 7 WR, MSWD = 4.9; Fig. 10E), 502 ± 42 Ma (In Tounine, 8 WR, MSWD = 5.2, recalculated from Cheilletz et al., 1992; Fig. 10F).

These five pluton ages give a weighted mean of 512 ± 10 Ma (MSWD = 0.88), suggesting that the Rb–Sr isotopic system gives, as a mean, a younger age for the Taourirt province than the U–Pb and Ar–Ar geochronometers. This is further sustained by the only isochron obtained on a Taourirt pluton (i.e. Teg'Orak) when only considering samples having $^{87}Rb/^{86}Sr < 20$: the calculated age is 482 ± 11 Ma (11 WR, MSWD = 0.72). This suggests that the Taourirt plutons have been subjected to fluid perturbation during early Ordovician slight re-

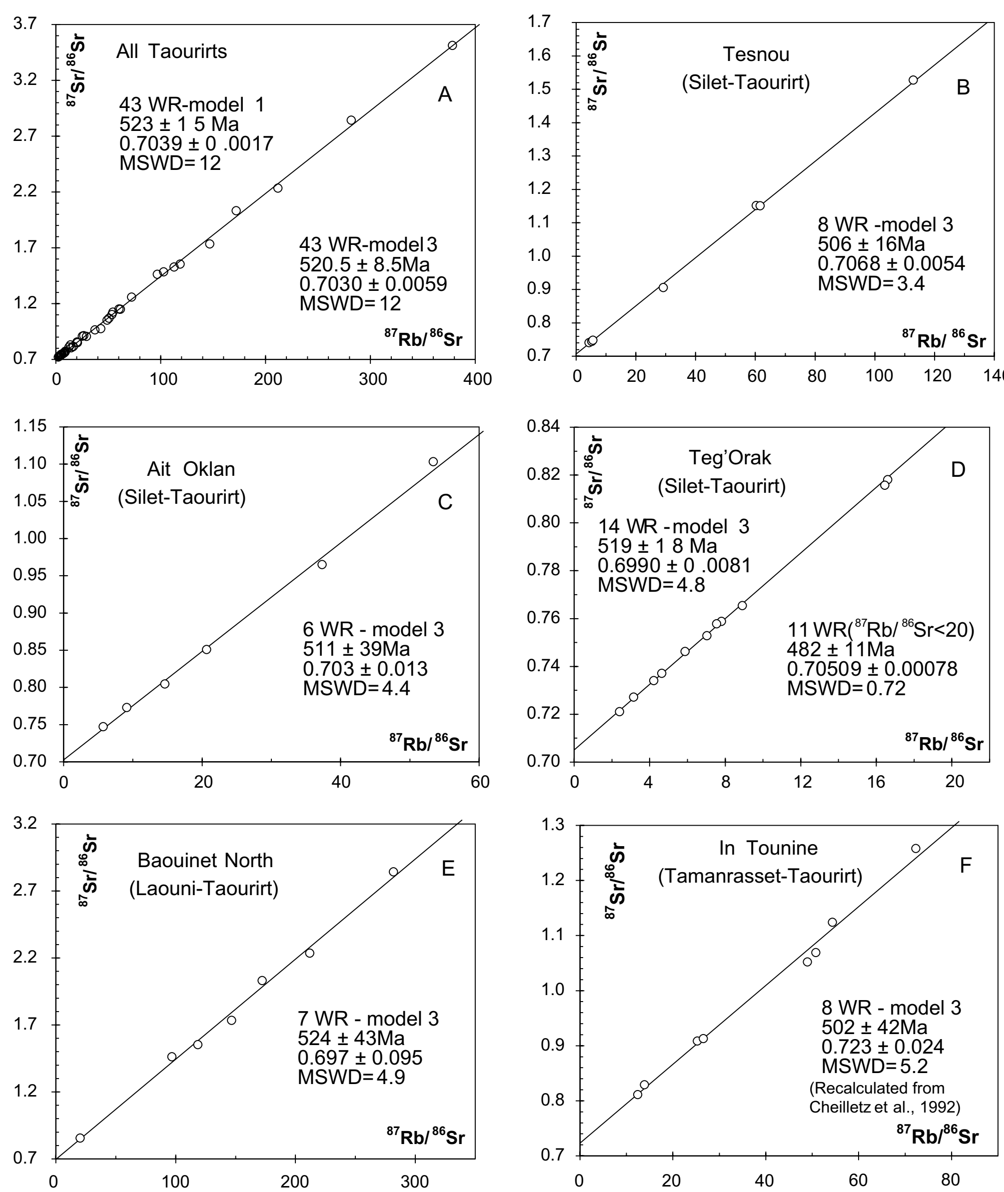

Fig. 10. Rb–Sr isochrons and errorchrons from the Taourirt complexes calculated following Ludwig (1999). A: All analyzed Taourirt samples; B: Silet-Taourirt Tesnou complex; C: Silet-Taourirt Ait Oklan complex; D: Silet-Taourirt Teg'Orak complex; E: Laouni-Taourirt Baouinet north complex; F: Tamanrasset-Taourirt In Tounine complex (recalculated from Cheilletz et al., 1992).

activation of shear zones. This reactivation has induced large variations of Ordovician Tassilis sandstone thickness and the presence, close to shear zones, of conglomerates and breccias made of lode quartz (Beuf et al., 1968), indicating fluid circulation.

This implies that the calculated $^{87}Sr/^{86}Sr$ initial ratios have to be considered with caution. Moreover, many Taourirt samples have very high $^{87}Rb/^{86}Sr$ (up to 400), giving rise to imprecise Sr_i. Global Taourirt Sr_i is 0.7030 ± 0.0059 (then up to 0.7089; Fig. 10A). Individual Silet-Taourirts give Sr_i in the following range: 0.7068 ± 0.0054 (Tesnou; Fig. 10B), 0.703 ± 0.013 (Ait Oklan; Fig. 10C) and 0.6990 ± 0.0081 (then up to 0.7071, Teg'Orak; Fig. 10D). The Laouni-Taourirts and Tamanrasset-Taourirts yield similar Sr initial ratios within errors: 0.697 ± 0.095 (then up to 0.7065, Baouinet North; Fig. 10E) and 0.723 ± 024 (then down to 0.700, In Tounine; Fig. 10F, recalculated from Cheilletz et al., 1992), respectively. The weighted mean of these five values is 0.7059 ± 0.0028 (MSWD = 0.88). This mean value corresponds to the Sr initial ratios of the Iforas alkaline–peralkaline province (Liégeois and Black, 1987), but could mask a wider range of Sr initial ratios.

3.2. Nd isotope systematics

$^{143}Nd/^{144}Nd$ initial ratios have been calculated assuming an age of 525 Ma and the $\varepsilon_{Nd,525\,Ma}$ values are listed in Table 1.

Due to uncertainty on Sr initial ratios and to their likely perturbation during the Ordovician, the classical combination of individual Sr_i and ε_{Nd} cannot be used. Some of the samples show a correlation between silica (then differentiation) and ε_{Nd} (Fig. 11A). This is particularly apparent if samples with $^{147}Sm/^{144}Nd > 0.15$ (seagull wing-shaped REE) are not considered. Samples having $^{147}Sm/^{144}Nd > 0.15$ are mainly Silet-Taourirt GIIb subgroup, which, for high silica contents (75.5–76.5% SiO_2) has ε_{Nd} between −5 and −8. To be on the trend defined by most other samples, this subgroup should have ε_{Nd} between −10 and −12. This situation could be explained by interactions with the country-rocks of the Silet-Taourirts, which are Pan-African oceanic island arcs (Iskel and In Teidini terranes). No Nd data are available for these series, but data are available from the Tilemsi island arc (730–720 Ma; Caby et al., 1989), located to the west of the shield (Fig. 1), which, recalculated at 525 Ma, give ε_{Nd} between +3 and +6. This implies that a contamination during emplacement by this type of rocks would render less negative the Nd signature of the Silet-Taourirts. Such an interaction is plausible when considering the GIIb REE patterns (Fig. 5C) implying REE mobility probably due to F- and Cl-rich hydrothermal fluids. The diagram SiO_2 vs. ε_{Nd}, suggests a silica loss during this process (Fig. 11A), but this has to be confirmed.

ε_{Nd} is not correlated with most of the major and trace elements (e.g. Ba, Fig. 11B). The only elements showing some correlation with ε_{Nd} are the REE. The relation between ε_{Nd} and Nd (Fig. 11C) is similar to that with silica: most samples having $^{147}Sm/^{144}Nd < 0.15$ define a trend indicating contamination by an old crust, being more effective when Nd concentration is low. Here also, the GIIb subgroup samples suggest that the low concentrations in Nd linked to the seagull wing-shaped REE pattern is accompanied by less negative ε_{Nd} (contamination by oceanic island arc country-rocks having positive ε_{Nd}). Seagull wing-shaped REE patterns are also characterized by a strong increase of HREE concentrations, which in the model above, should be accompanied by less negative ε_{Nd}. This is indeed the case (Fig. 11D).

A major constraint is brought by the ε_{Nd} values and the T_{DM} model ages. Most GIIb samples have $^{147}Sm/^{144}Nd > 0.15$ and in that case, the evolution line of the sample is nearly parallel to that of the depleted mantle, leading to useless model ages. In the diagram opposing these two partly correlated values (Fig. 11E), the Silet-Taourirt GIIa defines a trend from $\varepsilon_{Nd} = -1$ and $T_{DM} = 1200$ Ma to $\varepsilon_{Nd} = -9$ and $T_{DM} = 1700$ Ma. The two samples from the Silet-Taourirt GI and GIIb subgroups (other GIIb samples have $^{147}Sm/^{144}Nd > 0.15$) can be included within this trend. Tilemsi arc Nd isotopic values (Caby et al., 1989) recalculated at 525 Ma have been plotted in Fig. 11E, as the current best approximation for the Iskel and In Teidini island arc terranes. This diagram clearly shows that the source of the analyzed Silet-Taourirts comprises an old component, which could only be the LATEA metacraton. In the north of Egere-Aleksod terranes (Fig. 1), Nd isotope data are available from the LATEA Archaean–Palaeoproterozoic basement (Peucat et al., 2003, this issue), from the Pan-African granitoids in the same area (Ounane granodiorite; Liégeois et al., this issue) and from the Laouni terrane south of the In Tounine pluton (Fig. 2; Anfeg pluton; Acef et al., 2003, this issue). The Nd isotopic parameters of these lithologies have been plotted in Fig. 11E. The Silet-Taourirts are located between the island arc signature and the LATEA Archaean–Palaeoproterozoic basement or the Pan-African Ounane granodiorite that originated mainly from this basement (Liégeois et al., 2003, this issue). The Pan-African Anfeg granitoids defines a trend similar to that of the Taourirts but with a more negative mean ε_{Nd}.

3.3. Some constraints given by the Nd isotopes within the regional framework

Two immediate conclusions can be drawn:

(1) the seagull wing-shape REE patterns, typical of a late magmatic F- and Cl-rich fluid action, are accompanied by a shift towards less negative ε_{Nd}

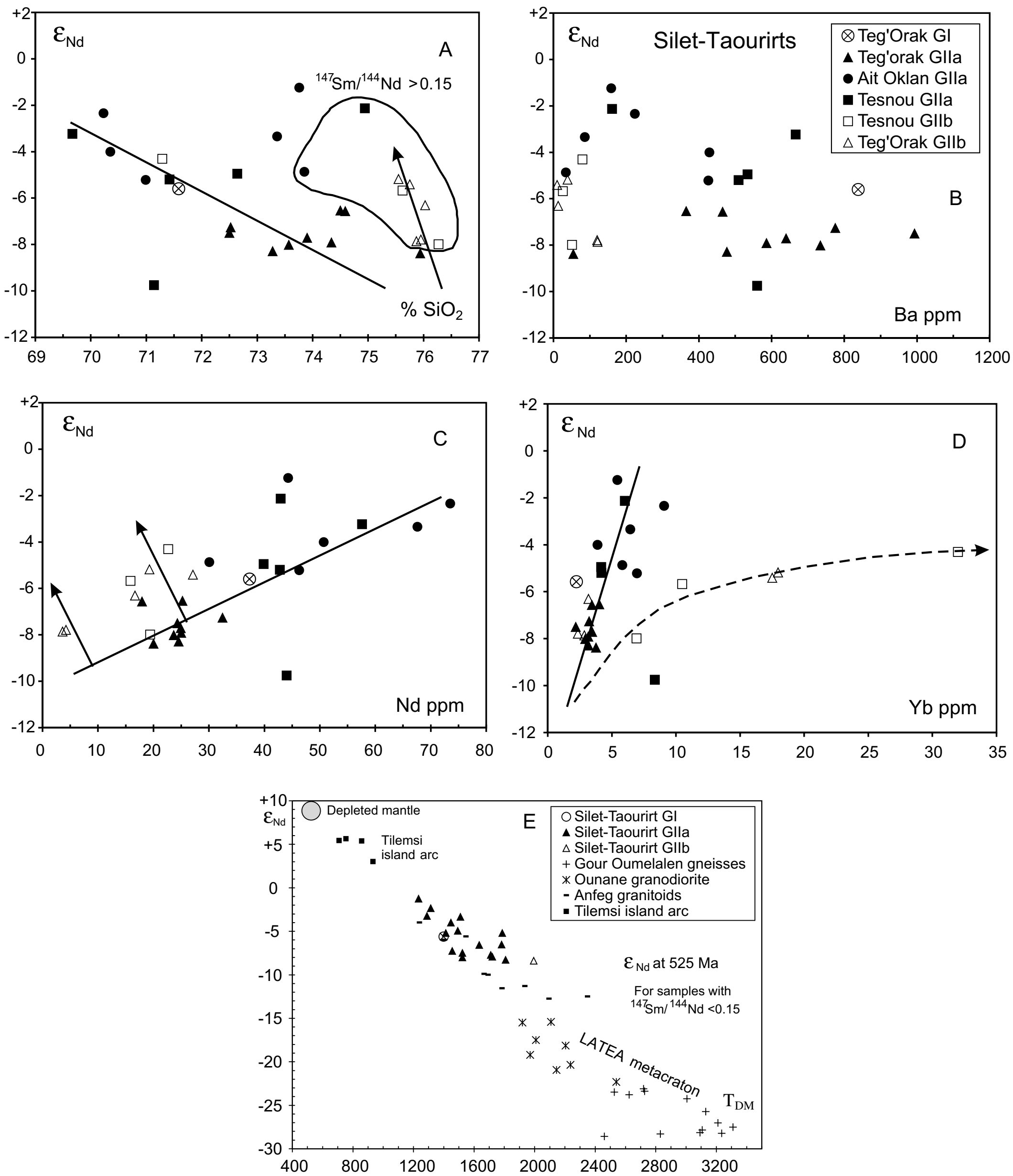

Fig. 11. Nd isotopes data. For A–D: symbols given in B. A: SiO_2 vs. ε_{Nd}; the line enhances the main Taourirt trend and the arrow enhances the trend made by subgroups IIb; B: Ba vs. ε_{Nd}; C: Nd vs. ε_{Nd}; the line enhances the main Taourirt trend and the arrows indicate the suggested effect of the basement (oceanic island arc) contamination; D: Yb vs. ε_{Nd}; the line enhances the main Taourirt trend and the hyperbolic arrow the trend made by subgroup IIb; E: T_{DM} vs. ε_{Ndd}; the Gour Oumelalen gneiss are from Peucat et al. (2003, this issue), the Ounane granitoids from Liégeois et al. (2003, this issue), the Anfeg granitoids from Acef et al. (2003, this issue) and the Tilemsi island arc rocks from Caby et al. (1989). Only samples with $^{147}Sm/^{144}Nd < 0.15$ have been used, excluding mainly the Silet-Taourirt GIIa subgroup.

values (Fig. 11A and C), indicating a major interaction with the upper crust, Pan-African island arcs for the Silet-Taourirts. Such an interaction would also be possible within the Laouni-Taourirts and the Tamanrasset-Taourirts, also showing seagull wing-shaped REE patterns (Fig. 5D–F). However, in the latter case, the country-rocks belong to the old LATEA metacraton. This could explain the differences observed among the Taourirt groups, as for example the absence of topaz-bearing leucogranites within the Silet-Taourirts as their country-rocks are much less aluminous than those of the Tamanrasset-Taourirts. This could also be an explanation for the high $^{87}Sr/^{86}Sr$ initial ratio postulated for the In Tounine pluton (0.724; Cheilletz et al., 1992) although this value has to be confirmed (Fig. 10F).

(2) The Nd isotopic signatures of the Silet-Taourirts imply the presence of an old crust at depth below the observed Neoproterozoic volcano-sedimentary sequences of the Iskel terrane. This is in agreement

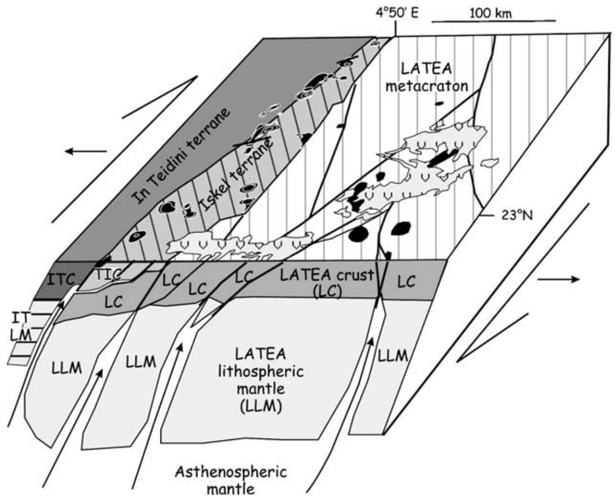

Fig. 12. Modelled 3D cross-section of Central Hoggar. The Iskel terrane is thrust onto the LATEA metacraton and has no proper lithospheric mantle. The LATEA metacraton has a thick cratonic lithospheric mantle (LLM) but has suffered linear lithospheric delamination along mega-shear zones during its dissection (metacratonization), corresponding to the main transpressional squeezing between the West African craton and the Saharan metacraton (mainly 620–580 Ma; Liégeois et al., 2003, this issue). At 539–523 Ma, the reworking of these shear zones during dextral transtensional shearing allowed the emplacement of the Taourirt province. Renewed linear delamination allowed the asthenosphere to rise, to melt by adiabatic pressure release and, due to the high heat flow, either to melt the lower crust or to deeply react with it, giving rise to the main common Taourirt isotopic signature (asthenosphere + old lower crust), whatever they intruded in: In Teidini terrane, Iskel terrane or LATEA metacraton. Recent volcanism could have originated in the same way. LLM = LATEA lithospheric mantle; LC = LATEA crust; TIC = overthrust Iskel crust; ITC = In Teidini crust; ITLM = In Teidini lithospheric mantle. The Taourirt plutons are in black. "V" are recent volcanic lavas.

with the model of overthrusting of the Iskel early island arc towards the LATEA metacraton (Liégeois et al., 2003; this issue; Fig. 12).

An important point concerning the LATEA metacraton is that it has not been affected by a major collisional regional metamorphism before the intrusion of the Taourirt plutons, having acted as a rigid body during the whole orogeny (Liégeois et al., 2003, this issue). LATEA became a metacraton at ≈615 Ma, age of the high-K calc-alkaline batholiths (Ounane and Anfeg types): LATEA has been dissected by mega-shear zones that induced several hundred of km of relative displacement, but preserved most of the thick lithospheric mantle, condition for a rigid behaviour (Black and Liégeois, 1993). Both Ounane and Anfeg plutons have been interpreted in that context as resulting from linear lithospheric delamination along mega-shear zones, allowing the hot asthenosphere to rise, to melt by adiabatic pressure release and to induce the melting of the Archaean or Palaeoproterozoic lower crust by a strong increase of the heat flow (Acef et al., 2003, this issue; Liégeois et al., 2003, this issue). The Ounane pluton (Fig. 11E) was derived mainly from the lower crust (Liégeois et al., 2003, this issue), while the Anfeg magma has been interpreted as having incorporated a larger amount of asthenosphere material, giving rise to a trend towards less negative ε_{Nd} (Acef et al., 2003, this issue).

Such a model could be adapted to the Taourirt province: reworking of the mega-shear zones provoked linear delamination, asthenosphere uprise and its partial melting due to adiabatic pressure release and either partial melting of the lower crust or strong interaction with it (Fig. 12). These late shear movements are marked by the intrusion of dyke swarms, ring complexes, molasses-filled small grabens and some spectacular tectonic effects on the complexes (Fig. 4C). All these features point to transtension (Fig. 12). This is confirmed by a magnetic susceptibly technique study (Djouadi et al., 1997), which indicated an intrusion during N–S dextral transtensional movements implying some rotation of the complexes (up to 30° for Tioueine). This is in contrast with earlier movements contemporaneous to large batholiths that were typically transpressional (Liégeois et al., 2003, this issue). In the Taourirt case, the lithosphere was already colder and thus less reactive, giving rise to a higher proportion of asthenosphere material in their mixed source (Fig. 11E). Such a model could also be applied to the recent volcanism, located on similar shear zones (Fig. 12), explaining why there is currently no thermal anomaly below Hoggar (Lesquer et al., 1989).

More data are needed, in particular for the Laouni-Taourirts and the Tamanrasset-Taourirts, to assess the model and to explain the differences observed in the subgroups. We can predict similar Nd isotopic values for these two Taourirt families as they belong to the same regional event and are also cross-cutting the LATEA metacraton (Fig. 12). Some difference however could arise from fluid-rich interactions with the country-rocks (positive ε_{Nd} and low Sr_i for the Silet-Taourirts, strongly negative ε_{Nd} and high Sr_i for the Laouni- and Tamanrasset-Taourirts). Differences in LATEA protoliths that were involved in the melting and in the proportion of the LATEA lower crust/asthenosphere should also be able to explain some observed differences. In western Hoggar, along the In Ouzzal metacraton (Fig. 1), the ≈592 Ma Tin Zebane late post-collisional alkaline–peralkaline dyke swarm has an asthenospheric signature (mean $Sr_i = 0.7028$, $\varepsilon_{Nd} = +6.2$, $T_{DM} = 646 \pm 31$ Ma; Hadj Kaddour et al., 1998). This is an important constraint to understand the chemical evolution observed within the Taourirt province.

4. Summary and conclusions

A post-collisional tectonic regime is characterized, prior to the final welding of the displaced terranes, by the continuation of the relative displacements and rotation of terranes often in an intracontinental setting (e.g., Liégeois, 1998 and references therein). In the whole Tuareg Shield, post-collisional igneous provinces with alkali-calcic or alkaline characteristics are widespread. The Taourirt magmatic province is the youngest post-collisional igneous event in the shield. It accompanied the latest deformations experienced by the central part of the shield along lithosphere-scale subvertical shear zones, such as the dextral 4°50′ E lineament and the conjugate faults, moving in transtension during the emplacement of the Taourirt province. The northern escape of the LATEA metacraton (Liégeois et al., 2003, this issue), bordered by oceanic domains and pinched in between the West African craton and the Saharan metacraton, was completed about 525 Ma ago and this end is marked by the intrusion of the Taourirt province.

Subsequent vertical movements along the north–south subvertical shear zones of the Tuareg Shield, resulting into slight deformations, angular unconformities and variations in the Tassilis sandstone thickness, are recorded in the sedimentary sequences (Beuf et al., 1971). Contemporaneous fluid circulations disturbed the Rb–Sr isotopic system of the Taourirts, which are located along the most active shear zones at the end of the orogeny. During the within-plate period, true within-plate alkaline magmatism occur mostly along older terrane boundaries. For example, Palaeozoic (≈410 Ma) ring complexes were emplaced along the western margin of the Saharan metacraton in Aïr (Moreau et al., 1994). Other boundaries were reactivated later on and triggered Permian to Mesozoic and Cainozoic within-plate magmatic episodes (Liégeois et al, 1991; Dautria and Girod, 1991).

Geochemical and Sr–Nd isotopic data demonstrate that it is correct to consider all the late high-level plutons from Central Hoggar as belonging to the same Taourirt province. It is however useful to divide the province into three parts (Silet-, Laouni-, Tamanrasset-Taourirts) to take into account the observed differences. Nd isotopes demonstrate the presence of the old LATEA basement below the whole province, implying that the Iskel early island arc terrane is thrust onto LATEA. A similar mixed deep source (asthenosphere + old lower crust) can then be ascribed to the whole Taourirt province. However, Nd isotopes indicate also that the most differentiated granites, showing high REE mobility (seagull wing-shaped REE patterns) due to F- and Cl-rich hydrothermal fluids, have strongly interacted with their country-rocks during emplacement. The nature of these country-rocks can also explain differences between Taourirt groups: Pan-African oceanic arcs for the Silet-Taourirts and old Archaean–Palaeoproterozoic LATEA metacraton for the Laouni- and Tamanrasset-Taourirts.

The Taourirt province can be linked as a whole to the same geodynamic environment, i.e. the last movements along the mega-shear zones that dissected the LATEA metacraton, which provoked linear delamination, asthenosphere uprise, leading to a mixed asthenospheric/old lower crust source. Differences, particularly in highly differentiated granites, should be linked to the contrasted nature of the country-rocks.

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Appendix A

After acid dissolution of the sample and Sr and/or Nd separation on ion-exchange resin, Sr isotopic compositions have been measured on Ta simple filament (Micromass Sector 54), Nd isotopic compositions on triple Ta–Re–Ta filament (Micromass Sector 54). Repeated measurements of Sr and Nd standards have shown that between-run error is better than 0.000015 (2σ). The NBS987 standard has given a value for $^{87}Sr/^{86}Sr$ of 0.710275 ± 0.000006 (2σ on the mean, normalized to $^{86}Sr/^{88}Sr = 0.1194$) and the MERCK Nd standard a value for $^{143}Nd/^{144}Nd$ of 0.511730 ± 0.000010 (2σ on the mean, normalized to $^{146}Nd/^{144}Nd = 0.7219$) during the course of this study. All measured ratios have been normalized to the recommended values of 0.710250 for NBS987 and 0.511963 for Nd Merck standard (corresponding to a La Jolla value of 0.511858). Sm and Nd concentrations were measured by isotope dilution. The error on the Sm/Nd ratio is ~4%. Used decay constants are 1.42×10^{-11} a^{-1} (^{87}Rb) and 6.54 10^{-12} a^{-1} (^{147}Sm). Sr and Nd isotope ratios are reported in Table 1.

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