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The subduction- and collision-related Pan-African composite batholith of the Adrar des Iforas (Mali): a review

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A large composite calc-alkaline batholith, in the Iforas region, Mali, occurs close to the Pan-African suture between the 2000 Ma old West African craton and the Trans-Saharan mobile belt. Its location in an embayment of the West African craton is probably responsible for the important production of magma. The Iforas batholith intrudes the western border of an old continental segment affected by early nappe tectonics (D1 event) and is flanked to the west by the Tilemsi palaeo–island arc. The batholith comprises several successive stages. The cordillera (>620 Ma), probably post-dating the D1 event, is essentially composed of volcanosedimentary sequences. The collision (620–580 Ma) is marked by the production of abundant granitoids mostly emplaced by the end of the D2 EW compressional event. The post-collision tectonic stages (D3 and D4; 580–540 Ma) are characterized by strike-slip movements, reversals in the stress field, and a rapid switch from calc-alkaline to alkaline magmatism. Magmas corresponding to each step show distinctive geochemical trends but all share low $^{87}Sr/^{86}Sr$ initial ratios (0·7035–0·7061). The possible successive sources have been evaluated from different entities in the Inforas region: Eburnean granulites for lower crust, Tilemsi palaeo–island arc for depleted subduction source and the Tadhak undersaturated province for asthenospheric more primitive mantle. A geodynamic model is proposed where all the calc-alkaline groups originated from a classical subduction source (depleted upper mantle modified by hydrous fluids from the subducted oceanic plate) which, some fifty million years after the beginning of the collision, was taken over by an asthenospheric source producing the alkaline province.

KEY WORDS Wilson cycle Calc-alkaline to alkaline magmatism Contrasting stress regimes End Pan-African Iforas batholith, Mali

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1. Introduction

The Pan-African orogeny (± 600 Ma) is the oldest period where the complete Wilson cycle of large-scale plate tectonics is well established. The complete cycle occurred in the Trans-Saharan belt along the eastern margin of the West craton (see review by Cahen *et al.* 1984; Black *et al.* 1979; Caby *et al.* 1981), and accreted island arc material in the Arabian-Nubian shield (Greenwood *et al.* 1976; Duyverman *et al.* 1982). A striking feature of the Adrar des Iforas is the presence, 100 km to the east of the suture zone, of a large batholith (Figure 1) which displays a complete record of calc-alkaline magmatism exposed at different structural levels, linked respectively to subduction, collision, and finally post-collision stages, with a rapid switch to alkaline within-plate magmatism 50 Ma after oceanic closure.

Since the excellent pioneering work by Karpoff (1961) and Radier (1957), research over the last ten years has led to the publication of a new geological map (Fabre *et al.* 1982) and in this paper reference is made to some key areas where problems have been studied in some detail. The joint gravity survey carried out in the region provided some good constraints especially on the shape and extent of buried basic bodies which outline the suture zone and on the structure of the batholith (Bayer and Lesquer 1978; Ly *et al.* 1984).

The tentative synthesis of the batholith presented here is the result of two convergent approaches. JPL and RB, after detailed studies of the alkaline ring-complexes and associated dyke swarms, have worked backwards in time focusing their attention on the calc-alkaline–alkaline transition; JMB, starting from the early nappe structure, has moved forward in time, paying particular attention to the structural control of the early stages of emplacement of the batholith.

2. Geological Setting

2a. The setting of the batholith in the Iforas segment

The Iforas segment may be subdivided from west to east into three domains (Figure 1):

- The Tilemsi 'accretion domain' which is the result of the tectonic evolution of an island arc (Caby 1981); metabasalts and serpentinites of oceanic origin also occur to the west of the suture in nappes translated onto the West African craton (Taounnant, Timetrine; Caby 1978; Caby *et al.* 1981).
- The central Iforas domain, which is characterized at least in its eastern part, by the occurrence of early intracontinental deformation involving basement nappes and associated metamorphic reactivation (Boullier *et al.* 1978; Boullier 1982). The Iforas composite batholith, whose relationships with the surrounding gneisses show complex tectonic and plutonic interactions (Bertrand and Wright 1986), occupies the western half of the Central Iforas. It incorporates pendants of gneiss and belts of low-grade volcanosedimentary rocks (e.g. Tafeliant Group, Oumassene Group; Fabre 1982).
- The Eastern Iforas, delimited by the Adrar fault, forms the southern prolongation of the eastern branch of the Pharusian belt defined in the Hoggar (Caby *et al.* 1981; Bertrand and Caby 1978; Davison 1980; Caby *et al.* 1985).

2b. Lithological environment of the batholith

High-grade and low-grade formations are juxtaposed in the Central Iforas (Figures 1 and 2) and are separated by stratigraphical unconformities (Tafeliant,

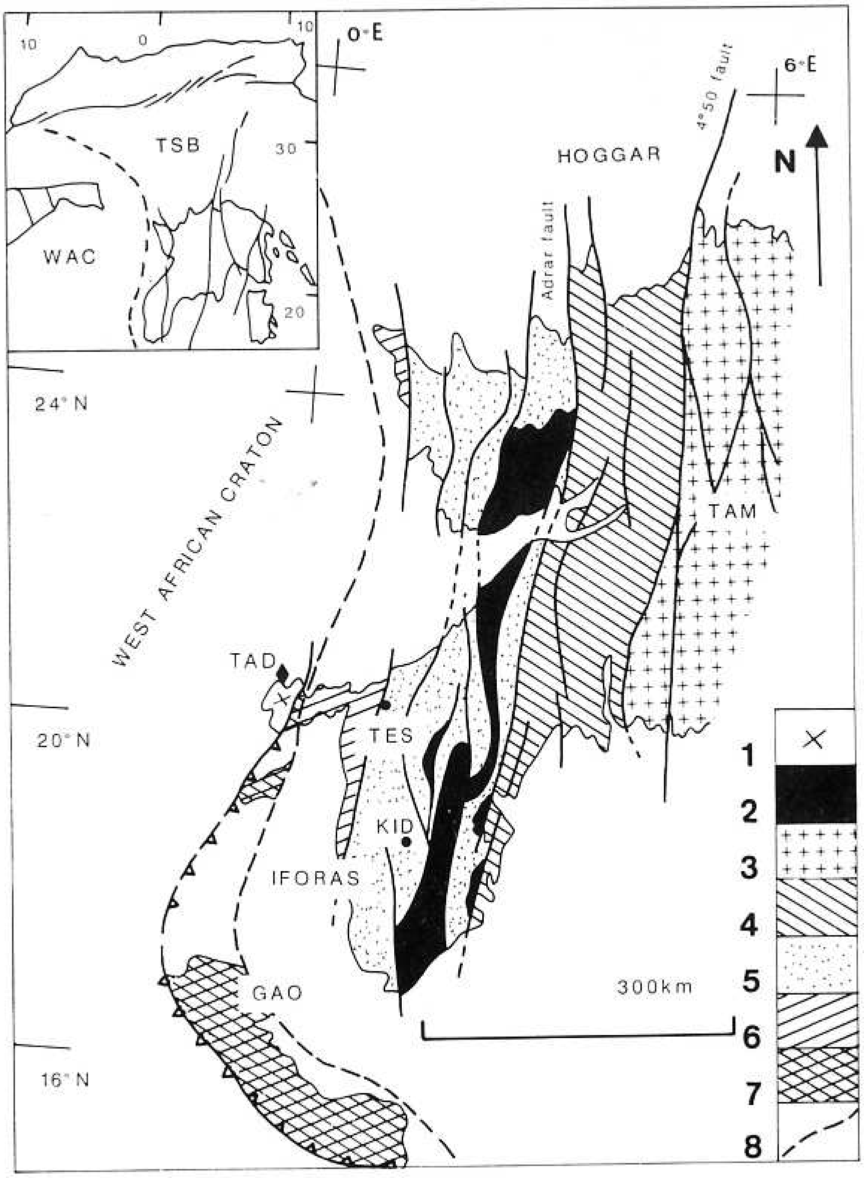

Figure 1. Sketch map of the northern part of the Trans-Saharan belt. 1) Eburnean gneisses of the West African craton. 2) Eburnean granulites within the mobile belt. 3) Reactivated pre-Pan-African basement of the Central Hoggar. 4) Eastern branch of the Pharusian belt. 5) Western branch of the Pharusian belt. 6) Tilemsi island arc. 7) Gourma and Timetrine nappes. 8) Suture zone. WAC= West African craton; TSB=Trans-Saharan belt; TAM=Tamanrasset; TES=Tessalit; KID=Kidal; TAD=Tadhak.

Ourdjan), tectonic contacts, or large areas of plutonic intrusives.

Amongst the high-grade rocks, the Iforas Granulitic Unit (IGU) is of Eburnean age (Lancelot *et al.* 1983) and is generally non-penetratively deformed and retrogressed during the Pan-African orogeny (Davison 1980; Boullier 1982). According to these authors the IGU forms a large-scale early nappe emplaced onto another high-grade complex, the so-called Kidal Assemblage. This latter unit is a 'sack term' for an association of different lithologies whose common features are polyphased deformation and high-grade metamorphism. It comprises, together with ubiquitous gneisses (reactivated granulites), abundant pretectonic intrusives and some highly deformed lenses of metasediments (quartzites, marbles and meta-

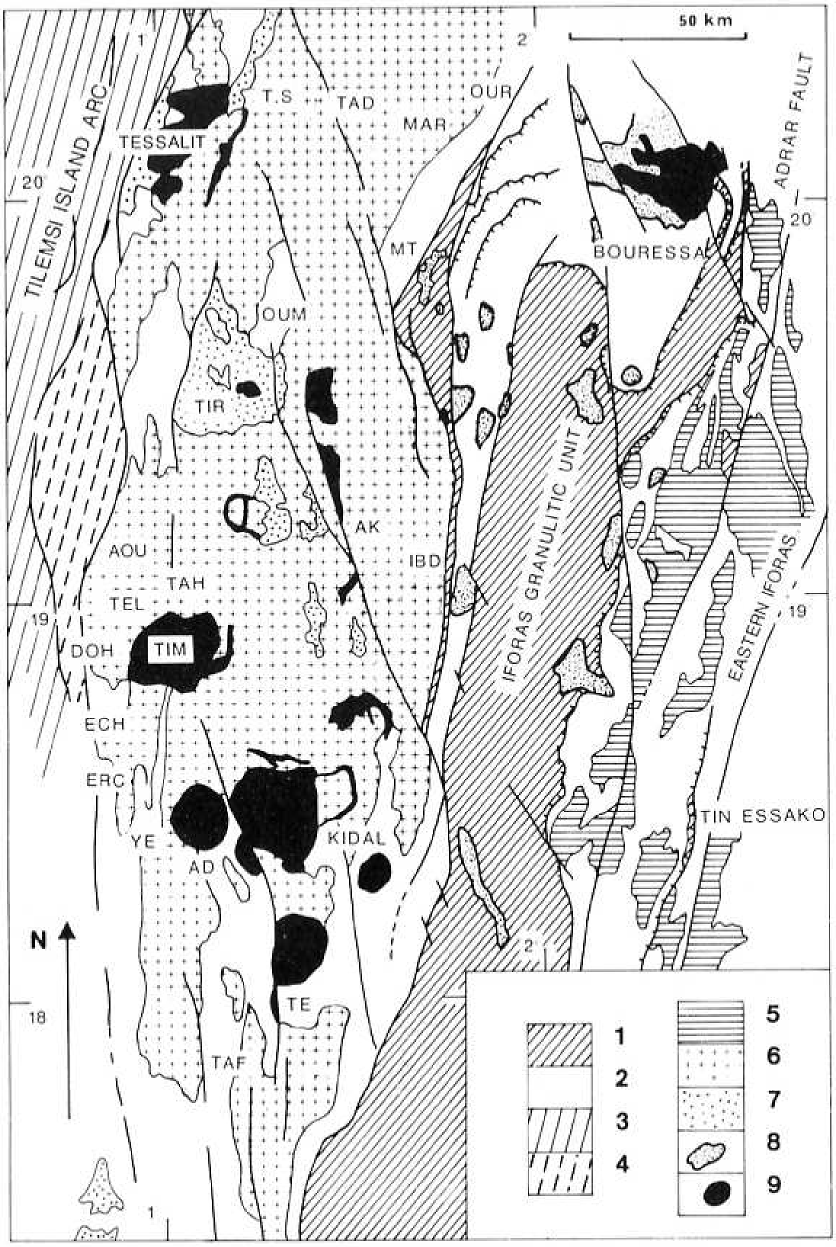

Figure 2. Sketch map of the Central Iforas. 1) Eburnean granulites (Iforas granulitic unit (IGU), Bezzeg unit, Tin Essako unit). 2) Undifferentiated schists and gneisses. 3) Volcanic and associated plutonic bodies of the Tilemsi island arc. 4) Aguelhoc gneisses. 5) Pan-African plutonic bodies of the eastern part of Central and Eastern Iforas, undifferentiated. 6) Iforas composite batholith. 7) Rhyolite flows. 8) Post-tectonic plutons in the Kidal Assemblage and in the IGU. 9) Alkaline ring-complexes. Localities quoted in the text: AD=Adma; AOU=Aoukenek; AK=Akoumas; DOH=Dohendal; ECH=Echaragalen; ERC=Erecher; IBD=Ibdeken; MAR=Mareris; MT=Mareris-Tichedait volcano-sedimentary unit; OUM=Oumassene; OUR=Ourdjan; TAD=Tadjoudjemet; TAF=Tafeliant; TAH-=Tahrmert; TE=Teggart; TEL=Telabit; TIM=Timedjelalen; TIR=Tiralrar; T.S.=Tin Seyed; YE=Yenchichi.

pelites) assoicated with orthoamphibolites. Old supracrustals rocks which may have been affected by amphibolite facies metamorphism, include a sequence of aluminous quartzites, pelites and metarhyolites or alkaline leptynites which have been dated at 1837 ±13 Ma (Caby and Andreopoulos-Renaud 1983) and a unit characterized by the association quartzite–marble, with some pelites, meta–arkoses and minor volcanics, similar to the 'Série à Stromatolites' of northwest Hoggar (Caby 1970) traditionally attributed to the early Upper Proterozoic. This sequence is well developed on the eastern edge of the batholith and to the east of the IGU where it occurs as high level nappes overlying the granulitic unit; its deformation history is similar to that of the Kidal Assemblage. A similar unit displaying greenschist facies metamorphism may also be observed as a narrow monocline resting stratigraphically on top of the IGU 50 km ENE of Kidal.

The low-grade rocks comprise several volcanosedimentary units: the Tafeliant Group, a shallow sea clastic sequence containing a tillite, felsic and basic flows and dykes, which occurs as a N–S belt measuring 150 × 10 km between the Timedjelalen and Takellout complexes (Fabre 1982; Ball and Caby 1984); The Oumassene Group, a continental sequence composed essentially of andesites and subordinate pyroclastics; a volcanic sequence consisting mainly of dacites and rhyolites in the Mareris–Tichedait region and greywackes in the Ourdjan area. Along the western margin of the batholith, long and narrow belts of volcanics and greywackes have not been described in detail. They are unconformably overlain by molassic type formations (Echaragalen, Fabre *et al.* 1982). Large unconformable plateaux of rhyolite flows and ignimbrites (Tiralrar, Figure 2) are part of the late alkaline province and were previously called Nigritian by Karpoff (1960). Small undeformed basins of molassic red arkoses and conglomerates attributed to the Cambrian by comparison with the similar 'Série Pourprée' of northwest Hoggar (Caby 1970) are preserved along the major N–S shear zones.

2c. The structural evolution of Central Iforas

A succession of four main tectonic events has been recognized in the Central Iforas (Boullier *et al.* 1978; Davison 1980; Boullier 1979, 1982; Boullier *et al.* 1986; Champenois *et al.* 1986).

— The first event, D1, is characterized by the emplacement of large northward verging nappes, involving the 2000 Ma old Eburnean granulites (IGU). The lower and higher grade part of the nappe pile corresponds to the Kidal assemblage, while the upper nappes (Ibedouyen area) are metamorphosed under greenschist facies conditions. A possible equivalent of these upper nappes is known in the Ourdjan area (see Figure 2). The dating of the D1 event is a major problem as Rb–Sr and U–Pb isotopic systems have apparently been reset during a D2 event (Bertrand and Dautel unpublished data) and as a consequence are poorly constrained.

— The D2 event is compressional and varies in time from a SE–NW to a E–W shortening direction. It is clearly related to the collision and took place *c.* 600 Ma ago (Bertrand and Davison 1981; Bertrand *et al.* 1984b; Liégeois abnd Black 1984). In the Tafeliant area, the compressional deformation is accompanied by a sinistral N–S movement which can be confined to an age range between 620 + 8/−5 Ma (U/Pb on zircon age) and 595 ± 24 Ma (Rb–Sr whole rock isochron). These ages have been obtained from the late-tectonic Adma pluton (Figure 2) emplaced in the volcanosedimentary formation (Andreopoulos-Renaud in preparation; Liégeois and Black 1984). In the northern part of the batholith, Bertrand and Wright (1986) describe a large-scale dome-like structure, which is attributed to this phase of deformation.

— The D3 event corresponds to a reversal in the stress field expressed by dextral strike-slip movements along N–S to N20° shear zones and faults whose age has been estimated in the range 566–535 Ma (Lancelot *et al*, 1983). The shortening direction is NE–SW but rotates with time to E–W (e.g. in the Abeibara– Rharous shear zone; Boullier 1985).

— The last D4 tectonic event occurred in brittle conditions producing a conjugate set of strike-slip faults, the shortening direction having swung back to NW–SE. The spectacular intrabatholitic E–W and N–S acid dyke swarms were emplaced between the D3 and D4 event and are related to the rotation of the stress field (Boullier *et al.* 1986). The age of 545 ±16 Ma obtained in the Yenchichi area (Liégeois and Black 1984) probably dates the D4 event. The D4 event can be attributed to the last stage of the collision between the West African craton and the mobile belt (Ball 1980) even if these structures have been reactivated during the Phanerozoic.

An alternative interpretation has been proposed by Ball and Caby (1984), who dismiss the distinction between D1 and D2. They consider that the N–S trending open folds in the Tafeliant volcanosedimentary formation are the shallow expression of recumbent folds at depth, the entire edifice having resulted from continuous deformation. These features are interpreted as the result of underthrusting of the Kidal Assemblage below the Tafeliant unit. More precise geochronological constraints for the early stages are necessary to resolve this problem.

3. Petrology, geochronology and geochemistry

A summary of the magmatic succession is given in Table 1.

3a. Pre-D1 intrusives

The Kidal Assemblage, which outcrops along the eastern margin of the batholith (Figure 2), includes metatonalites associated with metatrondhjemites, gneisses, metasediments, metavolcanites, metagabbros, and ultramafites. All these rocks show polyphase structures only compatible with a pretectonic character. Between the northeastern margin of the batholith and the northern tip of the IGU, metatonalites occur as thick sheets displaying an easterly gently dipping foliation (30° to 50°) and have undergone complete recrystallization in amphibole facies conditions. No syntectonic intrusives have been recognized so far; metatonalites display only local partial melting during the D1 event. D1 features, which have been intensely overprinted by the D2 deformation and annealed by high-grade low-pressure metamorphism, can be found in numerous gneissic pendants within the batholith, east of a N–S line joining Tadjoudjemet and Kidal (Figure 2).

Even if the D1 nappe emplacement tectonics is related to the main collision (*ca.* 600 Ma), it is not clear whether or not the metatonalies of the Kidal Assemblage are linked to the subduction process. Indeed, all attempts to date these intrusions have failed, either by Rb–Sr whole rock dating or by U–Pb on zircon (Bertrand and Dautel unpublished results). Only the $^{87}Sr/^{86}Sr$ ratios 600 Ma ago can be estimated to be between 0·705 and 0·707. The geochemistry of the D1 pretectonic intrusions is characterized by low-K_2O content (1·3 to 2·0 per cent) and very little correlation with silica (Bertrand *et al.* 1984b). The trend shown on the SiO_2 versus K_2O diagram (Figure 3) and in the Q–F diagram (Figure 4) may be compared with those of the tonalite–trondhemite suite (Barker 1979).

Furthermore, geochemical data (major, trace, Ree elements) on the surrounding amphibolites which are regarded as metavolcanics show clear affinities suggesting

Table 1: Magmatic succession in the Iforas batholith

(R)Yenchichi 1 granite	S	544±16Ma	(0·7063±5)	(D4 tectonic)
(I)Timedjelalen ring-complex	C	549±6Ma	(0·7051±5)	
(I)Kidal ring-complex Lavas	S	561±7Ma	(0·7061±7)	WEAK EXTENSION
(I)N–S dykes	C	543±9Ma	(0·7050±3)	
(I)Tahrmert alkaline granite	C	541±7Ma	(0·7061±4	
(I)Yenchichi 2 syeno-granite	S	577±14Ma	(0·7038±10	
(I)E–W dykes:				
Telabit	C	544±12Ma	(0·70505±10)	UPLIFT
Dohendal	C	556±10Ma	(0·70511±12)	
Yenchichi	S	565±14Ma	(0·7048±5	
(EC)Aoukenek monzo-granite	C	591±18Ma	(0·7035±5)	(D3 tectonic)
(EC)Iforas monzogranite	C	"error chron"	(0·7042 to 0.7053)	
(EC)Adma granodiorite	S	595±24Ma	(0·70482±26)	COLLISION
(EC)Tin Seyed Q-monzodiorite	N	581±15Ma	(0·70530±14)	(D2 tectonic)
(E) Erecher tonalite	S	602±13Ma	(0·70590±8)	
(R)Ibdeken granodiorite	S	613±29Ma	(0·7057±2)	
(BC)Adma granodiorite	S	620±6Ma	(Andreopoulos-Renaud in preparation)	
(I)Yenchichi 1 granite	S		(<0·704)	
(E)Erecher tonalite	S		(<0·705))	SUBDUCTION
(I)Ibdeken granodiorite	S		(<0·705)	
(I)Tafeliant dykes	S	634+15Ma	(0·70505+6)	
(I)Teggart Q-diorite	S	696±5Ma	(Caby and Andreopoulos-Renaud, 1985)	(D1, tectonic)
(I)Pre-D1 intrusives	K	?		

(Q) = model quartz
(R) = rehomogenization
(EC) = end of crystallization
(BC) = beginning of crystallization
(I) = intrusion

The chronological order of this table is based on field relationships.
N=northern part of the batholith; C=central part; S=southern part.
K=Kidal Assemblage (just east of the batholith).

an extensional environment for the Kidal Assemblage pre-D1 metavolcanics and intrusives (Leterrier and Bertrand 1986). It should be noted, however, that there are examples of deformed plutons along the eastern margin of the batholith such as in the Mareris area which have slightly higher K_2O content and display trends intermediate between the Kidal metatonalites and the batholith in the K_2O versus SiO2 and Q – F diagrams. Although texturally indistinguishable from the Kidal Assemblage metatonalities, a cordilleran origin cannot be entirely dismissed.

3b The cordillera episode

This stage is characterized by volcanoclastic or volcanic deposits (Fabre 1982) representing marine, aerial or subaerial environments (Tafeliant Group, Oumassene Group, Ourdjan area, respectively). The Oumassene group is composed mainly of continental andeites with intercalated pyroclastics (Chikhaoui 1981).

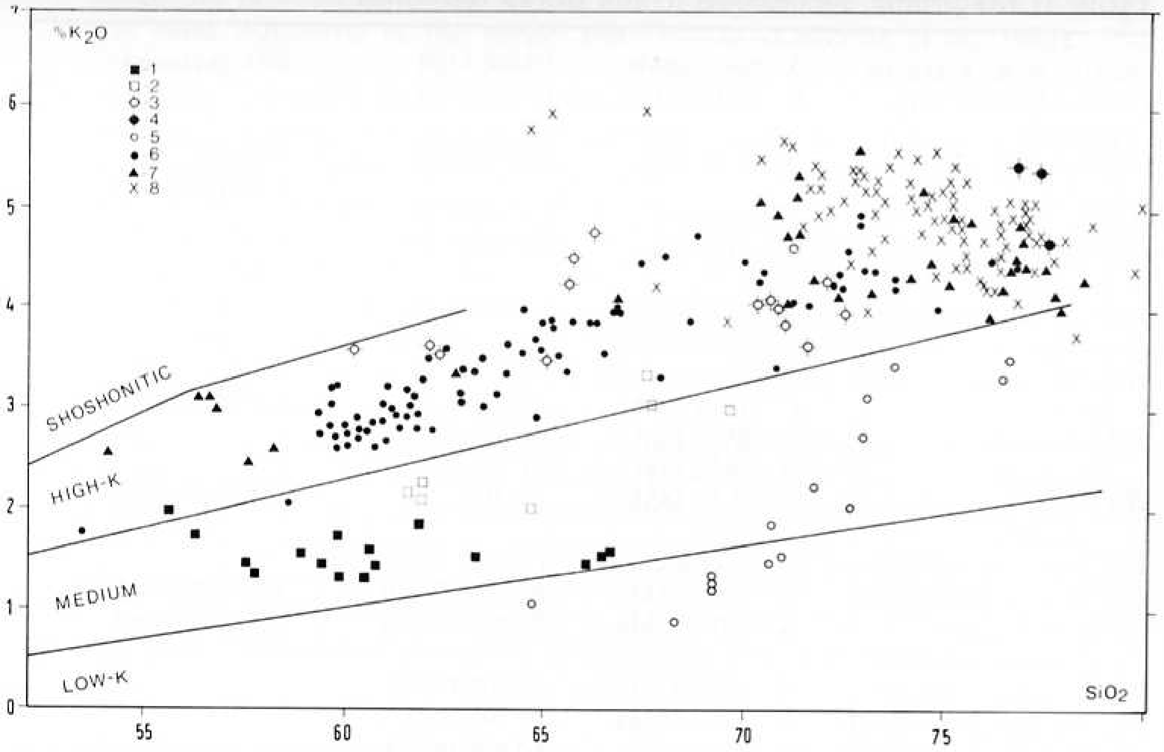

Figure 3. K_2O versus SiO_2 diagram. The field boundaries are from Ewart (1979) 1) Pre-tectonic metatonalites from the Kidal Assemblage. 2) Pre-D1 Marcris quartz-metadiorites. 3) Pre-D2 Ibdeken quartz-monzodiorites and granodiorites. 4) Pre-D2 RAPU. 5) Pre-D2 Erecher tonalite. 6) Late-D2 granitoids (from quartz-monzodiorites to monzo-granites). 7) Post-D2 high-level plutons and E–W dykes. 8) Post-D2 alkaline N–S dykes and ring-complexes

Dykes and sills, intruded in the Tafeliant formation, have been dated at 634 ± 15 Ma (Liégeois, Fabre and Caby work in progress).

The degree of the diachronism among these basins is unknown; however, all the volcanosedimentary sequences found within the batholith are monocyclic and, as in the case of the Tafeliant Group, are believed to lie unconformably upon deformed gneisses and on Upper Proterozoic sediments.

By contrast, large cordilleran-related plutons are scarce, the Iforas batholith being essentially late- to post-tectonic in character, with emplacement occurring after oceanic closure. Essentially three plutons have been recorded and studied, which share the pre-D2 character. The Teggart quartz-diorite (Figure 2) is the older, situated beneath the unconformity of the Tafeliant Group and has been dated at 696 ± 6 Ma (Caby and Andreopoulos-Renaud 1985). The detailed chemistry of this pluton has not yet been studied. This intrusion has been previously considered as having a syn-D1 character (Boullier *et al.* 1978; Caby *et al.* 1981) but recent observations show it to be earlier than the nappe structures (Caby and Andreopoulos-Renaud 1985).

The other two plutons are widely separate, one near the island arc boundary to the west, the other on the eastern edge of the batholith, not far from the Iforas Granulitic Unit. If the former (Erecher tonalite, Liégeois and Black 1984) is clearly intrusive into a volcanosedimentary sequence, the latter (Ibdeken quartz-monzodiorites and granodiorites) has no field relationships with such sequences.

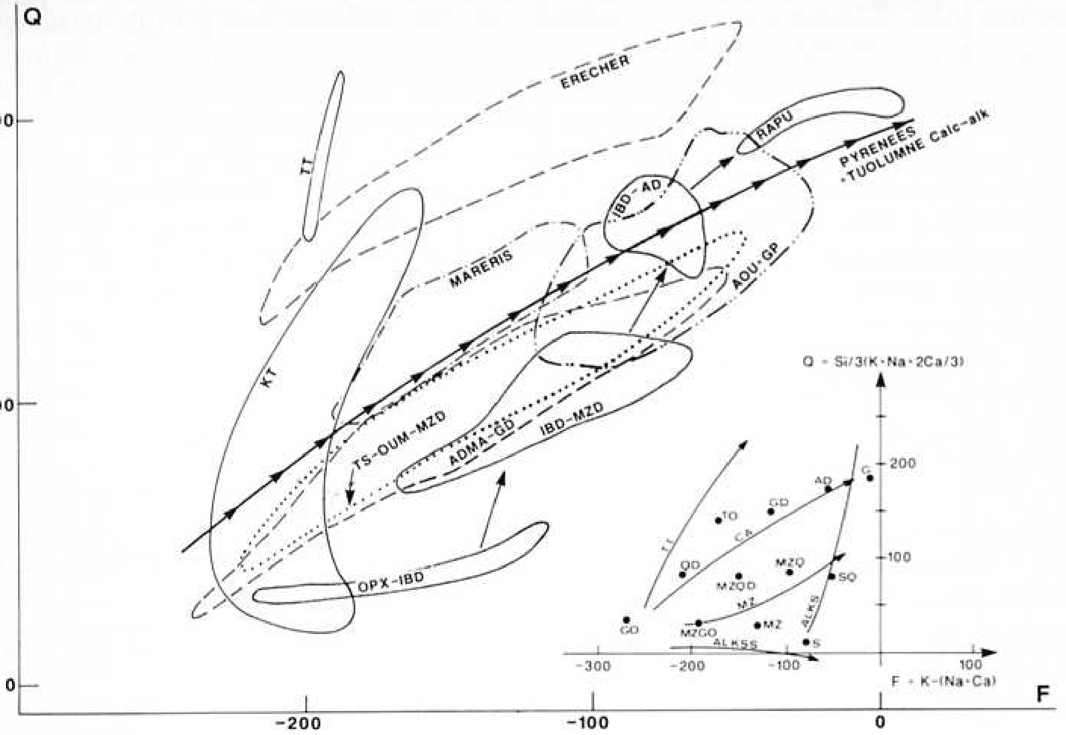

Figure 4. Q–F diagram (expressed in millications = gram-atoms × 10^3 in 100 g of rock or mineral, La Roche (de) 1962). Standard locus and terminology are from Debon and Le Fort (1983). Some typical suites are given in the insert where: Tr=tholeiitic (tonalite) suite from Afghanistan (Debon and Le Fort, 1983); CA=calc-alkaline suite from French Pyrénées (Debon, 1980); MZ=high-K suite from Vosges (Pagel and Leterrier 1980); ALKS=alkaline oversaturated suite from Afghanistan; ALKSS=alkaline saturated suite from Afghanistan (Debon and Le Fort 1983). In the main diagram: KT=metatonalites from the Kidal Assemblage; TT=particular metatonalites from the Kidal Assemblage (Bertrand *et al.* 1984a); OPX–IBD=OPX-bearing Ibdeken quartz-monzodiorites; IBD–MZD=Ibdeken quartz-monzodiorites; IBD–AD=Ibdeken granodiorites; TS–OUM–MZD=Tin Seyed quartz-monzodiorites; ADMA–GD=Adma granodiorite; AOU–GP=porphyritic monzogranite and Aoukenek fine-grained monzogranite; RAPU=red aplo-pegmatitic unit.

The two plutons give similar Rb–Sr whole rock ages, attributed to a resetting of the isotopic system during the D2 deformation related to the collision with the West African craton, the initial ratios being then considered as maximum values: Erecher tonalite: 602 ±13 Ma (Ri = 0·7059 ±8, 9WR, MSWD=1.0, Figure 7; Liégeois and Black 1984); Ibdeken quartz-monzodiorite: 613 ±29 Ma (Ri= 0·7057 ±2, 7WR, MSWD=1.6, Figure 5, Table 2).

The two units display different geochemical trends which may be explained by the variation of the K_2O associated with the spatial distribution of granitic plutons (Dickinson and Hatherton 1967). The main discrimination is the content in K_2O vs h where h is a measure of the vertical distance from the inferred subduction trench zone. More precisely, the Erecher tonalite (Liégeois and Black 1984) is characterized by a relatively high SiO_2 mean content and by the evolution of the more basic terms in the low-K calc-alkaline field and by a rapid enrichment in K_2O in the more felsic samples (Figure 3). In a general way, the Erecher tonalite displays a particular trend intermediate between a classical cordilleran magmatism and various island arc patterns. The location of this pluton along the western border of the batholith, near the island arc, could explain this feature. All

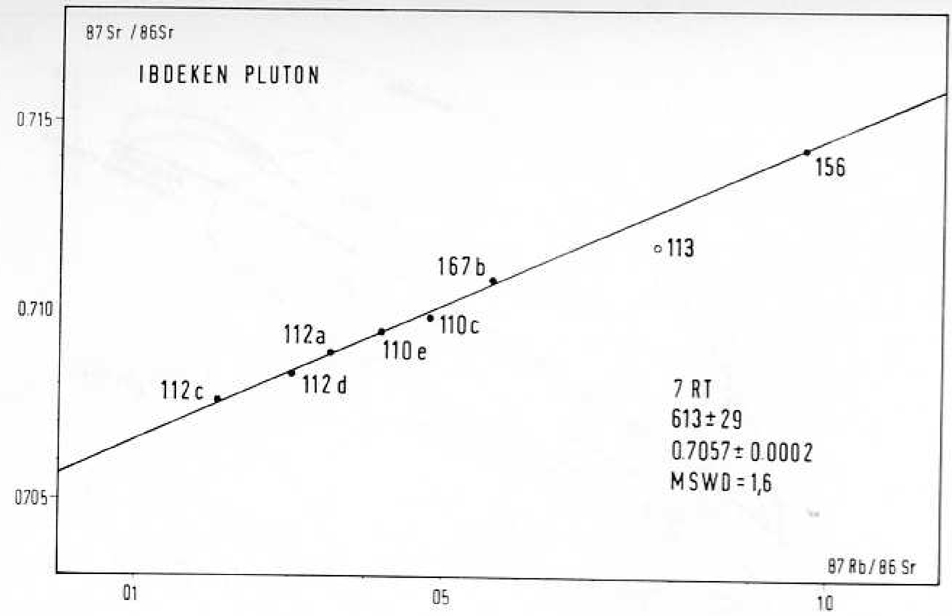

Figure 5. Rb–Sr isochron of the D2 pretectonic Ibdeken pluton (rehomogenization age). See Table 1 and appendix.

Table 2. Rb–Sr isotopic results for the Ibdeken and the Tin Seyed plutons

Sample	Rb ppm	Sr ppm	$^{87}Sr/^{86}Sr$	$\pm 2\sqrt{m}$	$^{87}Rb/^{86}Sr$
Ibdeken pluton					
Q110c	113	678	0·70979	0·00004	0·4824
Q110e	94	648	0·70941	0·00006	0·4198
Q112a	76	622	0·70887	0·00004	0·3536
Q112c	70	960	0·70761	0·00007	0·2110
Q112d	85	813	0·70829	0·00004	0·3025
Q113	138	513	0·71167	0·00004	0·7787
Q156	158	463	0·71423	0·00006	0·9946
Q167b	106	545	0·71080	0·00006	0·5630
Tin Seyed pluton					
JPL 499	96	629	0·70884	0·00006	0·4417
JPL 501	86	620	0·70854	0·00004	0·3995
JPL 502	97	525	0·70976	0·00004	0·5320
JPL 503	115	442	0·71140	0·00004	0·7531
JPL 505	124	460	0·71181	0·00004	0·7803
JPL 506	90	656	0·70859	0·00004	0·3983
JPL 507	152	343	0·71597	0·00004	1·283
JPL 508	174	311	0·71866	0·00005	1·621
JPL 509	136	374	0·71500	0·00005	1·053
JPL 510	78	685	0·70807	0·00004	0·3287
JPL 511	103	535	0·71005	0·00004	0·5572
JPL 512	157	330	0·71636	0·00004	1·378

the geochemical and geological characteristics indicate that the Erecher tonalite originated during the building of the cordillera; its geochemical and isotopic signature can then be taken to infer the characteristics of the subduction source near the trench. More data are necessary to define the problem, but the Ibdeken pluton is a good candidate to constrain the subduction source far from the trench.

In the same area as the Ibdeken pluton, there is an intricate altered and often highly deformed complex composed of aplitic and pegmatitic dykes and of leucogranitic pegmatitic irregular stocks. There is a possible genetic link between the RAPU (Red Aplo-Pegmatitic Unit) and the Ibdeken pluton following Bertrand and Wright (1986) and in this case, the RAPU may be considered to be similar to the Jaglot complex in the Kohistan arc of the Himalayas which is interpreted as the root of a cordillera (Petterson and Windley 1985). In view of the lack of constraints, however, a crustal origin for the leucocratic material cannot be excluded.

3c. The collision period: late-tectonic magmas

Granitoids of this group make up the bulk of the batholith. Although an absolute diachronism has possibly occurred in different areas of the batholith (250 × 100 km in size), the same relative chronology of intrusive phases has always been observed with an evolution from more basic to acid compositions. The whole group is intrusive into volcanosedimentary sequences with the frequent development of contact aureoles except when, as in the northern part of the batholith (Tin Seyed area), pendants of volcanites have been previously migmatized during D2.

Unlike the country rocks most of these intrusions have not undergone the climax of the D2 collision tectonics and are considered as 'late tectonic'. Liégeois and Black (1984) have described a two-stage crystallization, the older one being broadly contemporaneous with deformation while the younger was post-tectonic (Adma granodiorite, porphyritic granite).

New geochemical and isotopic data have been obtained on the Tin Seyed quartz-monzodiorite N–S plutonic alignment which stretches from the Oumassene andesites in the south to Tin Seyed. This band, comprising of three units generally showed undeformed or slightly deformed textures, except in narrow zones, and is composed of plagioclase, microcline, green hornblende and biotite, and rare quartz. Sphene, apatite and Fe–Ti oxides are common accessory minerals. An 11 point Rb–Sr isochron on the southern part of the Tin Seyed alignment, gave an age of 581 ±15 Ma (Ri = 0·70533 ±0·00014, MSWD=0·9, Figure 6, Table 2), which is within the range of other late-tectonic pluton ages shown in Figure 7 (Liégeois and Black 1984). The Sr initial ratios are all similar (0·7053−0·7048).

The main Iforas porphyritic granite which occurs all over the batholith and is particularly well developed in its western part, also shows, although less clearly, the two steps of crystallization, but is intrusive in the Tin Seyed quartz-monzodiorites. It yields only an errorchron for various reasons (discussed in Liégeois and Black 1984). However before the central part of the batholith was completely consolidated, it was intruded by the fine-grained Aoukenek granite with an estimated Sr initial ratio in the range 0·7042 – 0·7053. Bertrand and Davison (1981) have recognized subhorizontal layering of granodiorites and porphyritic monzogranites in the Tadjoudjemet area of the northern part of the batholith. This feature suggests sheet-like intrusion, parallel to the main foliation in the high-grade metavolcanics (interpreted as S2 by Bertrand and Wright 1986), with the porphyritic granite emplaced after the granodiorites. The area is cut by small bodies of fine-grained biotite granite. The heterogeneity of this area (from

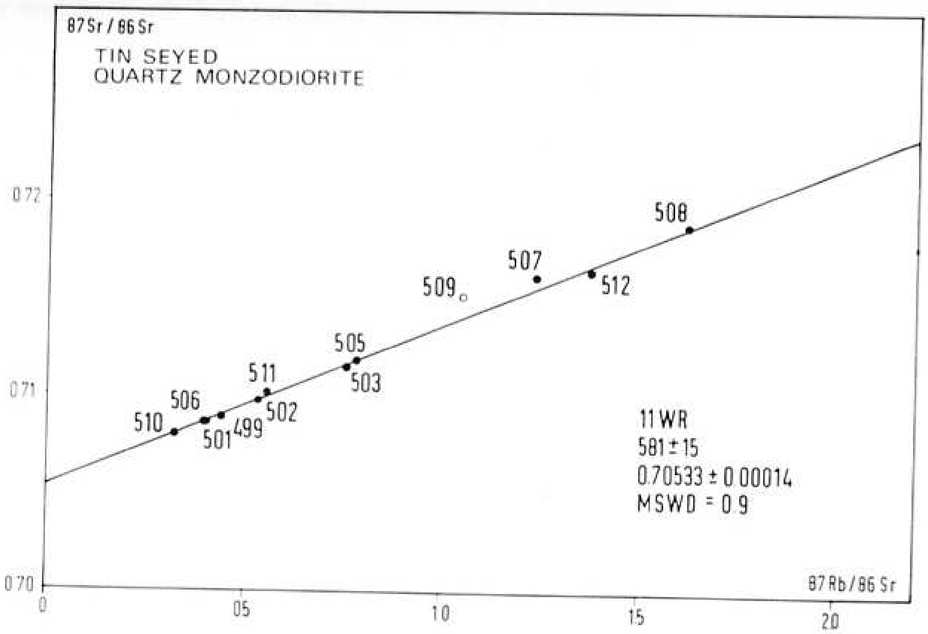

Figure 6. Rb–Sr isochron of the Tin Seyed late-tectonic quartz-monzodiorite. See Table 1 and appendix.

hornblende-bearing granodiorite to leucocratic varieties) probably explains the errorchron defined by the Rb–Sr method on seven whole rock samples (613 ±45 Ma, Bertrand and Davison 1981) and the scatter of the samples on most of the geochemical diagrams. Two samples of the porphyritic granite seem to suggest higher initial ratios, but more field and geochemical data are needed to evaluate the extent of the crustal contamination proposed by Bertrand and Davison (1981).

All the late-tectonic plutons show a well-defined high-K calc-alkaline trend (Figure 8.). Moreover, the Adma granodiorite, the porphyritic granite and the Aoukenek plutons determine a very good calc-alkaline array on the AFM diagram (Figure 9). A distinct and unique trend is yielded on various diagrams involving trace elements e.g. Sr versus Rb (Figure 10).

In conclusion, the different studied complexes, representative of the large collision-related magmatic group, have similar ages (Rb/Sr isochrons: 595 ±25 Ma, 591 ±18 Ma, 581 ±15 Ma), similar Sr initial ratios (0·7048, 0·7035, 0·7053), and similar geochemical evolution. Although they are not strictly cogenetic, these plutons can be considered as sharing the same source and evolution that characterize the collision environment. This geochemical evolution is very similar to that described for modern plate boundary series and closely ressembles the cordilleran magmatism of western U.S.A. (Ewart 1979, 1982; Figure 8). This similarity to subduction-related magmatism rather than collision-related magmatism will be discussed in the last section.

3d. The calc-alkaline – alkaline transition

This transition occurred in post-tectonic conditions relative to D2 after considerable uplift of the belt. The relationships with D3 (N–S to N20° dextral strike-slip shear zones and faults) and D4 tectonics (brittle sinistral NNW–SSE and dextral ENE–WSW conjugate faults) are discussed in details by Boullier *et al.* (1986) while the petrographic and petrogenetic point of view is discussed in Liégeois and Black (1984, 1986).

In this post-tectonic environment the calc-alkaline magmatic production (post-tectonic I group) is rapidly taken over by alkaline to peralkaline magmas (post-tectonic II group). The calc-alkaline post-tectonic I group is represented by extensive E–W dyke (e.g. Telabit, Dohendal swarms, Figure 2) which are cross-cut by circular high-level plutons (e.g. Yenchichi 2). Quartz–two-feldspar porphyry is the most common rock type in the E–W dykes, the majority of which are acid and high-K calc-alkaline. However, the largest swarm (Telabit) consists of dykes with a more basic composition (down to 54 per cent SiO_2) and the Dohendal swarm, west of the Timedjelalen alkaline ring-complex, shows calc-alkaline dykes with alkaline affinities such as perthitic alkali feldspar, the presence of fluorite,

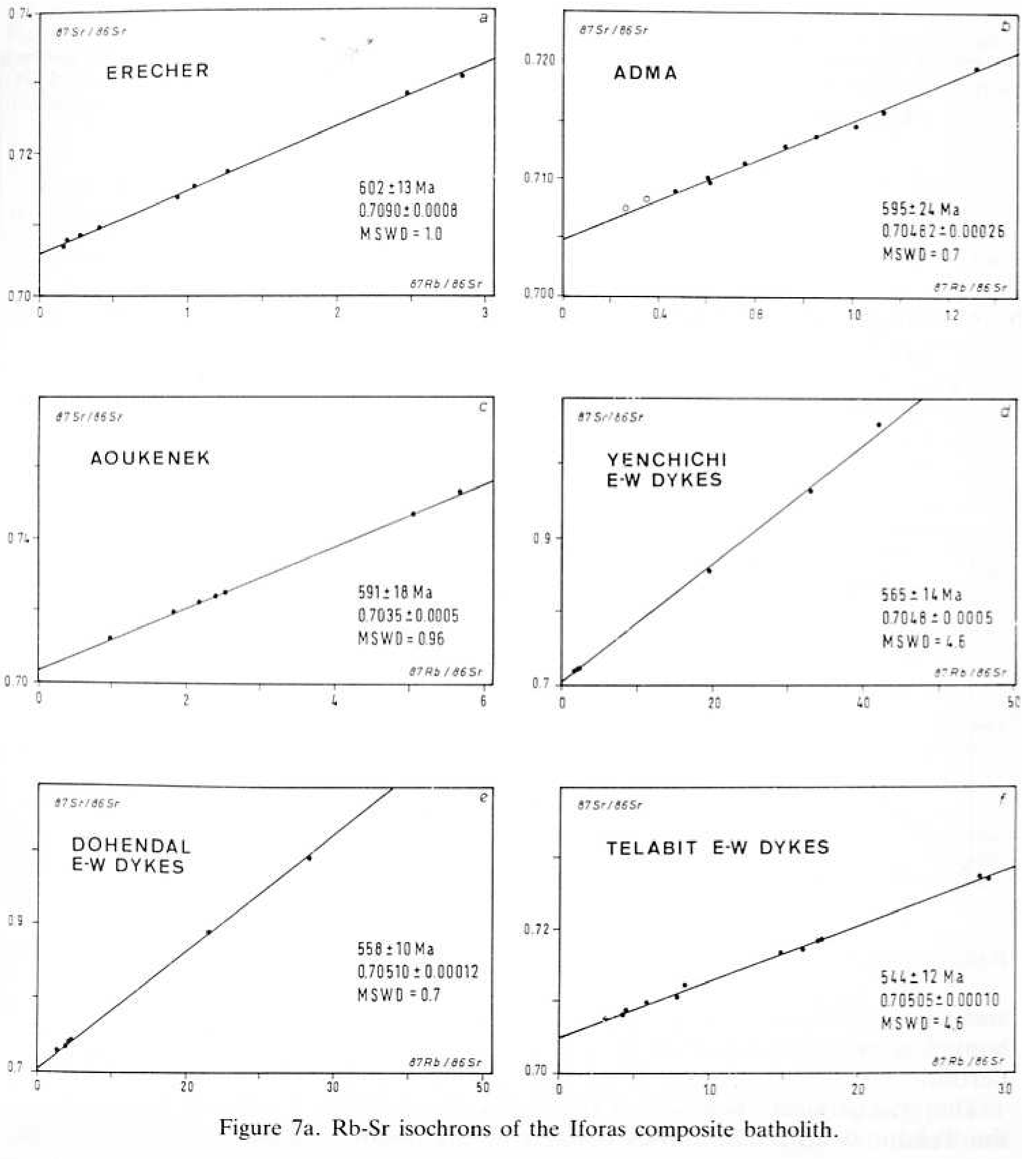

Figure 7a. Rb-Sr isochrons of the Iforas composite batholith.

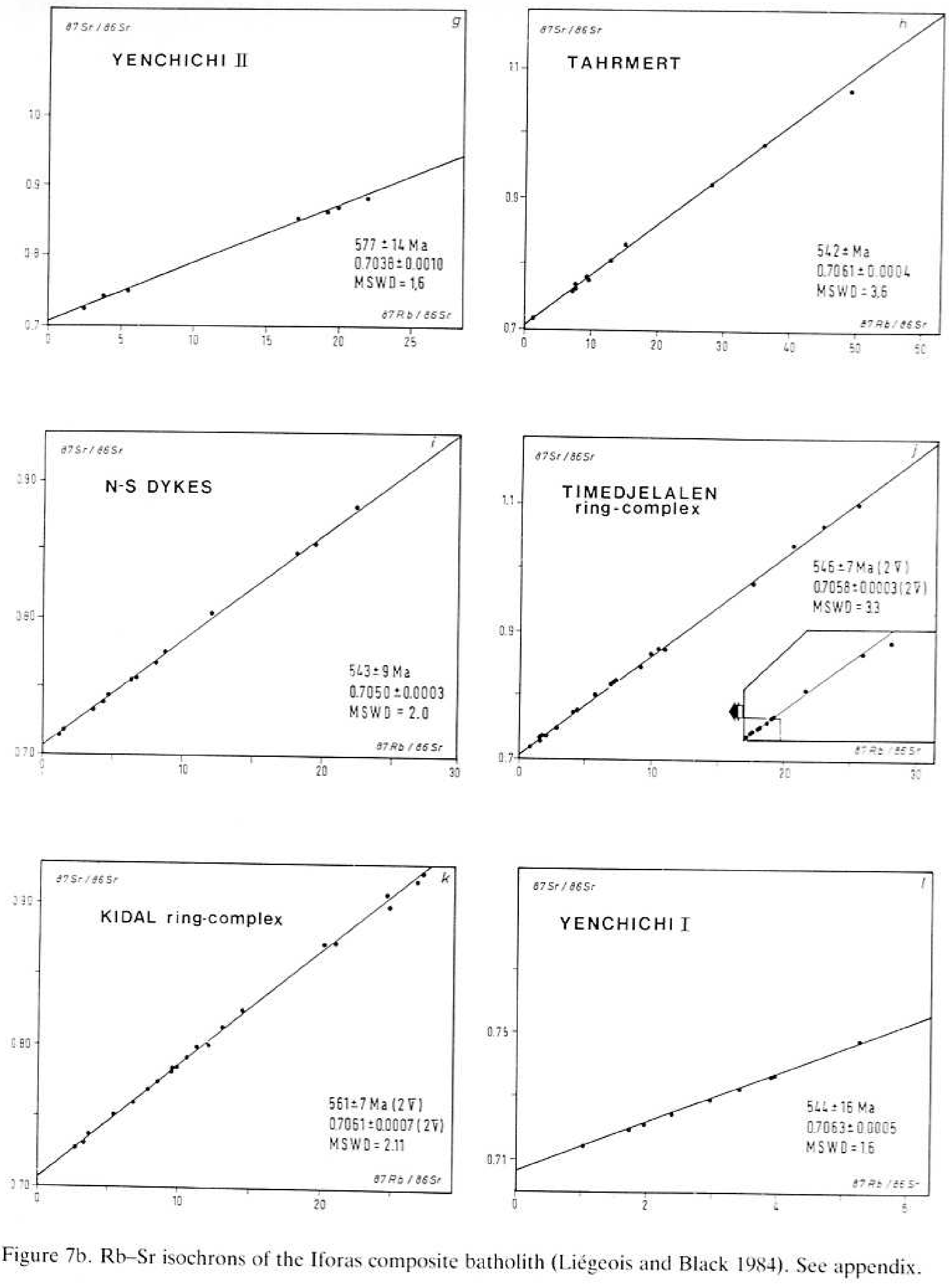

Figure 7b. Rb–Sr isochrons of the Iforas composite batholith (Liégeois and Black 1984). See appendix.

and the occurrence of red aphanitic felsites. The Yenchichi-type pluton is an homogeneous coarse-grained leucocratic biotite syenogranite (zoned oligoclase, perthitic microcline, quartz, and biotite).

The geochemical evolution of the post-tectonic group I is based essentially on the Telabit swarm. The trends defined by the major elements are similar to the

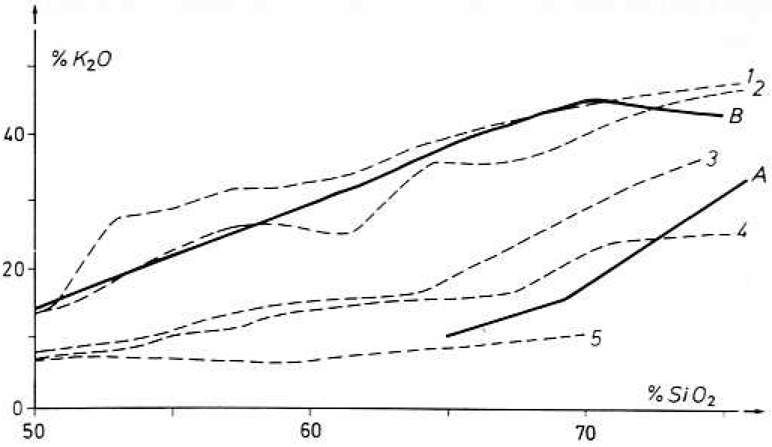

Figure 8. Schematic K_2O versus SiO_2 diagram comparing reference trends to the pre- (A) and late-tectonic (B) trends of the Iforas batholith. Ref. 1 to 4 from Ewart (1979) and 5 from Miyashiro (1974). 1. Western U.S.A., eastern zone; 2. Western U.S.A., western zone; 3. Northeastern Pacific (Cascades–Aleutians); 4. Northwestern Pacific (Kamchatka–Mariannes); 5. Central Kurilles.

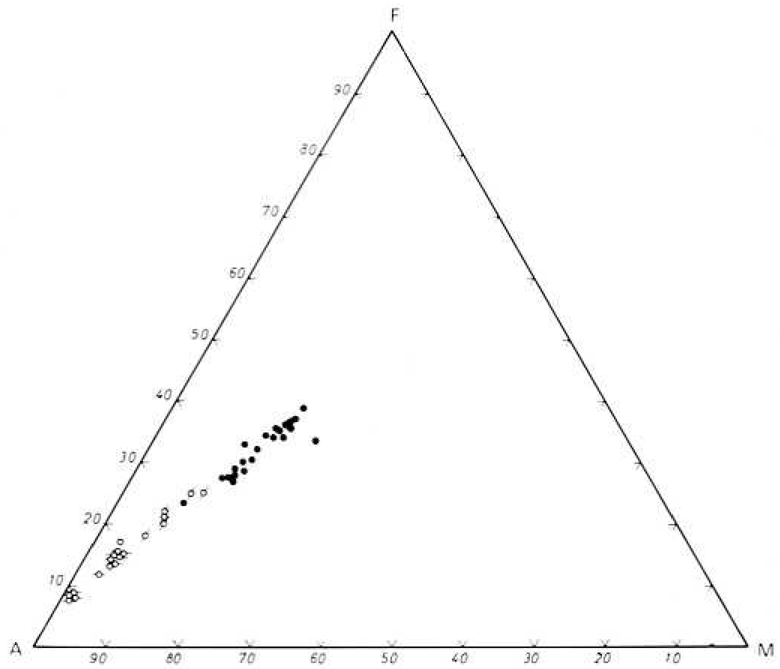

Figure 9. AFM diagram (A=Al_2O_3, F=Fe_2O_3+FeO, M=MgO) showing the calc-alkaline trend of the late-tectonic group of the southwestern part of the batholith. Filled circles: Adma granodiorite; open circles with inclined line: porphyritic monzogranite; open circles with horizontal line: Aoukenek fine-grained monzogranite.

calc-alkaline late-tectonic trend, with alkaline affinities for some samples as shown on the K_2O vs SiO_2 diagram (Figure 3). Trace element signatures clearly discriminate the group, placing it in an intermediate position between the late-tectonic and the alkaline groups, but always nearer to the former (see for example Figure 10).

Three dyke swarms (Yenchichi, Dohendal, Telabit) and one circular pluton (Yenchichi 2) have been studied isotopically and have yielded Rb–Sr isochrons

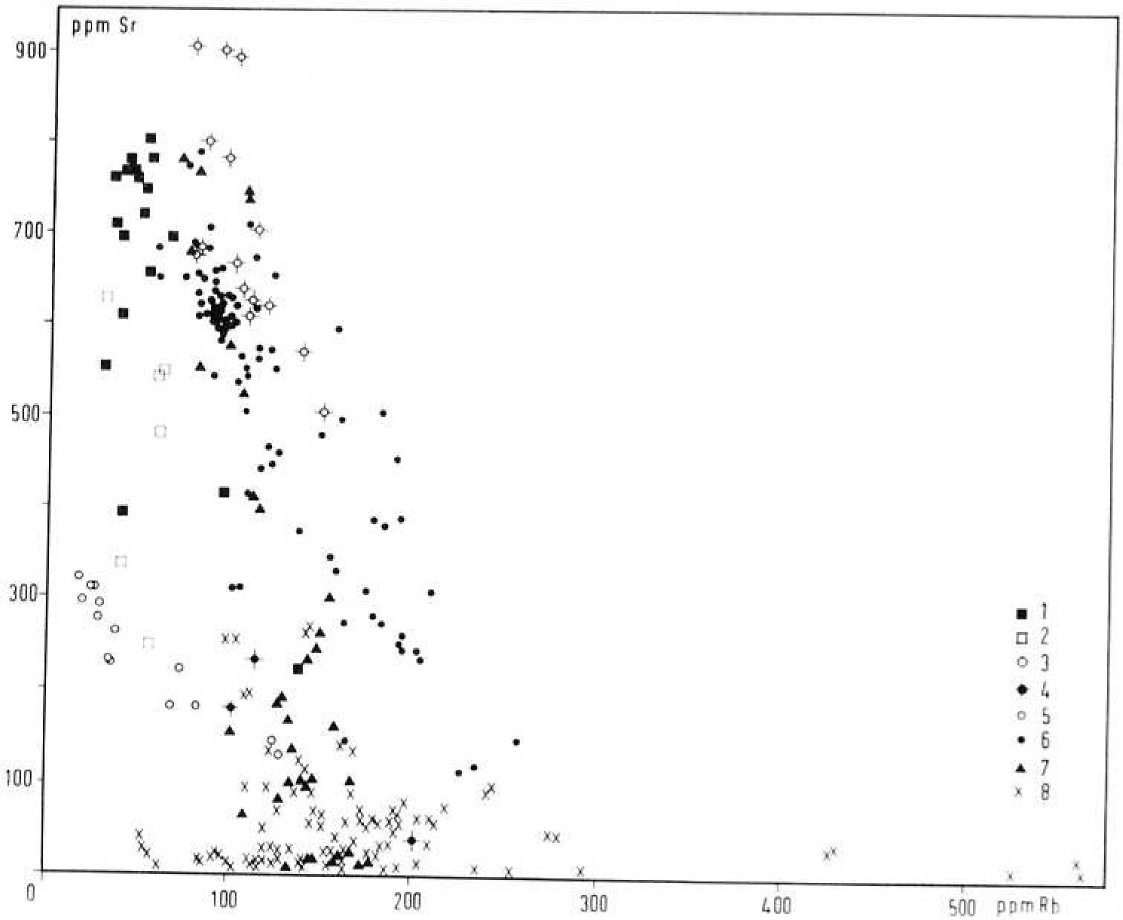

Figure 10. Sr versus Rb diagram. Same symbols as in Figure 3.

(Liégeois and Black 1984, see Figure 7). These data indicate an age trend from south (Yenchichi swarm: 565 ±14 Ma, Yenchichi 2 pluton: 577 ±14 Ma) to north (Dohendal swarm: 556 ±10 Ma, Telabit swarm: 544 ±12 Ma). This tendency is also apparent in the subsequent alkaline group (see below). The Sr initial ratios are in the range 0·7038–0·7051, which are very similar to the late-tectonic range (0·7035–0·7053).

This group, of relatively restricted occurrence, is considered as representing the end of the collision-source magma production with an incipient and erratic participation from a deeper alkaline source emplaced at high structural level during the uplift of the whole belt (from 575 Ma to 545 Ma).

In contrast, the alkaline post-tectonic group II is well represented in the western and central parts of the batholith. Field relationships have shown that the different terms of this group are always later than the post-tectonic group I, but the relative chronology of the different alkaline rocks is intricate. Indeed, the general succession of the Iforas alkaline province consists of early hybrid plutons, followed by giant N–S dykes swarms, rhyolitic and ignimbritic lavas and ring-complexes, but some N–S dykes cut the lavas and even some of the early phases of the ring-complexes. Likewise, the D4 brittle deformation does not affect all the ring-complexes. The hybrid plutons such as Tahrmert type (Ba *et al.* 1985) however are early as they mark the beginning of the unroofing accompanied by brittle behaviour, and the formation of an erosion surface on which the lavas have poured out. In detail, the Tahrmert pluton is a coarse-grained granite with alkaline-type felsic and accessory minerals (rounded quartz, perthites, zircon, sphene, Fe–Ti oxides and abundant fluorite) but with magnesian-rich mafic minerals.

The N–S dykes are typically alkaline, represented essentially by quartz- and quartz-feldspar porphyries and by some microsyenites with basic inclusions. Devitrified rhyolitic dykes are also abundant. Both metaluminous and peralkaline varieties are present. Most of these N–S dykes occur along the axial zone of the batholith centred on the major rhyolitic and ignimbritic plateau of the Iforas (Tiralrar) and may have been feeders to the lavas (Liégeois and Black 1984).

The alkaline complexes, about fifteen in number, include typical large size ring-complexes (20 to 30 km in diameter, e.g. Kidal and Timedjelalen ring-complexes). Several complexes are described in detail in Ba *et al.* 1985. All the rocks are rich in silica. Two distinct trends have been recorded, (in Figure 11) as a sodic peralkaline trend and a potassic aluminous trend (see Ba *et al.* 1985 and Liégeois and Black 1986). The peralkaline trend shows an evolution from quartz-syenite with an increase of Na+K/Al with constant K/Na represented by fractionation of plagioclase and early fayalite, Ca-pyroxene, and amphibole. There then followed a decrease in K/Na, controlled by substantial fractionation of K-feldspar, as the liquid line of descent crosses the peralkaline field and descends down the thermal valley (Bailey and MacDonald 1969). Late deuteric recrystallization has occurred in the presence of hydrothermal F-bearing fluids giving albite–microcline arfvedsonite granites.

The aluminous trend appears between the granite porphyries and the subsolvus biotite–chlorite granite, the trend being marked by a decrease of Na+K/Al and Na/K ratios reflecting the appearance of biotite and perthite with K>Na. A possible explanation can be provided by fractionation of basic oligoclase, Fe-hornblende, and clinopyroxene, if the dark inclusions, described by Ba *et al.* 1985, are cumulates. The two trends separated before the syenite stage. Nevertheless, a common deep source is likely for both granitic trends as their initial ratios are identical.

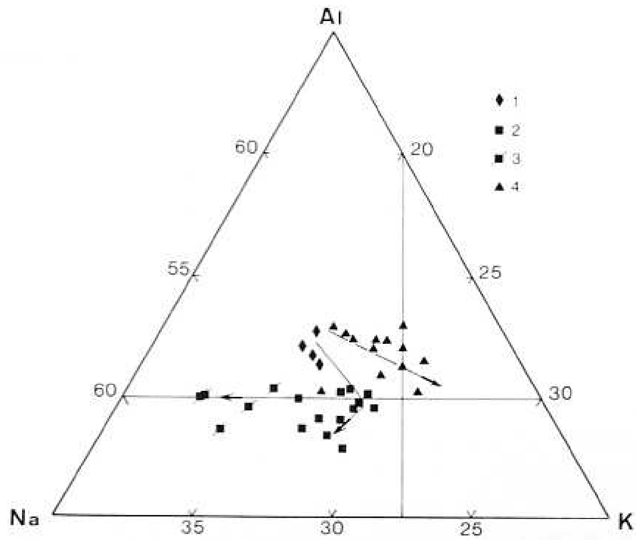

Figure 11. Atomic Na–K–Al diagram for the Kidal ring-complex (Ba *et al.*, 1985). 1. Syenite. 2. Peralkaline hypersolvus granite. 3. Albitic peralkaline granite. 4. Metaluminous granite.

The Iforas ring-complexes display then all the main petrological and geochemical characteristics of a typical anorogenic oversaturated province (e.g. Niger–Nigeria province; Black 1963; Black *et al.* 1967; Jacobson *et al.* 1958; Bowden and Turner 1974). The principal difference is the absence of volcanism centred on the ring-complexes. In the Iforas the Tiralrar volcanic plateaux have a fissural origin, related to the N–S dyke swarms. There is also a distinctive lack of basic rocks and of any economic mineralization in the Iforas. Although the Rb–Sr geochronology shows a general south to north migration in age, it is unable to separate the various overlapping alkaline intrusions (Figure 12).

A Pb–Sr–O study of the Timedjelalen ring-complex and of the Tiralrar N–S dyke swarm (Weis *et al.* 1986b), shows that meteoric alteration has been intense but only locally, namely at the ring dyke contacts, and that the ^{18}O values and Pb initial ratios are, as with the Sr initial ratios, only compatible with a deep subcrustal origin.

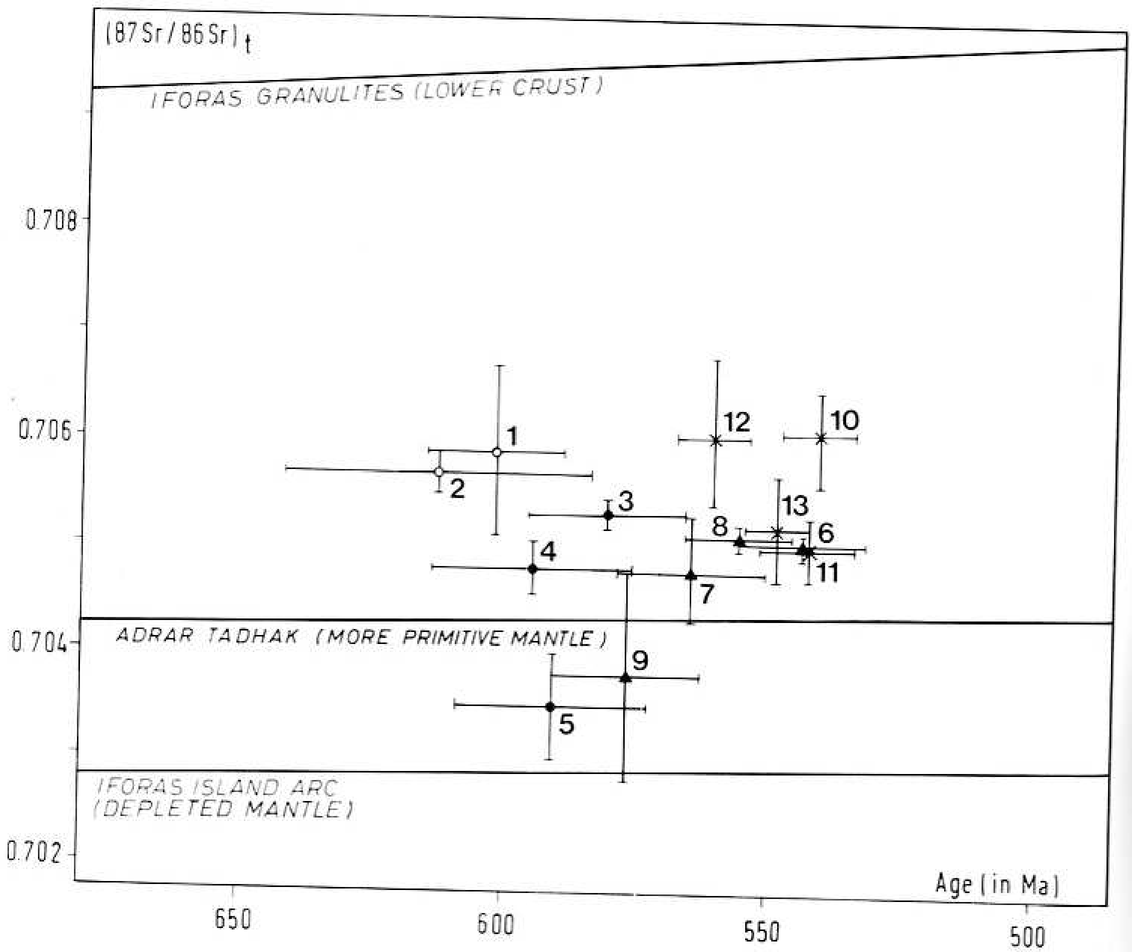

Figure 12. $^{87}Sr/^{86}Sr$ initial ratios versus time diagram for the Iforas composite batholith. Empty circles: pre-D2 plutons (rehomogeneization values); filled circles: late-tectonic plutons; triangles: post-tectonic I calc-alkaline dykes and plutons; crosses: post-tectonic II alkaline dykes and plutons. The different plutons and dyke swarms are: 1: Erecher tonalite; 2. Ibdeken quartz-monzodiorite; 3. Tin Seyed quartz-monzodiorite; 4. Adma granodiorite; 5. Aoukenek fine-grained monzogranite; 6. Telabit E–W dyke swarm; 7. Yenchichi E–W dyke swarm; 8. Dohendal E–W dyke swarm; 9. Yenchichi 2 syenogranite; 10. Tahrmert alkaline granite; 11. Tiralrar N–S dyke swarm; 12. Kidal ring-complex; 13. Timedjelalen ring-complex.

4. Discussion and conclusions

4a. The geodynamic evolution from structural data

The external shape of the composite batholith is controlled by the position of the suture zone. The batholith forms a large elongated body parallel to the suture, and at a distance of *ca.* 100 km from the suture (see Figure 2.). This feature implies an overall control by subduction and collision processes. In the batholith, the cordilleran-type volcanism and plutonism postdates a large-scale tectonometamorphic event whose age and significance are still in question (D1 event), and the bulk of the volume of plutonic rocks in post-oceanic closure. They have been affected by collisional processes operating either at a deep ductile level (D2 and D3 events) or in shallow and brittle conditions (D4 event).

The existence of the D1 event implies an early collision. Its intensity and kinematic characteristics are quite different from the second D2 collision which may be considered in the Iforas as a docking rather than a Himalayan-type confrontation (Boullier 1982: Liégeois and Black 1984). The poorly-constrained age of the D1 deformation leads one to envisage two geodynamic possibilities. If the D1–D2 interval is short, implying a genetic link between the two collisions, the shoulder shape of the suture near Niamey can play the role of a rigid promontory in an early phase, producing the nappe structure further north (Figure 13A). In the other case, i.e. if the D1 deformation occurred before e.g. 700 Ma, one must seek, an early collision elsewhere, as already proposed in the northern part of the Tuareg shield (Caby *et al.* 1981) or to the south with the Congo craton.

In this connection it should be recalled that stacking of crystalline nappes indicative of N–S shortening occurs in the Tassendjanet area in northwest Hoggar (Caby 1970) and is a characteristic feature of the Central Hoggar–Air domain of the Tuareg shield (Bertrand *et al.* 1985; Latouche 1986) where tangential tectonics occurred in the 630–580 Ma range (Bertrand *et al.* 1984d, 1986).

The D2 deformation marks the collision with the West African craton, which was oblique (Ball and Caby 1984). An important feature is the gentle dip of the main foliation (both in high-grade volcanosedimentary facies and in plutonic rocks) occurring in the batholithic domain and contrasting sharply with the N–S upright folds and cleavage affecting the margins and the low-grade volcanosedimentary basins. This contrast could be related either to a flattening induced by the interface between large-scale plutonic domes and surrounding schists (Brun 1981; Bertrand and Wright 1986) or to a difference in exposed structural level. A striking feature is the N–S subhorizontal stretching related to sinistral shear observed along the western margin of the Tafeliant belt.

The D3 deformation, still ductile in the mylonites near the granulites (Boullier 1985), marked a reversal in the stress field and now corresponds to a NE–SW shortening direction (Figure 13c). After uplift leading to the removal of at least 10 km of material (low-pressure sillimanite outcropping at the pre-rhyolitic flow erosion surface), the D3–D4 transition reflected a complete reversal in direction of the maximum compressive stress (from NE–SW back to ESW–NNW; Figure 13d). Boullier *et al.* (1986) suggest that such reversals can have a profound disruptive effect without necessarily large strike-slip movement and in this case correspond to the emplacement of alkaline magmas (Black *et al.* 1985).

4b. Origin and evolution of the magmas

From the field, petrological, geochemical, and geochronological data a model can be proposed for the petrogenetic evolution of the Iforas batholith. The

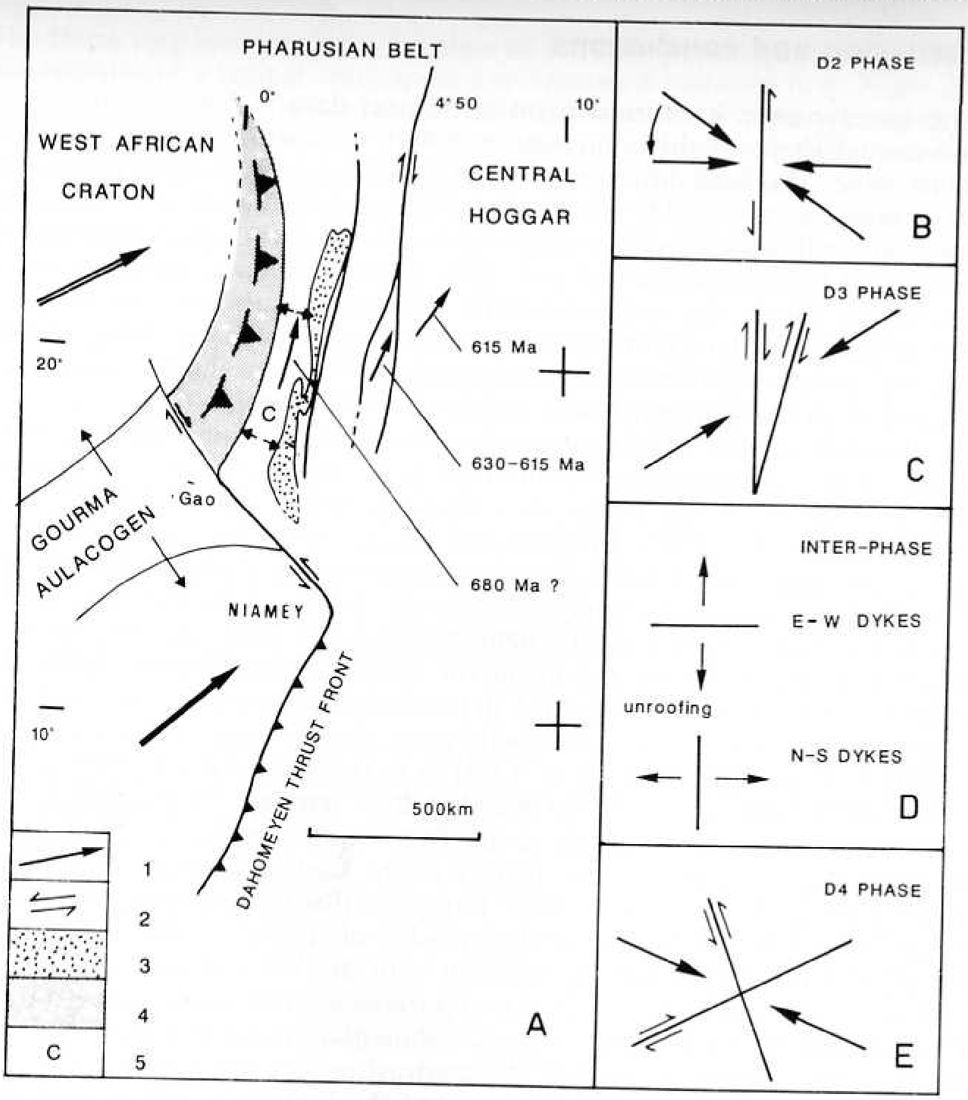

Figure 13. (A): Sketch map showing the Trans-Saharan belt just after an early oblique collision (680 Ma?) producing the nappe structures. The Iforas island arc and cordillera would have been protected by the embayment of the West African craton around the Gourma aulacogen. In this area, the collision (in fact a docking) has occurred later, around 600 Ma. The two eastern thrust ages are from Bertrand *et al.* (1984c, 1986), the 680 Ma (?) is hypothetical (see text). Arrows in the West African craton indicate the postulated movement of the craton relative to the mobile belt and the extension resulting in the Gourma aulacogen. 1. Early D1 thrusts and wrench faults; 2. Post-D1 relative movements. 3. Eburnean granulitic units. 4. Oceanic domain with subduction; 5. Cordillera. (B) to (E) (based on Boullier *et al.* 1986): shortening (B, C, E) and extension (D) directions during the successive collision (*ca.* 600 Ma) and post-collision (580–540 Ma) events.

studied plutonic bodies and complexes have relatively low $^{87}Sr/^{86}Sr$ initial ratios (0·.7035–0·7061, Figure 12) which preclude an origin from an old continental crust. The remaining possible sources are late-Proterozoic upper crustal rocks, lower continental crust or depleted or more primitive mantle. Isotopic characteristics of these reservoirs can be inferred in the Iforas region.

The lower crust. The Iforas granulitic unit (IGU) which is interpreted as a basement nappe (Boullier *et al.* 1978) can be taken as representing the lower continental crust. Granulite facies metamorphism has been dated *ca.* 2100 Ma (Lancelot *et al.* 1983) but in a northern extension of the IGU in Algeria (In Ouzzal unit), the material is Archaean in age (Ferrara and Gravelle 1966; Allègre and Caby 1972). Nine representative whole rocks have been measured for their Sr isotopic composition (Table 3).

Even if the data for sample 5513 is ignored, the mean ($^{87}Sr/^{86}Sr$) 600 Ma ratio is 0·7095. These results preclude an origin from the lower crust as represented by the IGU since the Iforas batholith is less radiogenic. To infer a hypothetical more depleted lower crust is difficult because the Aoukenek granite, for example, has a $^{87}Sr/^{86}Sr$ initial ratio as low as 0·7035 and such a depleted old lower crust is not propitious for producing a huge quantity of magma. Thus, we think that the Iforas lower crust has not played a role as a magma source, but may have acted as a contaminant.

The young upper crust. The Pre-cordilleran young crust consists of Proterozoic shelf sediments and the Kidal Assemblage. The former are very poorly-represented, particularly in the western batholith and can be ignored; the latter is not known with certainty west of the Tadjoudjemet–Kidal N–S line and in any case, its ($^{87}Sr/^{86}Sr$) 600 Ma mean ratio is also too high as shown by the representative samples of the Table 3 (mean: .07062). Its role would then be similar to that of a lower crustal contaminant.

The depleted mantle. The composition of the depleted mantle can be inferred from the magmatism of the Iforas palaeoisland arc (Caby 1981), where no basement remnants have been found. It is composed of trench-type volcanosedimentary sequences intruded by basic and ultrabasic rocks. The $^{87}Sr/^{86}Sr$ initial ratios 700–600 Ma ago are around .07030 (Dupuy, Liégeois and Caby in preparation), and are interpreted as the lithospheric depleted mantle with alkali-rich hydrous fluids coming from the subduction oceanic slab (Thorpe *et al.* 1976).

Table 3. Rb–Sr isotopic results of representatives of the Iforas Granulites and of the Kidal Assemblage

Ech.	Rb. ppm	Sr ppm	$^{87}Sr/^{86}Sr \pm \sqrt{m}$	$^{87}Rb/^{86}Sr$	($^{87}Sr/^{86}Sr$) 600 Ma
Iforas Granulites					
Q178b	34.4	253	0·71112±00005	0.3936	0·7078
Q178c	35.4	597	0·70718±00004	0.1716	0·7057
Q180d	124	1048	0·71541±00005	0.3426	0·7125
IC5510	72.9	3027	0·70704±00004	0·0697	0·7064
IC5513	133	179	0·78796±00006	2·167	0·7694
JPL484	2.9	194	0·70468±00011	0·04818	0·7043
JPL485	28.4	179	0·72092±00005	0·4597	0·7170
JPL486	37.2	359	0·71722±00004	0·3001	0·7147
JPL487	9.1	386	0·70800±00004	0·06822	0·7074
Kidal Assemblage.					
JPL478	157	635	0·70708±00006	0·2504	0·7049
JPL491	33·5	409	0·70768±00005	0·2370	0·7053
JPL492	22·4	260	0·71018±00004	0·2494	0·7080

The enriched mantle. One hundred kilometres west of the batholith, the Permian undersaturated alkaline province (Figure 1; Liégeois *et al.* 1983) was intruded along the eastern margin of the 2 Ga old West African craton, just west of the palaeosuture. It has been demonstrated from Pb and Sr isotope studies (Weis *et al.* 1986a) that the Adrar Tadhak ring-complex is a pure mantle product and thus represents the deep mantle under the Iforas region 270 Ma ago. This deep mantle is assumed to be the asthenosphere (Liégeois and Black 1986). Indeed, along the Cameroon line, Fitton and Dunlop (1985) have shown that the lithospheric mantle cannot be the source of the Tertiary to Recent alkaline magmatism as their geochemical and isotopic characteristics are identical in the continental segment as well as in the oceanic domain. On the other hand, it is likely that the location of the alkaline anorogenic complexes was controlled by the structure of the lithosphere (Black *et al.* 1985; Boullier *et al.* 1986). It is clearly the case in the Iforas for the Pan-African province (along the plate margin, just after a collision) as well as for the Permian province which developed along the palaeosuture zone. These two complimentary arguments are most easily reconciled with an asthenospheric source or, at least, with an asthenospheric intermediate reservoir.

The source regions for different magmas which crystallized to form the Iforas batholith combined to form a dynamic model divided into three periods.

The subduction period. The pretectonic subduction-related magmatism in the cordillera seems to be essentially represented by the volcanosedimentary or volcanic sequences. The only well-established plutons related to subduction are the Erecher tonalite situated close to the island arc and the Ibdeken pluton located along the eastern edge of the batholith, compatible with a classical subduction origin (e.g. Thorpe *et al.* 1976). The characteristics of the Erecher tonalite, which is intermediate between continental and oceanic arc magmatism, are clearly distinguishable both in the field and on the geochemical diagrams (Figure 8). Such characteristics favour a relatively shallow mantle source for this tonalite. The Ibdeken pluton would represent the other extreme in the cordillera (Figure 14). The possibility of a marginal sea at this stage between the island arc and the cordillera, represented in part by the Tafeliant Group, is currently being studied (Liégeois, Fabre and Caby in preparation).

The collisional period. The collision in the Iforas is characterized by the apparent absence of S-type granites and by the preservation of the pretectonic subduction-related volcanites and plutonites. These two features are probably linked to the lack of nappe structures in the island arc and batholith domain during the D2 event. Here the collision is best explained by a 'docking' between the Tuareg shield and the West African craton. On the other hand, the geochemistry and the isotopic ratios are very similar to that of subduction-related magmatism, particularly, the Pb initial ratios (measured on feldspars, Liégeois and Lancelot, unpublished data). In addition the Ree patterns are identical (Liégeois and Hertogen, unpublished data). The main geochemical difference between the two groups seems to be, at a given distance from the palaeotrench, a greater potash content (and related elements such as Rb) for the late-tectonic group, which can be related to a K–h relationship (Dickinson and Hatherton 1967; Dupuy *et al.* 1978; Arculus and Johnson 1978). Thus we propose the same lithospheric mantle-source as for the pretectonic magmas with alkali-rich aqueous fluids coming from the dehydration of the subducted slab, but originating from a greater depth, due

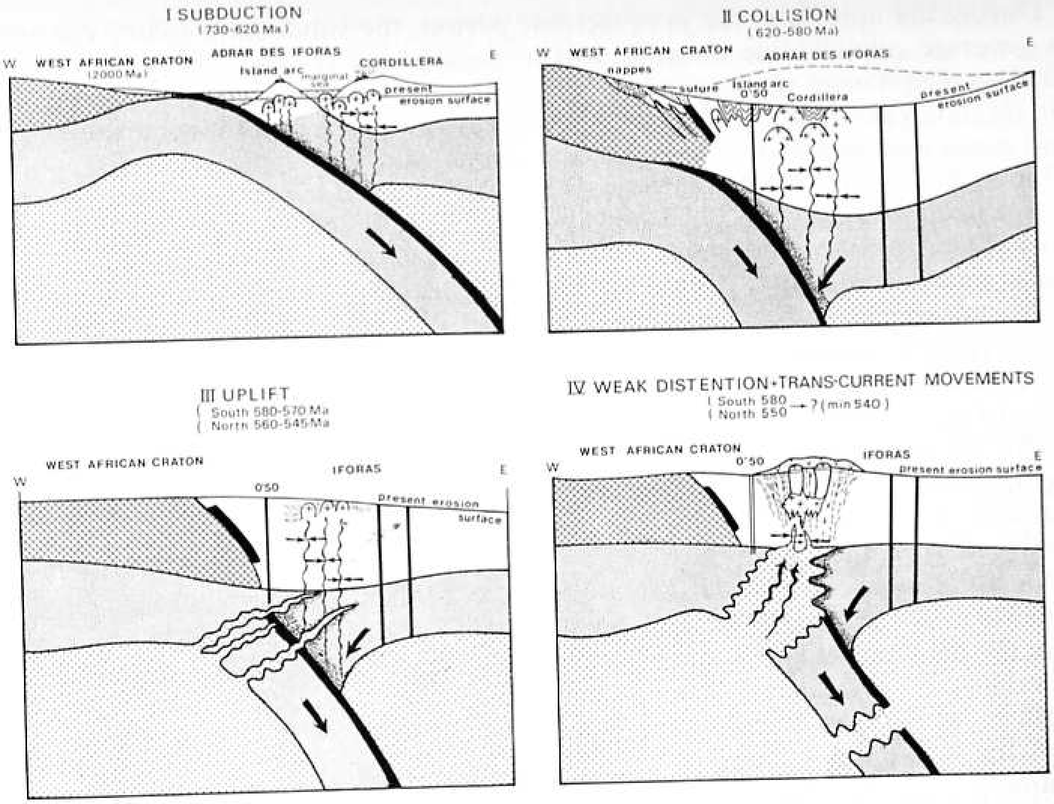

Figure 14. Schematic evolution model for the Iforas batholith during the Pan-African orogeny.

to the crustal thickening during the collision. These mantle products had to be slightly contaminated by the lower crust during ascent (Figure 14II).

The 'within-plate' period. As the post-tectonic group is poorly represented and very similar to the late-tectonic units, except for some erratic alkaline affinities, we consider it as the late manifestation of the source mobilized during the collision, linked to the initiation of an alkaline source. This group is contemporaneous with the rapid uplift of the belt and are only known as high level plutons and dykes (Figure 14III).

The alkaline group followed very rapidly, particularly in the Timedjelalen area where no break in time has been found. Its emplacement was contemporaneous with the end of the uplift, with the unroofing of the batholith when isostatic equilibrium was reached. A thick tabular sequence of rhyolites and ignimbrites fed by the N–S dykes, covered the erosion surface, into which the ring-complexes were emplaced. This is supported by the rhyolitic compositions of Tiralrar-type boulders in the late molasses of the belt (Fabre 1982). The emplacement of alkaline rocks is also roughly contemporaneous with the reactivation of the near N–S shear-zones and with the rotation of the stress field between the D3 and D4 tectonic events (Figures 13C, 13D, 13E; Boullier *et al.* 1986). The apparent diachronism between the emplacement of the two post-tectonic groups in the Kidal and the Timedjelalen area could be related to a different rate of uplift in the two regions, controlled by the oblique character of the collision (Boullier 1982; Ball and Caby 1984; Boullier *et al.* 1986).

During the uplift and the post-tectonic period, the subduction source continued to generate calc-alkaline magma (post-tectonic group I). The abrupt transition to alkaline magmatism suggests a new source region. The general tendency with time for the late calc-alkaline and post-tectonic group I is an evolution towards more acid types accompanied by a diminution of the $^{87}Sr/^{86}Sr$ initial ratios in the plutons (Oumassene quartz-monzodiorite: 0·7053; Adma granodiorite: 0·7048; Aoukenek fine-grained granite: 0·7035, Yenchichi 2 granite: 0·7038). As the alkaline group is younger, granitic, and emplaced as circular high-level plutons, the expected Sr initial ratios would be 0·7035–0·7040 rather than 0·7050–0·7061.

Crustal contamination cannot explain these higher initial ratios. Indeed, the upper crust is essentially represented by the batholith which did not have high enough initial Sr ratios 550 Ma ago. Moreover Weis *et al.* (1986b) have shown, using oxygen isotope data, that hydrothermal alteration could be intense but only locally. On the other hand, the Pb initial ratios (measured on K-feldspars; Liégeois and Lancelot, unpublished data) are similar for all the calc-alkaline groups but distinctly more radiogenic for the alkaline magmas. This precludes a greater involvement of the lower crust at the alkaline stage.

An asthenospheric mantle source seems to be then the best candidate for the Iforas alkaline family, with the enrichment in radiogenic Sr and Pb contributed from the mantle and not in the crust. We suggest that the asthenosphere originally underlying the subducted plate could be remobilized during its arise to shallow depth in the lithosphere after the rupture of the cold oceanic plate (Figure 14d.) Such fracturing could have occurred during reactivation of D3 shearing with a complete reversal in the stress field compared with D2 (Boullier *et al.* 1986; Black *et al.* 1985). The Iforas alkaline province is petrographically and geochemically very similar to the anorogenic Jurassic Nigerian province (see Ba *et al* 1985; Liégeois and Black 1986) which is totally unrelated to subduction processes and which probably shared the same asthenospheric source. But the two alkaline provinces are different because of the absence of Sn–W mineralization in the Iforas. This difference may be due to the nature of the basement which in Central Nigeria is partly crustal in origin (Van Breeman *et al.* 1977). In contrast the calc-alkaline Iforas batholith is mantle in origin, and its granulitic basement (IGU) in the Iforas is depleted in ore-bearing elements.

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Appendix: analytical techniques

The Sr isotopic compositions, after separation on ion-exchange columns, were measured on Re double filament on a FINNIGAN–MAT 260 mass spectrometer (Belgian Centre for Geochronology). The NBS 987 standard has given a value of 0·710235 ±0·000026 (2 σ_m) during previous measurements (Liégeois and Black 1984) and 0·710215 ±0.000015 during the measurement of the new data (Ibdeken, Tin Seyed, IGU and Kidal Assemblage). The ages were calculated following Williamson (1968) and all the errors are quoted at the 2σ level. ^{87}Rb = 1.42 10^{-11} a^{-1}. The Rb and Sr concentrations were measured by XRF when above 30 ppm and by isotope dilution when <30 ppm. The errors on the Rb/Sr ratios are estimated at 2 per cent.

The chemical analyses can be obtained from the authors on request.