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PAN-AFRICAN GRANITIC AND RELATED ROCKS IN THE IFORAS GRANULITES (MALI). STRUCTURE, GEOCHEMISTRY AND GEOCHRONOLOGY

GRANITES PAN-AFRICAINS ET ROCHES ASSOCIEES DANS LES GRANULITES DES IFORAS (MALI). STRUCTURE, GEOCHIMIE ET GEOCHRONOLOGIE

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ABSTRACT

The Iforas granulite unit (IGU) is a basement nappe composed of Eburnean granulites (2.1 By old) and emplaced during an early Pan-African event (D1), the age of which is still poorly defined. The internal deformation of the nappe during the Pan-African tectonic evolution consists of several separate or branched mylonite zones. Many small plutons were intruded during and after each stage of the tectonic history, most of them being emplaced within or close to the shear zones. From field evidence and structural analysis a relative chronology has been determined. From the petrography and the major element geochemistry it is shown that the pre-D2 plutons form a subalkaline assemblage. These plutons may be correlated with similar plutonic complexes to the west of the IGU, which predate the emplacement of the Main Iforas Batholith during the D2 event. The earlier granodiorites belonging to this batholith are well-dated from previous work at ca. 620-610 My. The results of the new geochronological investigations, using complementary methods (U/Pb and fission track on zircon, Rb-Sr on biotite) presented here are highly discordant. For the same pluton (Tin Toudadin) the fission track method gives an older age (635 ± 20 My) than the U/Pb age on zircon (lower intercept at 563 ± 8 My), the Rb-Sr biotite ages being in between (590 ± 12 My and 598 ± 12 My). Using the Rb-Sr biotite ages obtained from ten plutons it is possible to confirm the D2 age range defined in the Main Batholith area but we cannot assess whether the old fission track ages are meaningless apparent ages or if they reflect a post D1 cooling. The U/Pb zircon age is interpreted as the result of lead loss from inherited zircons.

RESUME

L'unité granulitique des Iforas (IGU) est une nappe de socle composée de granulites éburnéennes (2100 Ma) qui s'est mise en place durant une phase pan-africaine précoce (D1), dont l'âge est encore mal défini. La déformation interne de la nappe pendant l'évolution tectonique panafricaine consiste en plusieurs zones mylonitiques séparées ou anastomosées. De nombreux petits plutons se sont mis en place pendant ou après chaque stade de l'évolution tectonique, la plupart d'entre eux se mettant en place à l'intérieur ou au voisinage des zones de cisaillement. Une chronologie relative a été établie à partir des observations de terrain et de l'analyse structurale. La pétrographie et la géochimie des éléments majeurs montre que les plutons pré-D2 appartiennent à un assemblage subalcalin. Ces plutons peuvent être corrélés avec des complexes plutoniques similaires à l'ouest de l'IGU, qui sont antérieurs à la mise en place du batholite principal des Iforas au cours de la phase D2. Les granodiorites précoces appartenant à ce batholite sont bien datées au voisinage de 620-610 Ma par des travaux antérieurs. Les résultats de nouvelles études géochronologiques, utilisant des méthodes complémentaires (U/Pb et traces de fission sur zircon, Rb/Sr sur biotite), sont très discordants. Ainsi, pour un même pluton (Tin Toudadin), la méthode par les traces de fission donne un âge plus ancien (635 ± 20 Ma) que l'âge U/Pb sur zircon (intercept inférieur à 563 ± 8 Ma), les âges Rb/Sr sur biotite se situant entre 590 ± 12 Ma et 598 ± 12 Ma. A partir des âges Rb/Sr sur biotite obtenus dans dix plutons, on peut confirmer l'âge de la déformation D2 défini dans la région du batholite principal mais il n'est pas possible d'affirmer si les âges par traces de fission sont des âges apparents sans signification ou s'ils reflètent un refroidissement post-D1. L'âge U/Pb sur zircon est interprété comme le résultat de la perte de plomb par des zircons hérités.

INTRODUCTION

The geology and structural evolution of the «Adrar des Iforas» region has already been presented in several papers (Black *et al.,* 1979; Bertrand *et al.,* 1980; Bertrand and Davison, 1981). The geodynamic evolution of the belt is interpreted as the result of a major collision, occurring during the Pan-African epoch, between the passive margin of the West African craton and the active margin of an eastern continent (Caby *et al.,* 1981). Two hundred kilometers East of the suture, the *Iforas granulitic unit* (IGU), which forms the back-bone of the so-called Central Iforas domain, represents a particular tectonic unit of the complexly refolded and wrench-faulted nappe pile developed prior to, or during the main collisional event and affecting the eastern continental basement and its middle to upper Proterozoic cover (Boullier *et al.,* 1978). The IGU, fourty kilometers wide on average, may be followed northward in Algeria (In Ouzzal granulites) over a total length of approximately a thousand kilometers (fig. 1). Archaean ages have been determined on the granulites by the Rb-Sr isochron method (Ferrara and Gravelle, 1966; Allègre and Caby, 1972) but Lancelot (1975) and Lancelot *et al.* (1976) have shown from a zircon U/Pb study that the granulite facies imprint is related to the Eburnean orogeny, 2.1 By ago.

This study deals with a group of small plutons intruded within the IGU at different stages of its Pan-African tectonic evolution. The dating of two plutons (Tin Toudadin and Tassedrak) was attempted using both U/Pb and fission tracks methods on zircons with the hope of clarifying the chronology. Several biotites from other plutons were analyzed by the Rb-Sr method in order to constrain the cooling history.

STRUCTURAL SETTING

As shown by Davison (1980) and Boullier (1982), the IGU forms a large scale basement nappe emplaced in amphibolite facies conditions onto high-grade rocks corresponding to a tectonometamorphic assemblage of reactivated basement, presumed middle to upper Proterozoic metasediments, and pre- to syntectonic intrusives - the so-called *«Kidal assemblage».*

The tectonic evolution may be briefly summarized as follows (fig. 2) :

- **the D_1 event** is the main nappe - forming event. It is characterized by a locally gently dipping but more often refolded foliation with a conspicuous NNE trending, stretching lineation, especially well-developed in mylonitized granulites. On the basis of small scale polyphase structures and of metamorphic assemblages - evidence of remnants of intermediate to HP assemblages including kyanite and lenses of retrogressed eclogites - Boullier (1982) has defined two successive events D_1a and D_1b.
- **the D2 event** corresponds to N.S. trending upright to westward verging inclined folds. Corresponding metamorphic assemblages grade from amphibolite facies (W and N of the granulites) to greenschist facies (E of the granulites).
- **the D3 event** corresponds to late wrench-faults with locally associated minor folds.

Several sets of intrusives are syntectonically emplaced or intercalated in between these successive events (Bertrand and Davison, 1981). The timing of this evolution is not completely established especially for the D_1 event whose age - and hence significance with respect to the collision - is still in question; it is believed to have occurred prior to 690 My (Ducrot *et al.,* 1979). The D_2 event is better documented because the emplacement of the main

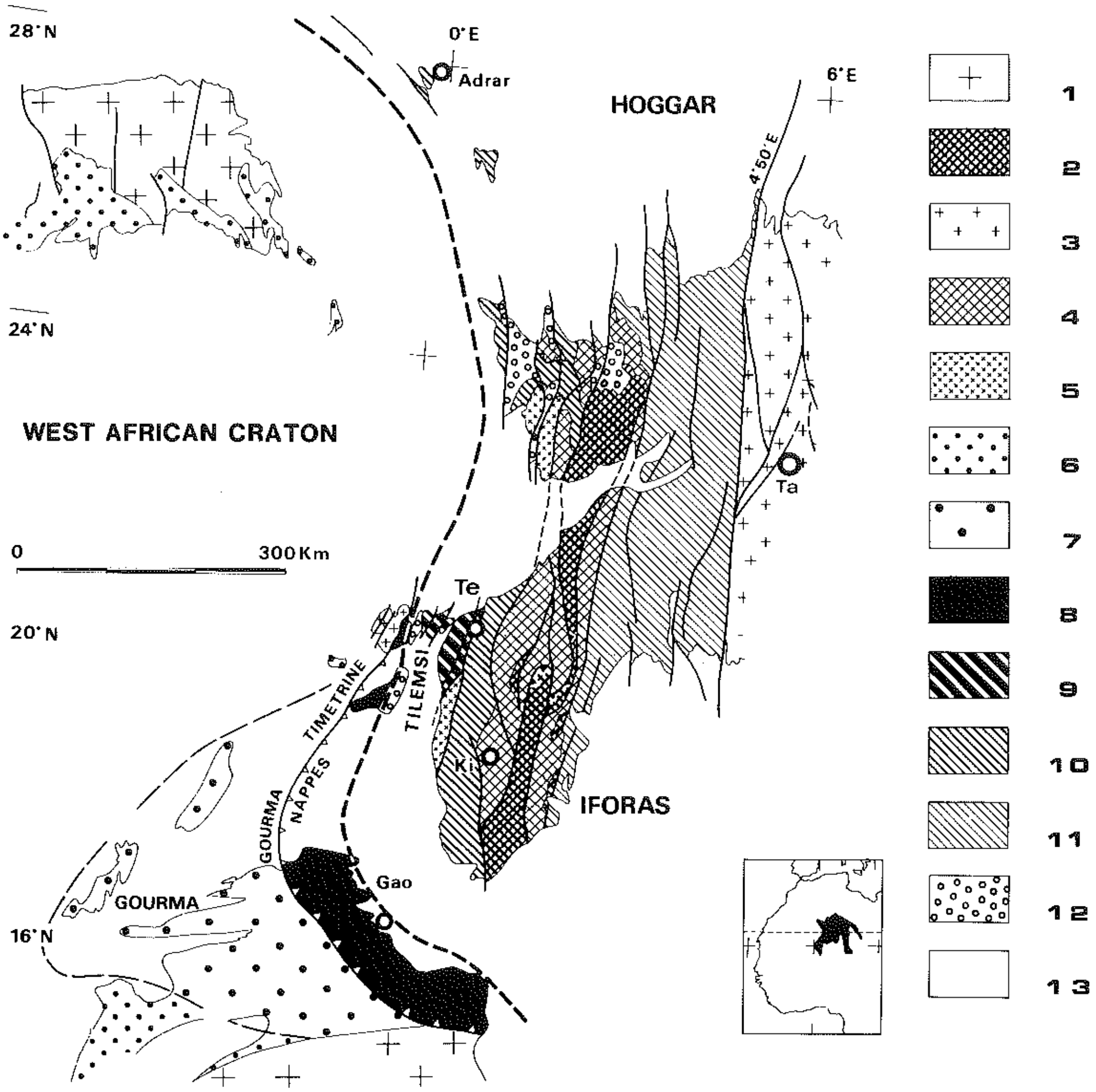


Fig. 1.- Simplified geological map of the western part of the Touareg shield. 1 : Reguibat shield (eburnean granites and volcanics); 2 : reactivated granulites (IGU and In Ouzzal); 3 : reactivated pre-Pan-African gneisses; 4 : undifferentiated Pan-African gneisses; 5 : late HT.LP metamorphism; 6 : Upper proterozoic shelf sediments from West African Craton; 7 : Upper proterozoic sediments of the Gourma aulacogen; 8 : Gourma and Timetrine nappes; 9-11 : late Upper proterozoic formations of the Tilemsi accretion zone, (9), of the western pharusian belt, (10), and of the eastern pharusian belt (11); 12 : molassic «série pourprée» (partly Cambrian); 13 : paleozoic to recent cover. Ta : Tamanrasset; Te : Tessalit; Ki : Kidal.

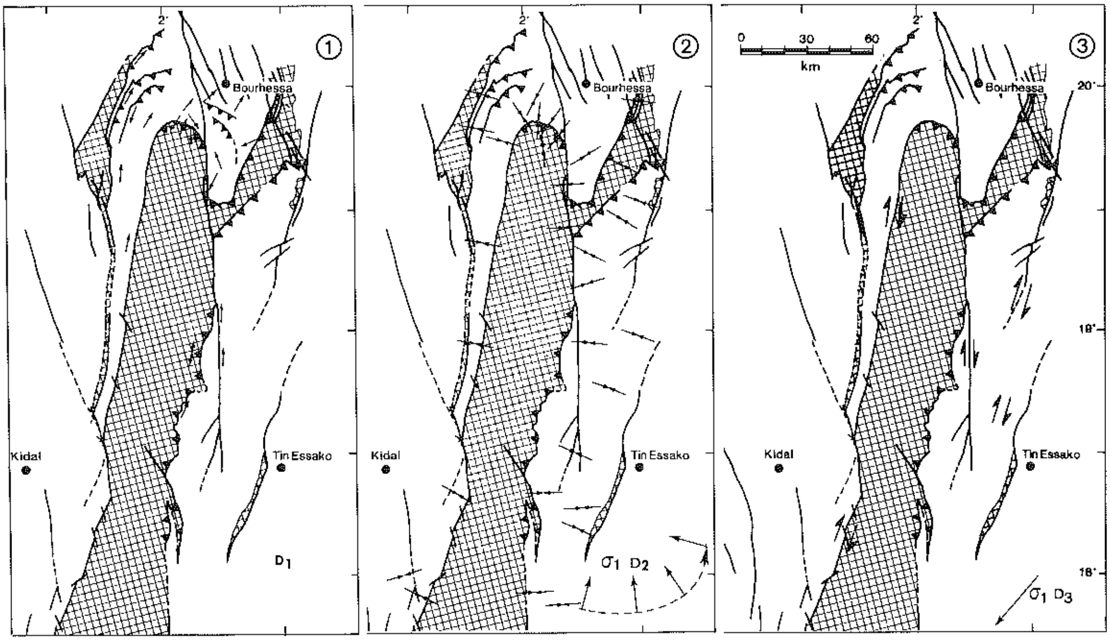


Fig. 2.- Movement pattern corresponding to D_1, D_2 and D_3 events. Hatched areas correspond to granulites. 1 : L_1 stretching lineations; 2 : D_2 shortening direction; 3 : D_3 wrench faults.

Iforas batholith, which outcrops to the west of the studied area, is broadly related to this event : it ranges from 610 My to 560 My (Bertrand and Davison, 1981; Black and Liégeois, 1983). A 560 My - 535 My age range is suggested by Boullier *et al.* (1979) and Lancelot *et al.* (1983) for the D_3 event on the basis of zircons U/Pb and ^{39}Ar/^{40}Ar ages from a granitic body deformed within the D_3 mylonitic zone forming the western margin of the IGU.

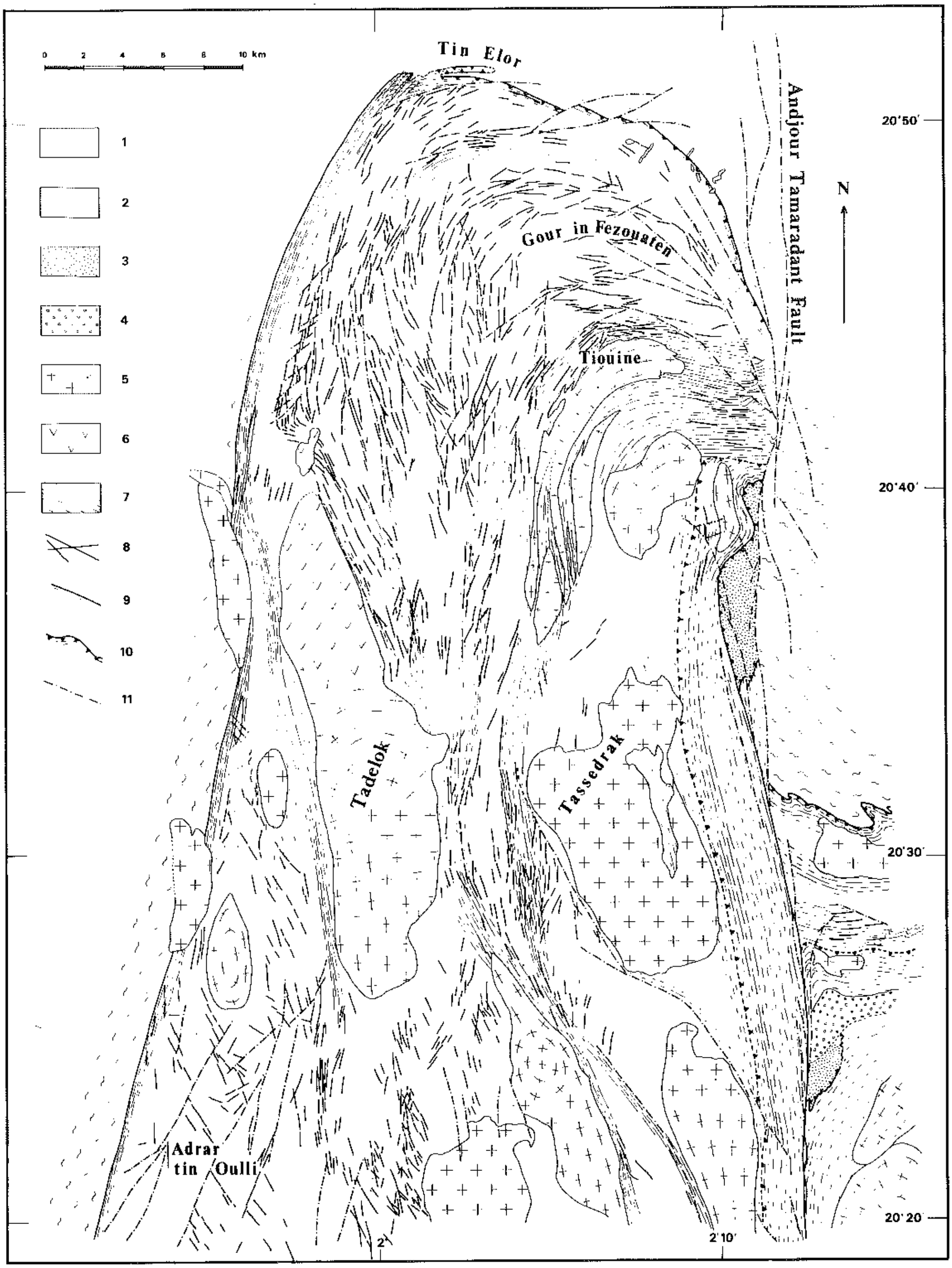
INTERNAL STRUCTURE OF THE GRANULITIC NAPPE : THE CONTROL OF GRANITOID EMPLACEMENT

During the Pan-African orogeny, the IGU has been tectonically and thermally affected; the effects of this reworking are heterogeneous and concentrated in linear zones of weakness. Using pre-Pan-African doleritic dykes as markers, it is possible to recognize (fig. 3) :

- the zones of internal deformation where the dykes rotate;
- the preferential locus of Pan-African intrusions cross-cutting the dykes.

Generally both types of zones coincide; they are shear zones characterized by a vertical mylonitic foliation which bears a horizontal stretching lineation. This foliation has been correlated to the D_2 event defined outside of the IGU. In some rare places, the mylonitic foliation has been seen superimposed on an older foliation which could correspond to the D_1 event (North of Gour in Fezzouaten, «Island» in the Tassedrak pluton). In the

Fig. 3.- Schematic map of the northern part of the IGU. 1 : eburnean granulites; 2 : Kidal assemblages; 3 : upper Proterozoic metasediments; 4 : late upper Proterozoic metasediments; 5 : Pan-African granitoids; 6 : Pan-African gabbros; 7 : retrogressive mylonitic zones; 8 : pre Pan-African doleritic dykes; 9 : D_3 mylonites; 10 : thrust contacts; 11 : faults.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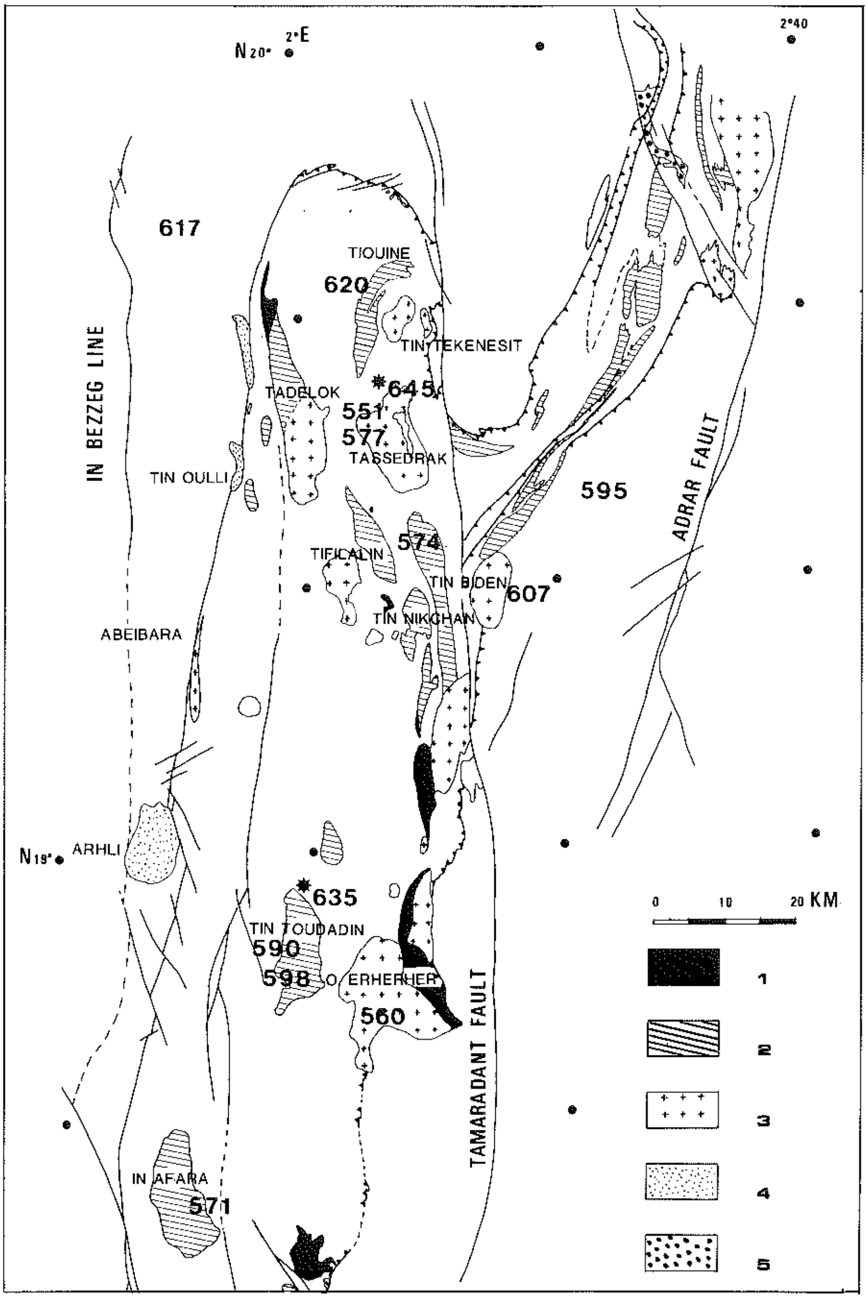

Fig. 4.- Relative chronology of the Pan-African plutons. 1 : pre D_1 gabbros; 2 : pre D_2 diorites and granodiorites (Tadelok, E Tifilalin, Tin Biden, Tin Nikchan, Tin Toudadin, In Afara), granites (Tiouine); 3 : post D_2 granodiorites and adamellites; 4 : post D_3 granites; 5 : late peralkaline granites. Areal distribution of biotite ages and fission track ages (*).

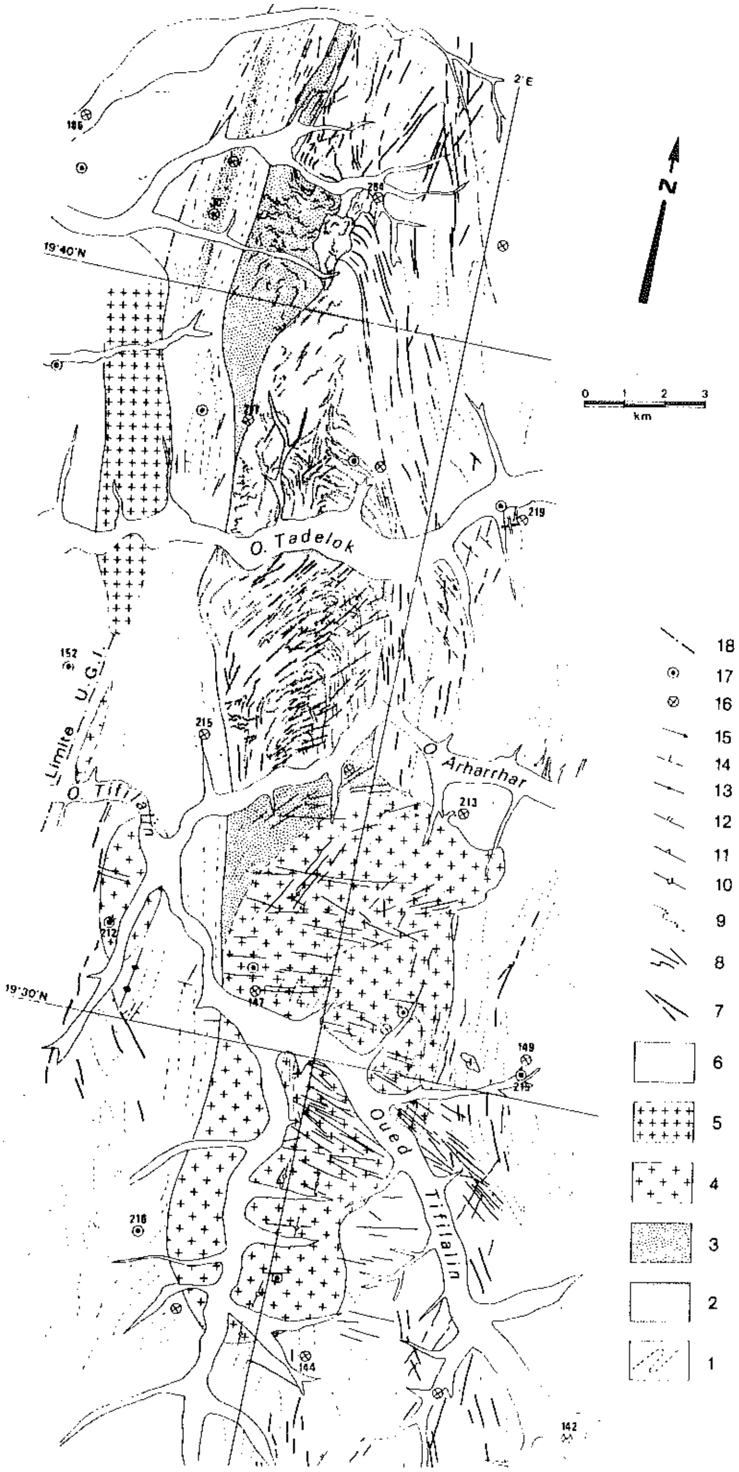

Fig. 5.- Sketch map of the Tadelok complex.
1 : granulites; 2 : pre D_1 banded gabbros; 3 : pre-D_1 (north) and pre D_2 (centre) diorites; 4 : post D_2 granodiorites and adamellites; 5 : post D_3 granites; 6 : quaternary alluvials; 7 : pre Pan-African doleritic dykes; 8 : aplites and microgranites; 9, 10, 11 : magmatic banding; 12 : eburnean foliation; 13, 14 : Pan-African foliation; 15 : stretching lineation; 16, 17 : aerial photograph (NE 31 XXI and NE 31 XX respectively); 18 : fault.

northern part of the IGU, mylonitic zones are curved and converge toward the external mylonitic borders of the unit. The width of these zones may in this case reach three kilometers. The mineral assemblages which defines the mylonitic foliation corresponds to the epidote - amphibolite facies. The microstructures of quartz (polygonization, dynamic recrystallization, subgrain and grain size) are very similar in all the mylonites zones suggesting that the deformation conditions (temperature, stress and then strain-rate) were the same. As supported by the horizontal stretching lineation, the N.S. segments of the shear zones are interpreted as strike-slip faults. Accordingly, their curved shape toward the North is assumed to be due to the «gouge» shape of the blocks moving at different relative speed (Boullier, 1979). The western mylonitic border of the IGU is interpreted as a dextral ductile strike-slip fault and is attributed to the late D_3 Pan-African event (Boullier, 1979 and in prep.).

Plutonic intrusions are mostly located within or nearby the shear zones. They are gabbroic to adamellitic in composition and emplaced in several pulses which can be bracketed by the deformation events. Correlations between emplacement of plutons and the D_2 and D_3 events are possible in the northern part of the IGU and a relative chronology has been established. This chronology and the name of individual plutons are shown on figure 4.

The complexity of the Pan-African plutonic history of the IGU can be well illustrated using one example : the composite Tadelok intrusion (fig. 5). The older intrusive stock is a layered gabbro (labrador + clinopyroxene + brown hornblende ± orthopyroxene ± olivine). The magmatic layering is characterized mainly by differences in grain size more than by differences in mineralogical composition and it is deformed, especially in the northern part of the stock. On both eastern and western margins, the gabbroic intrusion is also deformed in the D_2 shear zones. Dioritic intrusions, clearly pretectonic with respect to the D_2 event, cross cut the gabbros. Both types (diorites and gabbros) are crosscut by schistosed aplitic veins. Towards the south another intrusion was emplaced during, to slightly after the D_2 event. It has a concentric structure with an internally dipping layering consisting in thick layers of granodiorite and adamellite, and grading to a massive adamellite further south. This complex intrusion illustrates the persistence of the shear zones as weakness zones, with probably preferential fluid circulation during the tectonic reactivation of the granulites and, into which magmas have been preferentially emplaced.

PETROGRAPHY AND MAJOR - TRACE ELEMENT GEOCHEMISTRY OF TWO CONSTRASTING PLUTONS

We shall now focus on two plutons on which isotopic dating has been attempted : the Tin Toudadin pluton is believed to be emplaced prior to the D_2 event while the Tassedrak pluton cross cuts D_2 mylonites.

- **The Tin Toudadin pluton** (fig. 6) is located far from any internal mylonitic belt but its rock type assemblage is similar to other bodies where the relationships with well recognized pre-D_2 structures are clear (Tadelok, Afara and Tin Biden complexes). The bulk of the pluton is formed by banded and foliated biotite-hornblende bearing diorites associated with some granodiorites. Highly heteregeneous, it comprises many stocks and elongated enclaves, parallel to the banding, showing three main rock types : brown hornblende bearing

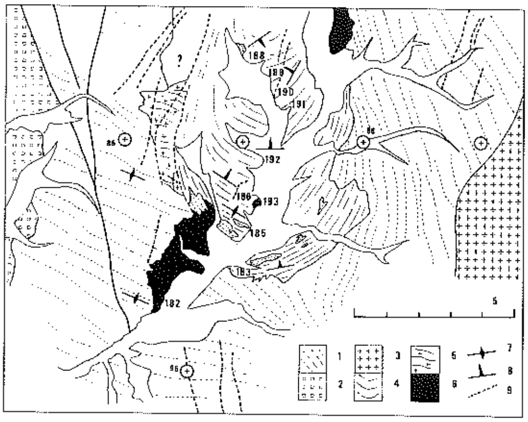

Fig. 6.- Sketch map of the Tin Toudadin pluton. Samples correspond to numbers; crosses are aerial photograph centres. 1 : eburnean foliation in the granulites; 2 : massive charnockite; 3 : late Pan-African granodiorites and adamellites (O. Erherher); 4 : banded heterogeneous diorites; 5 : granodiorites; 6 : porphyritic granites; 7-8 : foliation and banding dips; 9 : doleritic dykes.

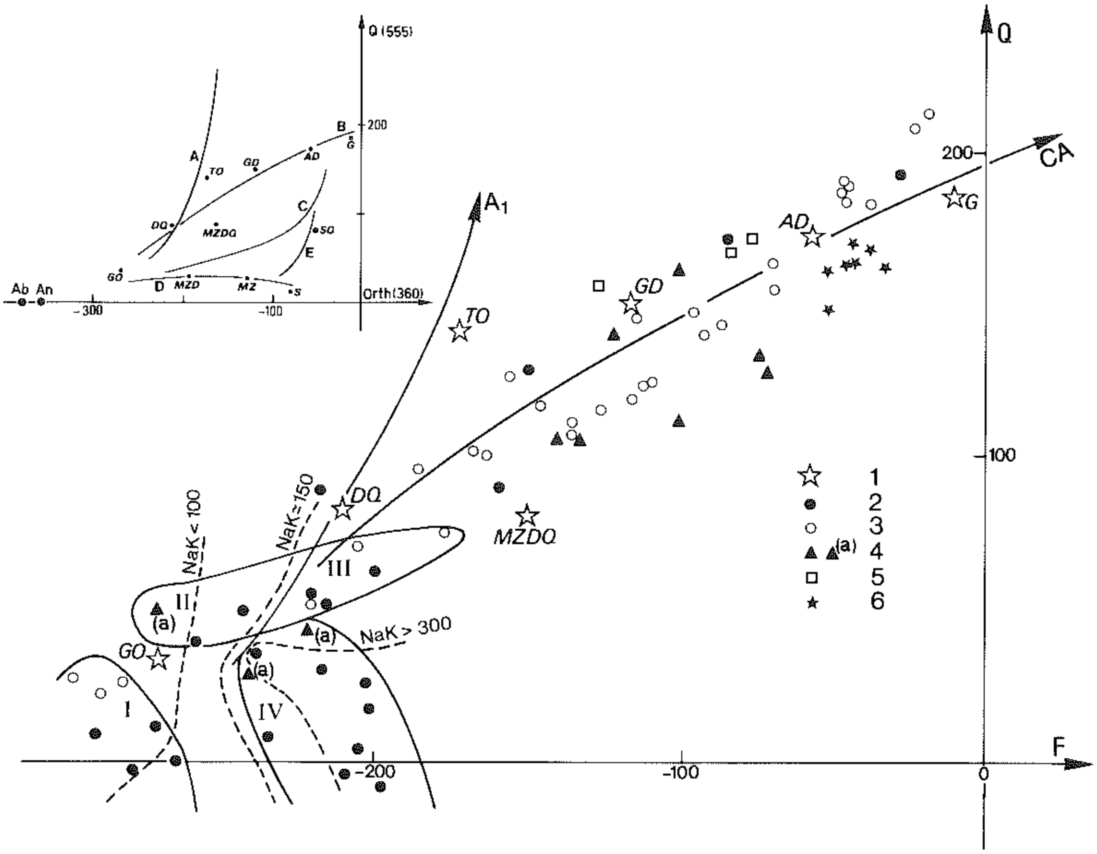

Fig. 7.- Q-F diagram : $Q = Si/3 - [K + Na + 2\ Ca/3]$; $F = K - (Na + Ca)$ expressed in millications (La Roche, 1962). Standard locus and terminology are from Debon and Le Fort (1983). Mineral locus and some typical suites are given in the insert where : (A) tholeitic (tonalite) suite from Afghanistan (Debon, Le Fort, 1983); (B) calcalkaline suite from French Pyrénées (Debon, 1980); (C) subalkaline suite from Vosges (Pagel, Leterrier, 1980); (D) alkaline saturated suite from Afghanistan (Debon, Le Fort, 1983); (E) alkaline oversaturated suite from Afghanistan (Debon, Le Fort, 1983).
The A_1 trend, close to A represents the pre-D_1 metatonalites from the Kidal assemblage (Iforas, Bertrand unpublished data); symbols are as follows : 1 : standard; 2 : Tin Toudadin complex; 3 : other pre-D_2 rocks; 4 : post-D_2 Tassedrak complex [(a) represents xenoliths]; 5 : pre-D_3 Abeibara complex (Lancelot *et al.*, 1983); 6 : Post-D_3 plutons.
For the Tin Toudadin complex, the Na + K value is given and fields are those discussed in the text. I : brown hornblende gabbros; II : orthopyroxene bearing coronitic gabbros; III : quartz, biotite, orthopyroxene diorites; IV : diorites.

gabbros, orthopyroxene - clinopyroxene - green hornblende coronitic gabbros, and orthopyroxene - quartz - biotite diorites. Banding and foliation are parallel to the margin of the pluton which shows a circular , upward facing horn shape. As no evidence of postcrystallization deformation is recorded, this foliation is interpreted as having formed during the emplacement of the pluton. Later, unorientated porphyritic adamellites were emplaced, especially along the margin of the body.

Within other complexes of the same group (Afara, Tin Biden), large xenoliths of migmatite and of pyroxene hornfelses occur frequently. The microtextures of the latter are very similar to those displayed by the orthopyroxene - quartz - biotite diorites associated with the Tin Toudadin pluton. These xenoliths are believed to represent pieces of the amphibolite facies rocks assemblage (the Kidal assemblage) dredged up from beneath the granulitic nappe.

- **The Tassedrak pluton** is more homogeneous and cross cut clearly the D_2 mylonites. Refolded D_1 mylonites can be seen in a large inlier outcropping along the eastern margin of the pluton (cf. fig. 3). The rock types range from granodiorite to adamellite, porphyritic in places. Locally, highly digested and recrystallized dioritic enclaves have been observed.

- **Geochemistry**. Whole rock analyses (77) have been performed on sixteen plutons amongst those presented in figure 4. They cover the whole range of composition displayed by the successively emplaced bodies. In fact two of these plutons, already presented, will be especially discussed, as representative of an old (Tin Toudadin) and a young (Tassedrak) pluton.

Major elements and V, Cr, Co, Ni, Cu were analyzed by plasma spectrometry (CRPG, Nancy); Rb, Sr, Ba, La, Ce, Zr and Nb were analyzed by X-ray fluorescence (St Mary's University, Halifax). All data are stored in the CRPG data-bank and available on request.

In the La Roche diagrams presented here (Q-F and R1 - R2, La Roche, 1962; La Roche *et al.*, 1980), the chemical data are assembled in parameters, chosen for their relationship with mineralogical assemblages. The Q-F diagram, in addition to a chemical classification and nomenclature (Debon and Le Fort, 1983), is useful to determine the main geochemical trends : $Q = Si/3 - (K + Na + 2\,Ca/3)$, expressed as millications, represents the silica not allocated to feldspars; $F = K - (Na + Ca)$ represents the feldspar balance.

The Q-F diagram (fig. 7) shows that almost all the analyzed granitoids may belong to the same association except for some porphyritic granites (Abeibara and Tiouine) which are located well above the reference calcalkaline trend (Debon, 1980). The Tin Toudadin diorites also differ from this trend and are shown below to represent a plagioclase cumulate. Most of the data show calcalkaline affinities but with a shift toward syenitic composition, the Tassedrak pluton being the best example (compare with insert in fig. 7). There is no consensus of nomenclature for such an association, it may be called subalkaline as proposed by Barrière (1977) or calcalkaline monzonitic as proposed by Lameyre and Bowden (1982), or hypoaluminous potassic subalkaline (Orsini, 1979).

On the AFM diagram (fig. 8), the contrast between the Tassedrak, close to classical calcalkaline associations (Fourcade and Allègre, 1981; Dupuy et al., 1979), and the Tin Toudadin which displays an iron enrichment (Fenner trend) related to its alkaline source, is emphasized. The problem with the AFM diagram is that it is not able to distinguish between alkaline and subalkaline affinities.

The R1 - R2 diagram (La Roche *et al.*, 1980) is a chemical transposition of the Yoder and Tilley (1962) normative mineralogical tetraedron (quartz, olivine, nepheline, clinopyroxene) for basalts. The critical plane (clinopyroxene, olivine, plagioclase) is projected on a line which represents the bisectrix of

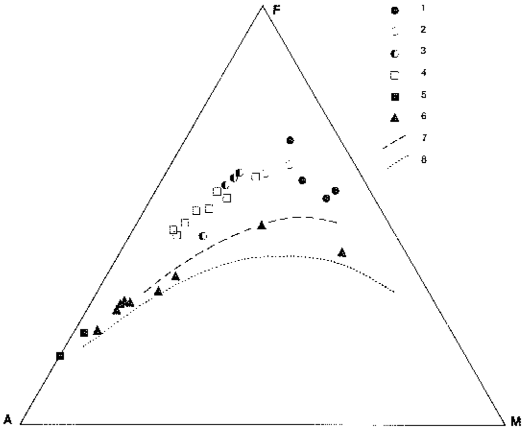

Fig. 8.- AFM diagram for the Tin Toudadin (1-5) and Tassedrak (6) plutons. 1 : brown hornblende gabbros; 2 : orthopyroxene bearing coronitic gabbros; 3 : quartz, biotite, orthopyroxene diorites; 4 : diorites; 5 : porphyritic granites; 6 : Tassedrak diorites, granodiorites and adamellites; 7 : calcalkaline trend from French Pyrenees (Fourcade and Allègre, 1981); 8 : calcalkaline trend from Sardinia andesites (Dupuy *et al.*, 1979).

the R1 - R2 diagram [with R1 = 6 Ca + 2 Mg + Al and R2 = 4 Si - 11 (Na + K) - 2 (Fe + Ti), expressed in millications]. This diagram is well adapted in discriminating between the calcalkaline and tholeitic associations on one side of the bisectrix, and the alkaline association on the other side. But a strong iron enrichment may deviate the differentiation line toward the left and a tholeitic association may cross over the bisectrix. On such diagram, the subalkaline association shows a characteristic trend. Typical magmatic associations are shown in the insert of figure 9.

Using the R1 - R2 diagram for the Tin Toudadin complex, provides a mean of interpreting its petrogenetic evolution (numbers refer to fig. 9):

- the brown hornblende gabbros (1) are probably derived from an alkali basalt source. All the samples show high Fe/Mg and some gabbroic members of other complexes (Tadelok, Tin Biden) have the same mineralogy and geochemistry;
- the biotite - hornblende diorites (4) are, from their textures (euhedral plagioclases and biotites - hornblende septa in between) and from their aluminous composition, interpreted as cumulates;

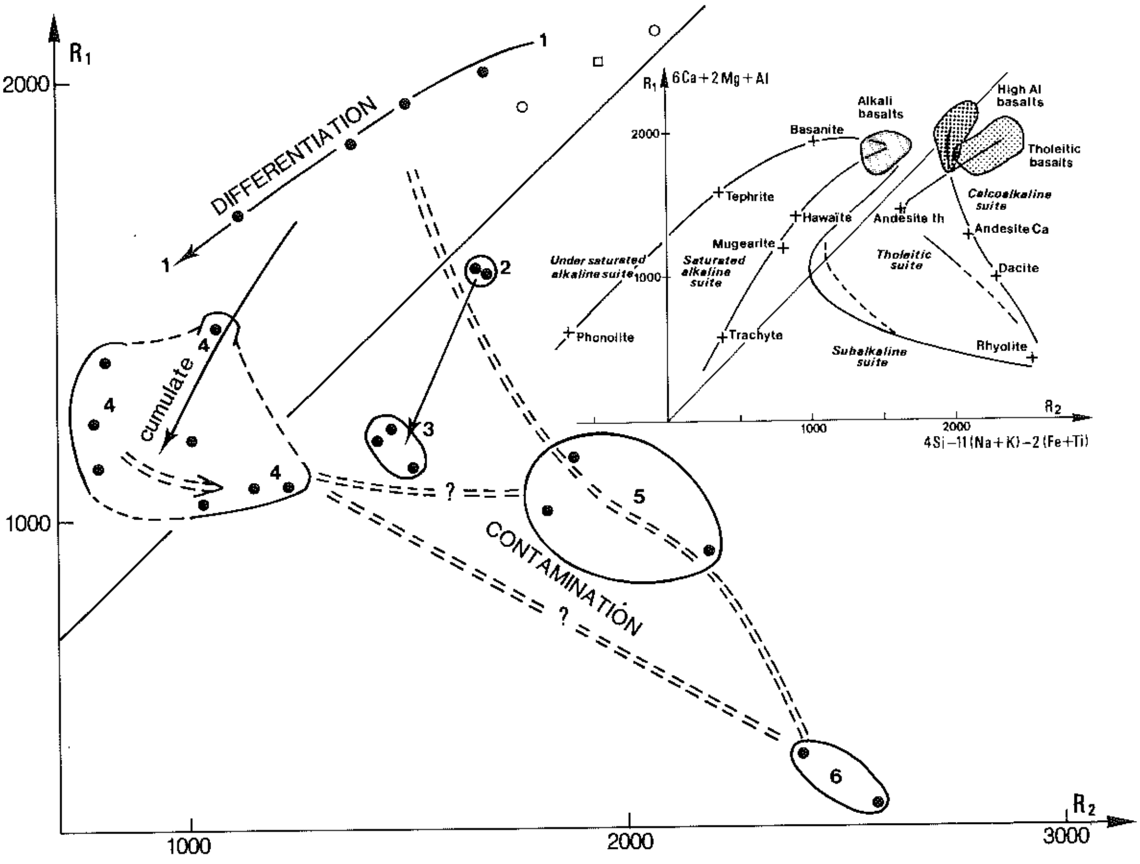

Fig. 9.- R1-R2 diagram for the Tin Toudadin pluton (R1 = 6 Ca + 2 Mg + Al; R2 = 4 Si - 11 (Na + K) - 2 (Fe + Ti), la Roche H. de *et al.*, 1980). 1 : brown hornblende gabbros; 2 : orthopyroxene bearing coronitic gabbros; 3 : quartz-biotite-orthopyroxene diorites; 4 : diorites; 5 : granodiorites (two of them are from another similar pluton : Tin biden); 6 : porphyritic granites. For comparison, open circles are from Tadelok complex, open square is an enclave from the Tassedrak pluton (see text for comments).

- the orthopyroxene bearing coronitic gabbros (2), which show a progressive mineralogical reequilibration, belong clearly to an early stage of the evolution, but it is not clear, from the diagram, whether or not their source is the same as that for the hornblende gabbros;
- the quartz - biotite - orthopyroxene diorites (3) could have been derived from a gabbroic magma (2) by Ca - pyroxene (or amphibole) fractionation. As suggested by a Zr - TiO_2 plot (fig. 10), such rocks cannot correspond to compositions intermediate between the biotite - hornblende diorites and the granodiorites. Instead they seem related to the orthopyroxene gabbros. The hornfels type texture with small rounded orthopyroxene grains, devoid of any corona, large poikilitic biotite and quartz replacing oligoclase suggest either a complete recrystallization of rocks contaminated during the emplacement or a fractionation of Mg olivine and clinopyroxene from the gabbros (2);
- the granodiorites (5) are often difficult to distinguish in the field from the biotite - hornblende diorites because they are rich in ferromagnesian minerals. As they are located in the diagrams (fig. 7, 9, 10) between the more basic rocks and the granites (6), a contamination process is suggested. For example the Zr - TiO_2 plot suggest a closer link with the hornblende gabbros (1) than with the diorites (4). From mineralogy and texture the other «path» with a question mark on fig. 9 and 10 are less likely but however it must be pointed out that the arrows in the dioritic field correspond to a shift toward more biotitic assemblages. Similar examples of intermediate rocks associated with gabbros and granites and interpreted as the result of a contamination have been described in southern Norway (Ploquin, 1972);
- the more leucocratic porphyritic granites (6) although emplaced later than the other groups and forming cross cutting stocks located especially along the edge of the complex could represent the melt composition responsible for the contamination process. In the haplogranitic system, their norms correspond to a melt produced at P H_2O close to 2 - 3 kb. This feature confirms that the granites postdate the D_1 event where metamorphic conditions of 6 to 7 kb are recorded (Boullier, 1982).

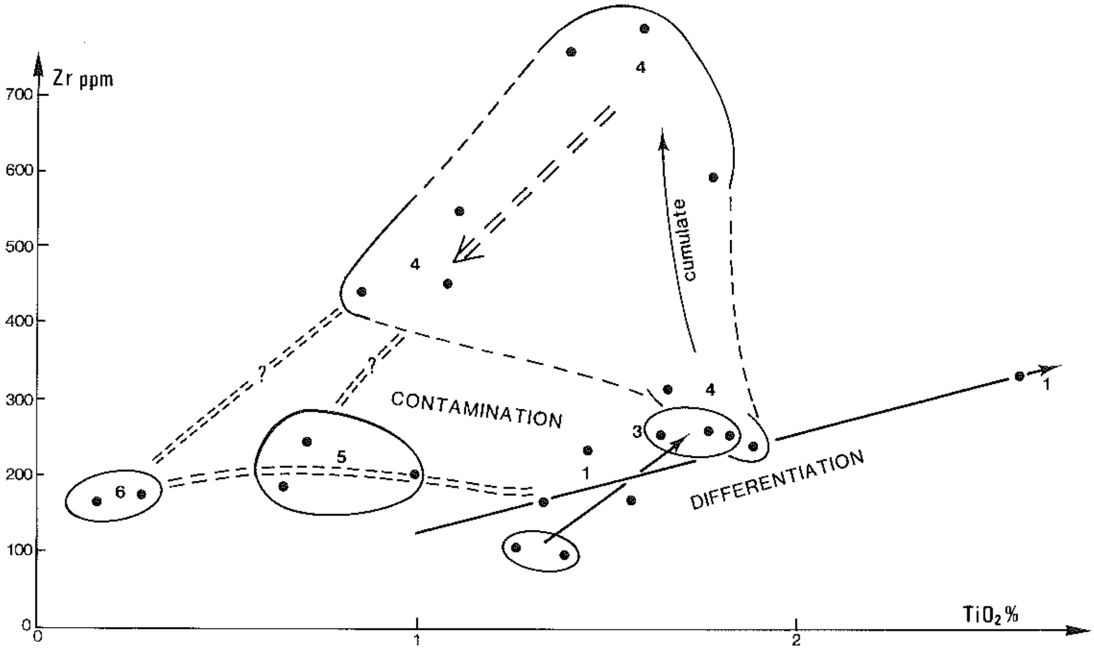

Fig. 10.- Zr - TiO_2 diagram for the Tin Toudadin pluton. Numbers are the same than for fig. 9 (see text for comments).

GEOCHRONOLOGICAL RESULTS

We have used three complementary approaches: fission track dating on zircons, U/Pb on zircons and Rb-Sr on biotites. The results are presented in Table 1.

1. Fission track ages

The fission track dating procedures were as recommended by Naeser (1978). The zircons were dated using the external detector method. Prior to irradiation, zircons are etched in an eutectic KOH-NaOH melt at 230°C for 2 to 4 hours. After irradiation, the muscovite detectors are etched in 48% HF for 15 minutes at 20°C. Samples received thermal neutron dose of 18.8 x 10^{15}n/cm^2 in the ILL reactor at CENG (Grenoble). The dose was monitored using ^{59}Co foils. To reduce the effet of anisotropy of etching, only the grains which show sharp polishing scratches are counted (Gleadow, 1978). Uncertainties are calculated using the method of Johnson *et al.* (1979).

The ages obtained are 635 ± 21 My (sample 2365, Tin Toudadin) and 645 ± 16 (sample 2421, Tassedrak). The fission track closure temperature generally accepted for zircons is about 250 ± 50°C. This wide temperature range reflects both estimates of uncertainty and variation in closure temperature with cooling rate (Dodson, 1981).

2. U/Pb ages on zircons

Eleven fractions of zircons have been analyzed from the two plutons (Tassedrak and Tin Toudadin). A mixed ^{208}Pb/^{235}U spike was added to the small teflon bombs before attack. Pb and U were separated by anionic resins using a technique sligtly modified from Manhes *et al.* (1978). Pb is loaded with H_3PO_4 and silica gel on a single Re filament. U

Table 1. - Available isotopic ages in and close to the Iforas Granulitic Unit. Comparison with the Main Batholith area. New data obtained during the studies are outlined.

Relative chronology	Location	Sample	Rb-Sr Biotite age	Fission track	U/Pb zircon	Rb-Sr isochron
Central Iforas						
pre D_1	In Bezzeg	N 186	617 ± 12 * (1)			
pre D_2	Ibedouyen	A20	595 ± 12 * (2)		$596 \pm ^{4}_{2}$ (4)	(642 ± 84) (1)
	Tiouine	Q 261/2429	**620 ± 12**			
	In Afara	Q 175.1/2354	**571 ± 12**			
	Tin Biden	Q 216.1/2392	**574 ± 12**			
	Tin Toudadin	Q 186.1/2365	**598 ± 12** *	**635 ± 21**		
		Q 192.1/2379	**590 ± 12** *		**$563 \pm ^{8}_{9}$**	
syn to late D_2	**Adjiri**	Q 212/2390	**607 ± 12**			
	Abeibara				566 ± 8 (3)	
post D_2	**Tassedrak**	Q 253.1/2419	**551 ± 12** *			
		Q 255.1/2421	**577 ± 12** *	**645 ± 16**	(563)	
	O. Erherher	Q 195.1/2381	**560 ± 12**			
Main Batholith						
pre D_2	O. Teggart	M 17			693 ± 1 (3)	
syn D_2	Oumassène	N 164	611 ± 12 * (1)			
	Tadjoudjemet	N 139	605 ± 12 * (1)			614 ± 45 (1)
	Adma				616 ± 11	
					613 ± 3 (3)	

Asterisk indicate biotite-whole rock pairs. Other data are from : (1) Bertrand and Davison, 1981; (2) Lancelot *et al.*, 1983; (3) Ducrot *et al.*, 1979; (4) Caby *et al.*, 1983.

Table 2. - U/Pb isotopic data (Tin Toudadin and Tassedrak plutons). Common Pb corrections are $^{206}Pb/^{204}Pb = 18.60$; $^{207}Pb/^{204}Pb = 15.50$. Errors on $^{206*}Pb/^{238}U$ and $^{207*}Pb/^{235}U$ is 1.5%. Constants used are from Jaffrey *et al.* (1971). The granulometry of fractions is expressed in mesh.

N°	Pb^{206}ppm	U ppm	206/204	Pb^{207*}/U^{235}	Pb^{206*}/U^{238}	207*/206*	Apparent ages		
				(1)	(2)	(3)	(1)	(2)	(3)
2421 <200	20.1	240.4	1032.8	0.7957	0.095590	0.060405	595	589	618
2421 170/11 (1)	18.4	227.5	2527.8	0.7914	0.093212	0.061612	592	575	661
2421 170/11 (2)	25.3	310.5	4572.3	0.8070	0.094254	0.062133	601	581	678
2419 2	0.0386	0.4784	1079.6	0.8719	0.092169	0.068650	637	569	888
2379 (2)	30.3	371.2	1019.1	0.8354	0.093263	0.065006	617	575	776
2379> 200 (3) n.m.	24.3	302.0	1805.4	0.7975	0.092773	0.062380	595	573	687
2379< 200 (4) n.m.	28.5	353.4	1455.2	0.8112	0.092708	0.063497	604	572	725
	28.4	353.4	1602.1	0.8098	0.092584	0.063473	603	571	725
2379 (1.1.1)>170 n.m.	49.0	577.9	1959.6	0.9667	0.097764	0.071760	687	601	979
2379 (2.1.1.)> 170 m.	84.8	1092	1059.2	0.7907	0.088802	0.064619	591	549	762
2379 big zircon	3.02	35.3	552.2	0.9990	0.096231	0.075338	703	593	1077

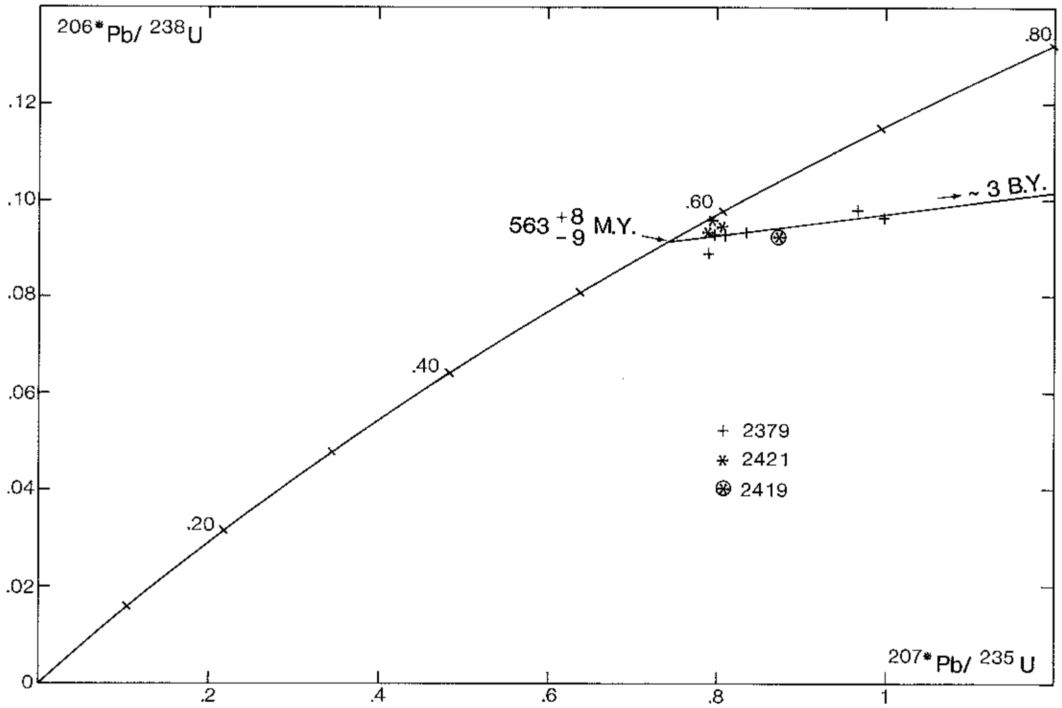

Fig. 11.- Concordia diagram for the Tin Toudadin (sample 2379) and the Tassedrak (samples 2421 and 2419) plutons.

is loaded either on double Re filaments or as U_2O_3 on a single W filament with Ta and H_2PO_4. Total lead processing blanks are smaller than 1 ng. The analytical data are given on Table 2. When plotted on a concordia diagram (fig. 11), the data show some scattering. Removing the fraction richer in uranium out of the regression line (magnetic zircons), the five remaining fractions of the sample 2379 (Tin Toudadin) define a discordia line intersecting the concordia at $563 \pm^{8}_{9}$ My with an upper intercept around 3.2 ± 0,5 By. This age is very similar to the results published by Lancelot *et al.* (1983) on the Abeibara granite.

The analytical points for the sample 2421 (Tassedrak) are close to the concordia and hence do not precisely define an age. The unique analyzed fraction of the sampe 2419 (Tassedrak) lies close to the discordia determined on the sample 2379.

In all the samples the zircons appear highly heterogeneous in thin section and on polished grains with cores and zoning. Cloudy yellow bipyramidal prisms are associated with clear pink long needles. A SEM and microprobe study has shown that in some crystals, zircon is replaced, either along the margin or in the core, by a hydrated Fe-Ca-Zr-silicate. The replacement has taken place in the form of concretions superimposed upon the zoning. The composition of this replacing mineral has been determined on three points (sample 2429 : Tiouine granite) : the CaO content varies from 4.5% to 6.5% and the FeO content from 1 to 9%.

This particular feature and the evidence of unherited cores in most of the zircon crystals may explain the results. When compared with fission track ages and with biotite ages, the lower intercept gives a younger age. Inherited zircons from the Eburnean to Archean granulites are consistent with the poorly defined upper intercept. The replacement of zircons by an hydrated zircono-silicate may have produced lead loss after the emplacement of the granitoids.

3. Rb-Sr biotite ages

The results are given in Table 1. Some ages are model ages, others are calculated from biotite-whole rock pairs. Ages are compared with previous data obtained from areas close to the IGU (Bertrand and Davision, 1981; Davison, 1981). Analytical data are given in Table 3. Three groups of ages may be defined :

Table 3. - Rb-Sr analytical data.

Location	Sample		Rb	Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
Tiouine	Q 261					
	(2429)	Bi	696	21.3	94.760	1.55176 ± 0.00085
In Afara	Q 175.1					
	(2354)	Bi	418	6.5	187.433	2.23114 ± 0.011
Tin Biden	Q 216.1					
	(2392)	Bi	262	9.5	80.086	1.36114 ± 0.0001
Tin Toudadin	Q 186.1	WR	28.7	1011	0.0821	0.70844 ± 0.00005
	(2365)	Bi	187	12.1	44.915	1.09115 ± 0.00016
	Q 192.1	WR	50.3	1007	0.1446	0.70816 ± 0.00007
	(2379)	Bi	246	10.6	67.465	1.27544 ± 0.00074
Adjiri	Q 212					
	(2390)	Bi	368	12.3	86.748	1.45732 ± 0.00074
Tassedrak	Q 253.1	WR	60.6	688	0.2549	0.70797 ± 0.00007
	(2419)	Bi	387	18.8	59.681	1.17708 ± 0.00009
	Q 255.1	WR	82.8	579	0.4141	0.70895 ± 0.00007
	(2421)	Bi	459	19.4	68.464	1.26873 ± 0.00007
O. Erherher	Q 195.1					
	(2381)	Bi	378	9.7	113.033	1.60837 ± 0.00009

* Biotite apparent ages have been calculated with an initial ratio of 0.7080.

- older than 600 My (Tiouine)
- ca. 600 My (Tin Toudadin)
- 580 - 560 My.

On the map (fig. 4), the areal distribution of these ages clearly shows that most ages of 600 My and older come from the granitoids outcropping outside of the IGU except for the Tiouine and Tin Toudadin which are located close to the middle of the granulitic unit. On the contrary, young ages correspond to plutons lying close to the margin of the IGU, irrespectively from their relative chronology.

DISCUSSION AND CONCLUSIONS

The precise chronology of the Pan African orogeny in the Iforas region is not well know despite an increasing amount of data. However it seems likely that during a time-span of 100 My, ca. 600 My ago, sporadic deformation and thermal events occurred, the youngest ones at least being clearly related to a plate collision process. A first approach using the Rb-Sr isochron method has confirmed the Pan African age for the evolution of the region as a whole but has failed to establish a precise chronology (Bertrand and Davison, 1981). More recent results (Liégeois and Black, 1983) focussed on the later evolution of the «*Main batholith*» have given a sequence of ages in good agreement with the relative chronology established in the field.

The main goal of this study was to describe and interpret the special case of the Pan African evolution of the older Iforas granulites characterized by heterogeneous tectonic and thermal behaviour. As many small plutons were emplaced during Pan African times, for which field evidence and structural analysis permit a good relative chronology to be established, it was hoped that the non penetrative behaviour may have favoured the persistency of the pre-D_2 ages. Petrological and geochemical investigations carried out on some pre-D_2 plutons confirm that they share many similarities with a plutonic unit defined in the Main batholith. Here a unit of deformed monzodiorites and orthopyroxene bearing monzonites associated with a high K pegmatitic granite predates the emplacement of the «*older batholith*» granodiorites (Bertrand and Davison, 1981). Rock types and geochemical trends (subalkaline affinities) are identical to those of the Tin Toudadin, Tadelok and Afara complexes intruded in the Iforas Granulitic Unit. South of Kidal, a quartz-diorite believed to belong to the same association has yielded a 690 My old U/Pb zircon age (Ducrot *et al.*,1979), though the orogenic significance of this age is still in question.

Thus, to the west of the Iforas Granulitic Unit, in the Main batholith region, we may consider that the timing of the D_2 and later evolution is fairly well known. The older plutonic components of the batholith - excluding the still older subalkaline complexes - are bracketed between 620 My and 600 My, and the Rb-Sr biotite ages are in the same range (Bertrand and Davison, 1981; Ducrot *et al.*, 1979; Liégeois and Black, 1983). To the east of the Iforas Granulitic Unit, the chronology is less clear and some ages close to 640 My determined by the Rb-Sr isochron method are questionable since Caby *et al.* (1983) report a 600 My age using U/Pb on zircons for pre-D_2 orthogneisses (Ibedouyen complex). However, most of the Rb-Sr biotite ages are also close to 600 My.

If we consider now the new results presented here, the biotite ages are very interesting. The more important figure is 620 My : the plutons which yield the older biotite ages were intensely recrystallized during D_2 and thus the 620 My age is probably close to the age of D_2. Following the same reasoning, the 600 My biotite ages outside the Iforas Granulitic Unit correspond clearly to plutons emplaced after the D_2 deformation. Thus the age range corresponding to D_2 (620 - 600 My) is the same in the Iforas Granulitic Unit area than in the Main batholith. This implies that the biotite ages younger than 600 My correspond either to plutons actually emplaced after D_2 or to reset ages related to some reheating process. Field evidence suggests that the Tassedrak and Erherher plutons correspond to the first case. Others plutons, apparently pre D_2, seem to have been reset. It has already been noted that the isotopically reset plutons (fig. 4) are located close to the margins of the Iforas Granulitic Unit where the D_3 deformation has been especially intense and where cross-cutting granites and adamellites are younger than D_3 (Arhli, Tin Oulli, fig. 4).

When considering the U/Pb results, the ill-defined Tassedrak age could be close to the emplacement age. On the contrary, the lower intercept of the discordia ($563 \pm ^{8}_{9}$ My) for the Tin Toudadin pluton seems to be geologically meaningsless when compared with the 600 My biotite ages on the same rocks. If the zircon alteration observed is related to fluid circulation in condition hot enough to reset the zircons, why are the biotites not also reset ? We prefer to interpret the U/Pb pattern as the result of lead loss from inherited zircons, the pluton being emplaced some time before 600 My. The upper intercept confirms only the existence of an old crustal component and has no age significance. A similar age and U/Pb pattern was recently published (Lancelot *et al.*, 1983) and interpreted as the emplacement age for a pluton which is proved from field evidence to be pre-D_3 in age (Abeibara granite). As its petrography and major element geochemistry is very similar to that of the Tiouine pluton (biotite age : 620 My) our data suggests that this interpretation is doubtful.

Classically, the fission track ages should be interpreted as the age of the last cooling (below 250 ± 50°C). Such an interpretation is not in good agreement with the results obtained on the same rock by other methods. The fission track ages obtained for the Tin Toudadin and Tassedrak plutons are either apparent ages or reflect the fact that the structural evidence leads us to expect older ages than those obtained both by U/Pb and Rb/Sr especially for the Tin Toudadin pluton. The actual emplacement age of Tin Toudadin is probably older than 600 - 620 My. Similarly the analyzed sample from the Tassedrak is taken from an agmatitic zone were early diorites displaying many geochemical similarities with Tin Toudadin diorites are mixed with adamellite; the zircon may thus be inherited from a pre-D_2 stage.

It must be stated that while the closure temperature is well defined for cooling systems, the opening temperature in the case of reheating is less well known as suggested by results obtained recently on zircons from an alpine ophiolite, submitted to alpine H.P. metamorphism, which retained its Triassic age (Carpena and Caby, 1983).

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