U-Pb dating and Sm-Nd isotopic analysis of granitic rocks from the Tiris Complex: New constaints on key events in the evolution of the Reguibat Shield, Mauritania

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Abstract: The Reguibat Shield of N Mauritania and W Algeria represents the northern exposure of the West African Craton. As with its counterpart in equatorial West Africa, the Leo Shield, it comprises a western Archaean Domain and an eastern Palaeoproterozoic Domain. Much of the southern part of the Archaean Domain is underlain by the Tasiast-Tijirit Terrane and Amsaga Complex which, along with the Ghallaman Complex in the northeast, preserve a history of Mesoarchaean crustal growth, reworking and terrane assembly. This study presents new U-Pb and Sm-Nd data from the Tiris Complex, a granite-migmatite-supracrustal belt, that intervenes between these units and the Palaeoproterozoic Domain to the northeast.

New U-Pb geochronology indicates that the main intrusive events, broadly associated with formation of dome-shaped structures, occurred at around 2.95 to 2.87 Ga and 2.69 to 2.65 Ga. This study also recognises younger regional metamorphism and intrusion of syn-tectonic granites located within major shear zones at around 2.56 to 2.48 Ga. Sm-Nd depleted mantle model ages indicate that magmatism involved recycling of crustal source components older than at least 3.25 Ga in age. Comparison with other Archaean units in the Reguibat Shield and in the Leo Shield illustrate the

importance of deformation and tectonism of a regional greenstone-sedimentary province prior to around 3.00 Ga as well as subsequent magmatic episodes broadly equivalent in age to those in the Tiris Complex.

1. Introduction

The Reguibat Shield of N Mauritania and W Algeria comprises an uplifted area of Precambrian rocks that has been stable since about 1.70 Ga. It forms the northern area of exposure of the West African Craton, the southern being the Leo Shield of equatorial West Africa (Fig. 1). Both shield areas comprise a western domain of mainly Archaean metamorphic and granitic rocks and an eastern domain of largely Palaeoproterozoic granitic and volcano-sedimentary rocks (Bessoles, 1977; Dillon & Sougy, 1974). In Mauritania, these crustal domains were juxtaposed during the, *c.* 2.10-2.00 Ga, Eburnean Orogeny (Schofield et al., 2006).

This paper is based on recent 1: 200,000 scale reconnaissance geological surveying combined with geochronological and whole rock isotopic studies from the Tiris Complex (O’Connor et al., 2005), a granitoid-migmatite-supracrustal belt exposed near the NE margin of the Archaean Domain (Fig. 2). The main aim is to provide an account of the geological features, provide new geochronological framework for this otherwise poorly reported region and consider their bearing on the overall evolution of the shield and West African Craton as a whole.

2. Geological setting

Rocci et al. (1991) proposed simplified ‘lithostratigraphic domains’ for the Archaean part of the Reguibat Shield: the Tasiast-Lebzenia domain in its southwest part; the Amsaga-Tiris-Ouassat domain in its central part; and the Ghallaman domain in its eastern part. The former has recently been reclassified as the Tasiast - Tijirit Terrane (Pitfield et al., 2005). The Amsaga-Tiris-Ouassat domain is herein treated as separate lithostratigraphic entities named Tiris and Amsaga complexes. The discreet assemblage of gneisses and intrusive igneous rocks of the Ghallaman domain is herein referred to as a Complex for consistency (Fig. 2). The Ouassat Complex has recently been shown to comprise accreted parts of the eastern Palaeoproterozoic Domain

(Schofield et al., 2006). The term “Choum-rag el Abiod Terrane” was introduced by Key et al. (2008) for the eastern part of the Archaean Domain and is largely synonymous with the Amsaga Complex. However, as the northward extension of this unit was not defined as part of that study, we have reverted to the older nomenclature.

2.1. Tasiast – Tijirit Terrane

The Tasiast - Tijirit Terrane comprises tonalitic and granitic gneisses interleaved with amphibolitic units interpreted as remnants of older greenstone belts. The overall architecture of the terrane is dominated by N to NE-oriented lithodemic belts and shear zones. These are cross-cut by plutons of biotite-tonalite and metaluminous granitoids which generally form the cores of dome-like structures (Key et al., 2008). Migmatite gneiss has yielded a metamorphic age of around 2.97 Ga, while felsic metavolcanics from the terrane have yielded Nd T_{DM} ages ranging from 3.05 to 3.60 Ga (Chardon, 1997) illustrating the contribution of older crustal source components (Key at al., 2008). Younger tectonothermal events are recorded by tonalitic intrusions dated using U-Pb geochronology at 2933 ± 16 Ma along with a syntectonic augen granite from the Tâçarât-Inemmaûdene Shear Zone intervening between the Tasiast-Tiirit Terrane and adjacent Amsaga Complex, dated at 2954 ± 11 Ma (Key et al., 2008).

2.2. Amsaga Complex

The Amsaga Complex was first surveyed by Barrère (1967) who outlined a number of informal lithologic associations. Recent mapping (Pitfield et al., 2005; O’Connor et al., 2005) has confirmed that a large part of the complex comprises a diverse association of quartzo-feldspathic granoblastic and migmatitic gneisses of tonalitic, trondhjemitic and granodioritic composition as well as hypersthene-bearing charnockitic gneisses with minor units of garnet-cordierite-sillimanite gneiss and basic – ultrabasic rocks, interleaved along a network of arcuate NNE- to N-trending ductile shear zones. Much of the Amsaga Complex preserves steep proto- to ultramylonitic fabrics associated with the array of ductile shear zones that dissect the region. However, competent quartzofeldspathic gneisses locally preserve areas of relatively low-strain and exhibit consistent NE-SW striking subvertical planar fabrics

(O’Connor et al., 2005).

Formation of gneisses in the Amsaga Complex has been constrained by ages of around 3.50 and 3.40 Ga (Auvray et al., 1992; Potrel, 1994; Potrel et al., 1996) including orthogneiss dated by the U-Pb method at 3515 ± 15 Ma and 3422 ± 10 Ma (Potrel et al., 1996). Incorporation of an even older crustal component is suggested by Nd T_{DM} ages of around 3.60 Ga (Potrel et al., 1996). A subsequent event has been proposed based on U-Pb dating of charnokite at 2986 ± 8 Ma (Potrel et al., 1998). The youngest thermal/magmatic event preserved in the complex was proposed by Potrel et al. (1998) on the basis of a granulitic gabbro dated by Auvrey et al. (1992) at around 2.71 Ga. This is supported by dating of discrete, apparently post-tectonic granite bodies including the Touijenjert Granite, which cross-cuts gneisses of both the Amsaga Complex and Tasiast-Tijirit Terrane and provides a minimum age for their amalgamation. This granite has yielded U-Pb ages of 2715 ± 11 Ma and 2726 ± 7 Ma (Auvrey et al., 1992; Potrel et al., 1998) and a Sm-Nd mineral isochron age for an associated gabbro of 2705 ± 54 Ma (Potrel et al., 1998). Their petrogenesis involved recycling of older crustal source components indicated by Nd T_{DM} ages of around 3.2 to 3.1 Ga (Potrel, 1994; Potrel et al., 1996; 1998).

2.3. Tiris Complex

The Amsaga Complex is juxtaposed against the Tiris Complex along a broad belt of aluminous gneisses (Bronner, 1977; Rocci et al., 1991; O’Connor et al., 2005). To the northeast, these pass into an extensive complex dominated by foliated and unfoliated granitic rock, locally hypersthene-bearing aluminous or migmatitic gneiss and ferruginous quartzite with several large (up to around 20 km long) bodies of amphibolite. The only published ages from the Tiris Complex are Rb-Sr isochron ages of 2779 ± 83 Ma and 2706 ± 71 Ma from granulite facies gneisses (Vachette & Bronner, 1975; Vachette, pers comm., in Cahen et al., 1984). The geology of the complex is described in more detail below.

The Tiris Complex is locally tectonically intercalated with metasediments of the Ijil Complex. The most extensive outcrop of this unit forms Kediat Ijil (Fig. 3), a broad inselberg south of the town of Zouerate comprising metasediments including ferruginous quartzite, capped by a distinctive conglomerate unit. Previous workers have interpreted the Ijil Complex as a klippe of Palaeoproterozoic rocks, resting allochthonously on Archaean basement of the Tiris Complex (e.g. Bronner, 1977; Bronner & Chauvel, 1979; Bronner et al., 1992; Huon et al., 1992, Schofield & Gillespie, 2007).

2.4. Ghallaman Complex

Two lithostratigraphic associations are recognised within the Mesoarchaean basement of the Ghallaman Complex (Lahondère et al., 2003): the Temmimichate-Tsabaya Complex comprising a granulite facies, basic to ultrabasic, meta-igneous association, and the Zednes Suite (Fig. 2), an association of tonalitic plutonic and gneissose rocks dated at around 3044 ± 5 Ma, intruded by a suite of unfoliated granite-granodiorites dated at 2915 ± 18 and 2832 ± 4 Ma (Lahondère et al. 2003). Relationships between the domain and the Tiris Complex are largely obscured by younger cover rocks and superficial deposits. However, recent surveying has demonstrated that gneisses of the Temmimichate-Tsabaya Complex are structurally contiguous with granitic gneisses and ferruginous quartzites of the Tiris Complex, have at least some penetrative deformation in common and share the same overall W-E structural grain dominant in that area (Schofield et al., 2003; O'Connor et al., 2005).

3. Geology of the Tiris Complex

In general, the Tiris Complex comprises a region of granitoid domes with intervening keels of supracrustal rocks, crosscut by linear belts of tight folding and steep fabrics. It is estimated to comprise approximately 70% granite (*sensu stricto*) and contrasts markedly with the adjacent Archaean units. The following provides a description of the granite lithologies, their host rocks and overall structural setting.

3.1. Lithodemic divisions

The new geological survey of the region (O'Connor et al., 2005) has defined three units within the Tiris Complex that are as follows:

3.1.1. El Gheicha Formation

The El Gheicha Formation crops out in the southwestern part of the study area (Fig. 3). It preserves an arcuate contact with the Mirikli Formation to the NW, following the overall structural grain of the region and is near-coincident with the southern limit of bands of ferruginous quartzite and northern limit of aluminous facies recognised by Bronner (1977). It typically preserves locally migmatitic, cordierite and biotite bearing gneisses with or without garnet, sillimanite or kyanite and more rarely orthopyroxene as well as thin, impersistent units of ferruginous rock and metamafite (see Supplementary Data A for lithological details). The garnet-cordierite-sillimanite ± spinel and orthopyroxene-bearing assemblages preserved in the El Gheicha Formation indicate granulite facies conditions. The gneisses are predominantly cordierite-bearing which indicates metamorphic conditions in the range 600-850^{o}C and <8Kb. The southern margin of the unit is in contact with foliated porphyritic granite, with subordinate leucogranite and gabbronorite of the F'Derik Suite, which intervenes between the Tiris and Amsaga complexes. This magmatic suite is confined within an anastomosing plexus of ductile shear zones that juxtapose these two units. It is elongate and foliated parallel to the shear zone and interpreted as being syn-tectonic.

3.1.2. Mirikli Formation

The Mirikli Formation occupies the central and northeastern parts of the Tiris Complex (Fig. 3) and comprises abundant schlieric granite, granite and monzonite (see Supplementary Data A for lithological details). These are locally foliated or migmatitic, preserving a variety of banded fabrics suggestive of both anatexis of source gneisses and cross-cutting, mixing and mingling of various intrusive facies. Grain scale and penetrative sub-solidus fabrics are also locally preserved within more homogeneous portions. Prominent bands of ferruginous quartzite and aluminous paragneiss are common throughout well-exposed parts of the unit; several of these are currently exploited as a source of iron ore. Bands and pods of metamafite (commonly amphibolite) are widespread. Calcsilicate-rock, aluminous gneiss, quartzite, quartzofeldspathic gneiss, hypersthene gneiss, 'charnockitic' granite and monzonite occur as minor lithological components. Widespread migmatisation, the presence of mica (mainly biotite) in quartzofeldspathic rocks, and widespread occurrence of hornblende-bearing amphibolite indicates that large parts of the formation have not exceeded middle to upper Amphibolite Facies conditions. However, the presence of 2-

pyroxene-bearing metamafic rock at Guelb el Rhein and an occurrence of sillimanite-garnet-quartz-K-feldspar-plagioclase-cordierite gneiss at Guelb Touijinjert suggest that granulite facies assemblages are preserved locally in rocks of suitable (e.g. mafic or aluminous) composition. Cuney et al. (1975) reported granulite facies, peak metamorphic conditions from ferruginous quartzites containing quartz-orthopyroxene-magnetite ± Ca-pyroxene ± garnet assemblages.

3.1.3. El Khadra Formation

The El Khadra Formation is wholly enclosed by the Mirikli Formation and crops out in the north of the study area (Fig. 3). Like the Mirikli Formation, it consists of a lithologically variable assemblage of quartzofeldspathic and calc-silicate metasedimentary and (meta-) igneous rocks (see Supplementary Data A for lithological details). However, it is distinguished by a higher proportion of metasedimentary rock at outcrop and the common and widespread occurrence of numerous, generally closely-spaced bands of ferruginous quartzite. The dominantly quartzofeldspathic character of much of the formation is unhelpful in terms of determining metamorphic conditions. The metacarbonate rocks indicate the original limestones contained a range of impurities (silica, alumina etc.), rendering a precise estimation of metamorphic grade very difficult. Nevertheless, the widespread occurrence of metamafic rock in which amphibole is the principal mafic mineral suggests that the formation was metamorphosed under Amphibolite facies conditions.

3.2. Structure

Bronner (1992) indentified three domains in the Tiris Complex (Fig. 3) that provide a useful framework for description and interpretation of the structure. Despite marked contrasts between the three structural domains and intervening tectonic boundaries, contiguity of lithodemic units argues against an exotic relationship.

The structure of the southwestern part of the study area (SW domain) is characterised by NW-striking, steep to moderately inclined planar fabrics with steeply-plunging mineral lineations and NW-elongate, more or less upright elliptical folds (Fig 4a). At least three superposed fold generations are preserved in this domain with prominent type 3 interference figures (Ramsay, 1962) preserved at outcrop scale

(Fig. 5) indicating coplanar refolding of earlier inclined or recumbent structures. The last, upright fold generation (local F3) deforms a10’s to 100’s of metres-scale interlayering of metasedimentary units and foliated granitic rocks. The boundary between this structural unit and the Central Domain is taken at a steep, linear high strain zone extending NW from the southern margin of Kediat Ijil (Accident Sud Ijilien of Bronner, 1992; Fig. 3). This zone preserves increasing strain toward the NE margin of the domain in which folds become tighter, and locally isoclinal, fabrics are invariably steeply inclined and locally mylonitic with steeply plunging mineral lineations, locally cross-cut by narrow granitic dykes.

The central part of the Tiris Complex (Central domain) is characterised by the absence of a strong regional structural trend, although a history of polyphase folding is preserved within the thin units of metasedimentary rock (Bronner, 1992) that also attests to an early generation of recumbent structures and metamorphic fabrics. The overall structure is dominated by the “mantled gneiss domes” described by some earlier workers (e.g. Rocci et al., 1991). First order (local) F3 structures in this area form a series of impinging ellipsoidal, dome-shaped or sheath-like antiforms (Fig. 6), of several kilometres diameter, cored by foliated to unfoliated granite and migmatite, and separated by complex, tight synforms preserving the main units of ferruginous quartzite and metasedimentary gneiss. Hinges are strongly curvilinear and steeply plunging, and are associated with a well-developed, steeply, sub-radially plunging, mineral stretching lineation that is strongly developed in the metasediments, but largely absent from the granite cores (Fig. 4b). Granite fabrics are generally more intense toward the synformal margins of the domes, consistent with those in expanding or syn-kinematic plutons (e.g. Ramsay, 1981; Cruden, 1990) suggesting that they are coeval with dome/synform formation.

In the northeast of the study region (NE domain) the structure is characterised by an approximately W-trending grain and W-elongate, upright elliptical F3 folds. This domain is uniquely characterised by linear zones of steeply NE to SE-plunging *ls*-tectonites preserved in the metasedimentary rocks with local NE to SE-dipping planar fabrics (Fig. 4c). These are unaffected by earlier fold phases and are interpreted as recording the youngest deformation episode episode in this part of the study area. The northern margin of this domain is defined by the El M’dena Fault Zone (Fig. 2) that juxtaposes the Ghallaman Complex against Late Archaean rocks and Palaeoproterozoic metasediments and granitoids intercalated during the ca. 2.1 Ga Eburnean Orogeny. The exposed southeastern margin of the domain is contiguous with another belt of imbricated metasedimentary rocks attributed to the Early Palaeoproterozic Idjil Complex, the El M’haoudat range (Fig. 3).

4. U-Pb geochronology and Sm-Nd isotope geochemistry

In order to augment the existing database of U-Pb analyses from the Reguibat Shield, four samples were collected from the Tiris Complex for geochronological study. The main aim was to constrain the age of the widespread granite magmatism preserved in this part of the shield to enable a more detailed understanding of its overall tectono-thermal evolution. The samples represent granites from the SW and Central structural domains, the Accident Sud Ijilien and the F’derik Suite. The NE structural domain was not represented, partly due to the dominance of metasedimentary rock and absence of suitable material for dating. U-Pb ages were determined by Laser Ablation Multi-Collector Inductively Coupled Plasma Mass Spectrometry (LA-MC-ICP-MS) at the NERC Isotope Geosciences Laboratory (NIGL), Keyworth, UK. Zircons were separated from the rock sample using standard separation techniques and mounted in 1” diameter epoxy resin mounts and polished down to expose an equatorial section through the crystals. Analyses were conducted following Thomas et al. (2009) except that GJ1 zircon was used as the primary reference material with 91500 and Plesovice run as validation materials. The Concordia age result for 91500 was 1059.4 ± 4.3 Ma (weighted average Pb/U age = 1059.5 ± 5.2 Ma, MSWD = 1.3 n = 25) and the Concordia age result for Plesovice was 337.0 ± 1.2 Ma (weighted average Pb/U age = 336.2 ± 1.2Ma, MSWD = 0.57, n = 49). Data were reduced and uncertainties propagated using an in-house spreadsheet calculation package with ages determined using the Isoplot 3.16 macro of Ludwig (2003). Despite careful selection of all mineral grains the zircons were of relatively poor quality resulting in largely discordant data. This is not unusual for zircons from Archaean and Proterozoic terranes and only interpretable, concordant data have been plotted in the figures. All data are however provided in the supplementary data tables (Supplementary Data B).

Whole rock Sm-Nd isotope dilution analyses of the four samples used for U-Pb age determination were also carried out at NIGL using thermal ionisation mass spectrometry (ID-TIMS). Sample dissolution, chemical separation and analysis procedures are detailed in the supplementary text (Supplementary Data C). Tabulated results for both U-Pb and Sm-Nd analyses are lodged as supplementary materials (Supplementary Data D).

4.1. Sample 23120012

This sample comprises pinkish-grey, biotitic, fine granite with scattered cm-scale biotitic clots and schlieren and was collected from the Mirikli Formation (23°02’49”N / 12°20’21”W). This sample was collected as a representative component of the syn-tectonic granite domes of the central structural domain with the aim of constraining the age of magmatism and dome formation, also providing a minimum age on the earlier flat lying structures. It yielded fairly poor quality zircons with no apparent cores or rims (Fig. 7a). Forty analyses were conducted on twenty seven zircons. Most of the analyses were strongly discordant; however, five near concordant analyses suggested two age components (Fig. 8a). These are interpreted to represent either crystallization of the granite at 2948 ± 11 Ma with ancient Pb-loss or 2875 ± 18 Ma with inheritance. This sample yielded an $^{\varepsilon}$Nd value of –1.4 at t = 2948 Ma and T_{DM} 3.25 Ga.

4.2. Sample 22120276

This sample comprises pink to red, schlieric, foliated, fine to medium grained, garnet-bearing, biotite granite and was collected from the Mirikli Formation in the SW domain (22º22'10"N / 12º37'00"W). The schlieric character (prominent biotite-rich clots and trails) points to an anatectic origin. This sample was collected to provide a date for magmatism in this domain. Monazite (Fig. 7b) and variable quality zircons were recovered from the sample. The zircons were mainly elongate with some larger, more blade-like crystals (Fig. 7c). Eight monazites and fifteen zircons were analysed, multiple times in the case of zircon. Fifteen zircon analyses were included in a Concordia age result (Fig. 8b) of 2654 ± 8 Ma (2σ). This is interpreted to represent the crystallisation age of the rock. Seven of the eight monazite analyses result in a concordia age of 2482 ± 7 Ma (2σ, Fig. 8c). This is interpreted to represent the timing of metamorphism that crystallised the garnet in this sample. This sample yielded an $^{\varepsilon}$Nd value of –1.9 at t = 2654 Ma and T_{DM} 3.04 Ga.

4.3. Sample 22120262

This sample was collected from the Mirikli Formation within the high strain zone of the Accident Sud Ijilien (22º37'20"N / 12º42'15"W) and comprises foliated, weakly porphyroclastic, biotitic metagranitic rock sampled from one of a series of dyke-like intrusions forming 10 m-scale bodies cross-cutting the main foliation adjacent to the Accident sud Ijilien. These bodies are interpreted as syn-tectonic and were collected in order to constrain the maximum age of deformation within this zone, post-dating the formation of pervasive gneissosities within the host rock. Modally, the rock lies close to the monzogranite-granodiorite boundary, and plagioclase is partly altered to clinozoisite and epidote. Heavy mineral separation yielded abundant zircon. Two distinct populations were distinguished (Fig. 7d). More than 90% of the grains were variably cloudy and altered, elongate, smaller crystals with aspect ratio of 2:1-5:1. The second population comprised clearer, more glassy-looking crystals, suggesting a lower uranium concentration than the first population. Of twenty-seven zircon analyses from this second population six provided near concordant data. The age spread suggests crystallization of the granite at 2487 ± 8 Ma (2σ, Fig. 8d) with inheritance at c.2550 and 2700 Ma (Fig. 8d). This sample yielded an $^{\varepsilon}$Nd value of –5.7 at t = 2487 Ma and T_{DM} 3.14 Ga.

4.4. Sample 211200139

This sample comprises porphyritic granite collected from the F'Derik Suite at the southern margin of the complex (21º31'47"N / 12º52'19"W). This unit of syntectonic granitic rocks was collected to provide an age constraint on movement along the shear zone intervening between the Amsaga and Tiris complexes. It yielded good quality titanite and allanite (Fig. 7e) and good quality bipyrimidal and elongate zircons (Fig. 7f). Thirty one analyses from twenty two zircons were performed on this sample. Four analyses were excluded from a calculation giving a Concordia age of 2472 ± 6 Ma (2σ, Fig. 8e). This is interpreted to represent the crystallization age of the rock. This sample yielded an $^{\varepsilon}$Nd value of –2.1 at t = 2472 Ma and T_{DM} 2.9 Ga.

5. Discussion

Taken together with their field relationships, the U-Pb and Sm-Nd analyses presented herein provide new constraints on the geological evolution of the Tiris Complex. Despite significant challenges presented by the paucity of modern geochronological determinations, we go on to discuss these in the context of the evolution of the Reguibat Shield and West African Craton as a whole.

5.1 Geological development of the Tiris Complex

The oldest rocks preserved in the Tiris Complex, pre-dating the main phase of granite magmatism at around 2.95 Ga, comprise metasedimentary ferruginous quartzite and aluminous and hypersthene-bearing paragneiss of the Mirikli Formation. These may be equivalent to similar assemblages preserved in the El Khadra and el Geicha formations. The presence of bands and pods of metamafite intercalated with the metasedimentary host indicate that there was also an early phase of mafic dyke emplacement, although the age of this also remains unconstrained.

Early tectonism, also pre-dating the main intrusive episode, is recorded by structures common to all three structural domains. The earliest of these (F1) are flat-lying, probably high grade metamorphic fabrics and recumbent folds. Indeed, Bronner (1992) argued that there are in fact only a small number of units of ferruginous quartzite that are repeated by tight to isoclinal folding and associated thrust imbrication during the early phase of deformation.

One sample from the Mirikli Formation (23120012) was intruded between 2948 ± 11 Ma and 2875 ± 18 Ma. This sample records the maximum age constraint on intrusion of nested dome like structures and development of elliptical periclinal folds (F3). The T_{DM} of 3.25 Ga from this sample, together with an intimate association between granite *sensu stricto* and anatectic migmatite lithologies implies contribution of older crustal material as a source component. A minimum age constraint for this magmatic episode is provided by the crystallisation age of 2654 ± 8 Ma for granite from the Mirikli Formation (22120276) along with inheritance at 2691 ± 11 Ma from granite within the Accident Sud Ijilien (22120262). This was also associated with recycling of older crustal components indicated by T_{DM} of 3.14 and 3.04 Ga respectively from these samples. In this context, the Rb-Sr ages of 2779 ± 83 Ma and 2706 ± 71 Ma could represent either partial isotopic resetting of the gneisses, although both analyses are also within error of one of the end member magmatic events. Similarly, a U-Pb age of 2821 ± 45 Ma, lying within the range of magmatic ages from the Tiris Complex, was recorded as an inherited component in zircon from a sample of Palaeoproterozoic migmatite of the adjacent Eburnean mobile belt (Schofield et al., 2006).

In a previous review of the district, Rocci et al. (1991) concluded that the diapirs formed by partial melting of silicic metasedimentary rock, which ascended through denser, less readily fused metasediments that in turn tended to sink through the ascending melt. We concur with this conclusion having observed a predominance steeply plunging mineral lineations, which provide evidence for constrictional strain resulting from strong vertical extension (analogous to the "vertical tectonics" of McGregor, 1951), as well as concentric planar granite fabrics within the domes, which present an arrangement of structures typical of many diaper-like plutons (e.g. Schwerdtner, 1990). Together, the widespread migmatisation, granite intrusion and formation of nested diapiric domes are speculatively considered to record local convective overturning of the lithosphere (cf. Collins et al., 1998).

The younger intrusions from the Tiris Complex include foliated syntectonic granite within the Accident Sud Ijilien dated at 2487 ± 8 Ma (22120262). This is interpreted to provide a minimum age for the formation of penetrative fabrics in the host gneisses. Granite from the F'Derik Suite (21100139), located within the high strain zone abutting the Amsaga Complex, yielded an age of 2472 ± 6 Ma. Together, these illustrate an episode of more spatially-focussed magmatism localised within the major transecting shear zones during earliest Palaeoproterozic times. This tectonothermal event clearly also had a wider influence in the region indicated by a U-Pb metamorphic age of 2482 ± 7 Ma on monazite from one sample (22120276). This later phase of magmatism also involved input from older source components, indicated by T_{DM} of 3.14 and 2.9 Ga for these samples.

The latest penetrative tectonism to affect the Archaean Domain of the Reguibat Shield occurred during the ca. 2.1 Ga Eburnean Orogeny. To the NE of the Tiris Complex, the main Palaeoproterozoic mobile belt records metamorphism, granite magmatism, sinistral transpression and translation of Early Palaeoporterozoic units, including those of the Kediat Ijil across the Archaean foreland of the Tiris Complex (Schofield et al., 2006; Schofield & Gillespie, 2007). Rejuvenation of the partitioned shear zones in the Tiris Complex as thrusts and back-thrusts was implicit in the model of Schofield & Gillespie (2007), however the detailed structural relationships are less clear. In the NE of the complex, the presence of later inclined zones of *ls*-tectonites is indicative of NE-SW oriented non-coaxial horizontal translation that is speculatively consistent with overprinting Eburnean transpression as preserved in the adjacent suture zone and outliers including El M'haoudat and Kediat Idjil (Schofield et al., 2006).

5.2 Implications for assembly of the Reguibat Shield

The oldest known rocks exposed in the Reguibat Shield are approximately 3.51 Ga orthogneisses preserved in the Amsaga Complex. These were interpreted as potential source components to the younger supracrustal rocks with which they are intercalated and have been argued to provide a maximum age for their deposition (Potrel et al., 1996). A minimum age constraint is given by Granulite Facies metamorphism, constrined by the age of charnockite intrusion at around 2.98 Ga (Potrel, 1994; Potrel et al., 1996). Granulite Facies mineral assemblages from the Amsaga Complex metasediments compare well with those of aluminous gneisses in the Tiris Complex and provide a compelling link between the two units. This comparison is strengthened by the recognition of early high grade metamorphism and isoclinal folding in the Tiris Complex (Bronner, 1992), pre-dating ca. 2.95 Ga granite dome formation, as well as development of ca 3.04 Ga high grade gneisses in the Ghallaman Complex. In the Tasiast-Tijirit Terrane, no direct dating of supracrustal rocks has been carried out, although a zircon evaporation age on migmatite gneiss of around 2.97 Ga as well as Nd T_{DM} values ranging between 3.05 and 3.60 Ga from felsic metavolcanics (Chardon, 1997) suggest formation of the volcano-sedimentary succession prior to around 3.00 Ga, comparable to that of the Amsaga Complex metasediments.

From these available data it is evident that parts of all successions were deposited after around 3.60 Ga and prior to around 2.98 Ga. Furthermore, the overlap in age and prevalence of mafic volcanic rocks and units of ferruginous quartzite, predominant many Palaeo- Mesoarchaean sedimentary successions (see review of Trendall & Blockley, 2004) illustrate clear commonalities between the Archaean supracrustal rocks.

Key et al. (2008) interpreted the intrusion of a syntectonic granite at 2.95 Ga intervening between the Amsaga Complex and adjacent Tasiast-Tijirit Terrane as recording the maximum age of amalgamation of these two terranes into their current positions, while the minimum age is constrained by intrusion of the Touijenjert Granite, dated at around 2.72 Ga (Auvrey et al., 1992; Potrel et al., 1998).

The proposed maximum age for amalgamation was accompanied by an episode of more widespread, protracted magmatism recorded by intrusion of charnockitic rocks from the Amsaga Complex which have yielded ages of 2.98 to 2.95 Ga, as well as intrusion of discrete tonalitic plutons within the Tasiast-Tijirit Terrane, one of which has been dated at around 2.93 Ga (Key et al., 2008), and granitic intrusion in the Ghallaman Complex dated at 2.91 and 2.83 Ga (Lahondère et al. 2003). In the Tiris Complex, granitic rocks of this age (ca. 2.95 and 2.87 Ga) contrast with similar age rocks elsewhere in the Reguibat Shield in that they form part of a broad belt as opposed to isolated post-tectonic plutons or linear syn-tectonic intrusions of the other units.

Noearchaean magmatism is recorded in the shield by ca. 2.71 Ga post-tectonic granites (and gabbro) of the Tasiast-Tijirit Terrane as well as 2.69 and 2.65 Ga granite magmatism and inheritance form the Tiris Complex.

The strongly localized nature of younger, ca. 2.56 and 2.48 Ga, syn-tectonic granite intrusions in the Tiris Complex is reflected in their emplacement into major shear zones. Magmatism of this age has not been identified elsewhere in the shield and is interpreted as reflecting structural reactivation within the zone of earlier crustal reworking. During the ca. 2.1 Ga Eburnean Orogeny, The Tiris Complex occupied the outboard marging of the shield, attested to by further reactivation as well as accretion of adjacent Palaeoproterozoic successions and arc-granitoids.

5.3 Archaean Crustal Evolution in the West African Craton

The two exposures of West African Craton; the Leo Shield in equatorial West Africa and the Reguibat Shield to the north both comprise western Achaean and eastern Eburnean domains. Similar ages for tectonic events and structures illustrate co-evolution of the craton during Palaeoproterozoic times. However, modern studies of the Archaean Domain of the Leo Shield are poorly represented in the literature (see review of Rocci et al., 1991). In general the Archaean, Kenema Man Domain of the Leo Shield comprises belts of greenstone successions interleaved with granitic rocks. Williams (1988) described a typical greenstone succession as comprising ‘isolated elongate outcrops of basaltic amphibolites, minor ultramafites, overlain by a sedimentary succession of greywackes, pelites and banded iron formation’, ‘engulfed by and infolded into a heterogeneous granitic migmatite complex’. Recognition of granulite facies assemblages in some supracrustal belts in contast with amphibolite facies assemblages in others led some workers to propose two distinctive tectonothermal events (e.g. Camil, 1984; Macfarlane et al., 1981), an earlier Leonian event and a younger Liberian event, constrained by a number of Rb-Sr isochron ages between around 3.12 Ga and 2.65 Ga (e.g. Camill & Tempier, 1982; Camil et al., 1983; Hurley et al., 1971). However, Williams (1978) and Williams & Culver (1988) contended that these two events reflected a progressive continuum of tectonothermal processes. According to Cahen et al. (1984) the best constrained age is that provided by Beckinsale et al. (1981) who reported a Pb-Pb isochron age of 2960 ± 96 Ma from a granitoid that also yielded an Rb-Sr isochron age of 2753 ± 30 Ma interpreted as resetting of the Rb-Sr system and illustrating the two end member tectonothermal events. This latter piece of evidence provides the most compelling comparison between the Leo and Reguibat shields as it illustrates that the main tectonothermal events in both regions are approximately coeval. Furthermore, both comprise an older greenstone-sediment succession with mafic and ultramafic rocks, as well as units of banded iron formation, but are locally dominated by intrusive granitic rocks and migmatite.

6. Summary

The Tiris Complex makes up the northeastern-most tectono-stratigraphic unit of the Archaean Domain of the Reguibat Shield. It comprises a complex of granitic and migmatitic gneisses as well as metasedimentary units that can be subdivided into a several lithodemic units named the El Geicha, Mirikli and El Khadra formations after O'Connor et al. (2005). Of these the El Geicha and El Khadra formations are dominated by paragneisses, with the southernmost El Geicha formation locally preserving garnet-cordierite-sillimanite and orthopyroxene-bearing assemblages. The Mirikli Formation is dominated by granitic rocks that are most extensive in the central structural domain, characterized by extensive domes with intervening complex synforms cored by paragneiss including thin units of ferruginous quartzite. New U-Pb dating and whole rock Sm-Nd isotopic analysis from four samples of granitic rocks has provided constraint on the evolution of the complex as a whole. The main phase of magmatism recorded by the granite domes is dated by one sample (23120012) at either 2948 ± 11 Ma with ancient Pb-loss or 2875 ± 18 Ma with inheritance. Subsequent, Neoarchaean, magmatism is recorded at 2654 ± 8 Ma (22120276) along with inheritance at 2691 ± 11 Ma (22120262). Foliated granite intrusions, interpreted as syn-tectonic, record later movements on transecting shear zones at 2487 ± 8 Ma (22120262) and 2472 ± 6 Ma (21100139) along with a U-Pb metamorphic age of 2482 ± 7 Ma on monazite from one sample (22120276). All these magmatic episodes involved contribution of older continental crust indicated by Nd T_{DM} values ranging from 3.25 to 2.9 Ga, the latter yielded by the youngest dated granite.

Comparison with other units allows a tentative chronology for the Archaean and Early Palaeoproterozoic evolution of the West African Craton as a whole to be proposed. This comprises: 1) formation of Eoarchaean crust, illustrated by various Nd T_{DM} values as well as the metamorphic age of orthogneisses exposed in the Amsaga Complex dated at around 3.51 Ga; 2) formation of a Mesoarchaean greenstone-sedimentary province across the craton along with subsequent intrusion of dispersal and high grade metamorphism prior to; 3) a main magmatic event recording reassembly of individual terranes, crustal reworking and intrusion of large volumes of granitic magmas constrained between around 2.98 and 2.83 Ga; 4) a subsequent Neoarchaean magmatic episode between around 2.71 and 2.65 Ga, largely confined to intrusion post-tectonic plutons and isotopic overprinting; 5) intrusion of late Neoarchaean to Early Palaeoproterozoic syn-tectonic intrusions within reactivated shear zones adjacent to the outboard margin of the craton; 6) accretion of outboard Eburnean successions and localized structural reactivation at around 2.1 Ga.

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Figure 1. Regional geology of West Africa.

Figure 2. Geological sketch map of the Archaean domain of the Reguibat Shield. MF: El M'dena Fault. Box indicates approximate area of detailed survey.
*Temmimchate-Tsabaya Complex.

Figure 3. Geological sketch map of the BGS 1: 200 000 scale survey area. A: area of Fig. 5; B: area of Fig. 6; KI: Kediat Ijil; M: El M'haoudat range; AI: Accident Sud Ijilien. Ages are U-Pb zircon or monazite (mon) reported herein. NE, Central and SW domains after Bronner (1992).

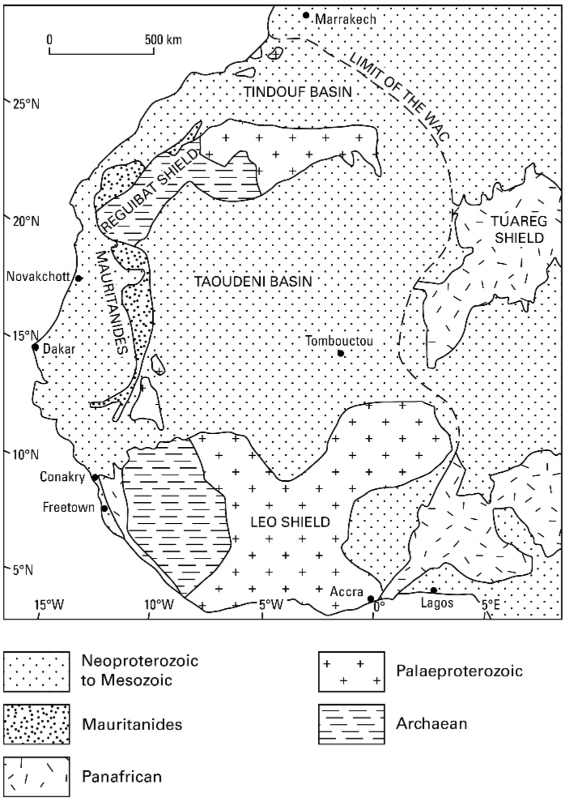
Figure 4. Stereographic projections (equal area, lower hemisphere) representing planar and linear fabric elements from the Tiris Complex: a). SW Domain b); Central Domain; c). NE Domain. Circle: pole to planar fabric, square: direction and plunge of linear fabric.

Figure 5. Sketch map of the fold interference pattern outlined by ferruginous quartzite units in the SW structural domain in the area east of Gleib El Freidi, to the south of Kediat d'Ijil, derived largely from interpretation of satellite imagery and showing superpositioning of F3 over F2 isoclinal folds.

Figure 6. Sketch map of the Guelb el Aouj area in the Central structural domain, derived largely from interpretation of satellite imagery and incorporating some structural data from Bronner (1977) illustrating domical F3 structure with intervening tight synclines.

Figure 7. Photomicrographs of: a) zircons separated from sample 23120012; b) monazites analysed from sample 22120276; c) zircons analysed from sample 22120276; d) populations of cloudy, altered zircons (Population 1; left) and glassy, clear zircons (Population 2; right) separated from sample 22120262; e) titanite (left) and allanite (right) separated from sample 211200139; f) zircons separated from sample 211200139.

Figure 8. U-Pb Concordia plots of: a) zircon analyses from sample 23120012; b) zircon analyses from sample 22120276; c) monazite analyses from sample 22120276; d) analyses of the second population of zircons from sample 22120276; e) Zircon analyses from sample 221200139.



Marrakech
0
500 km
LIMIT OF THE WAC
TINDOUF BASIN
25°N
REGUIBAT SHIELD
20°N
TUAREG
SHIELD
Novakchott
MAURITANIDES
TAOUDENI BASIN
15°N
Dakar
Tombouctou
10°N
Conakry
Freetown
LEO SHIELD
5°N
Accra
Lagos
15°W
10°W
5°W
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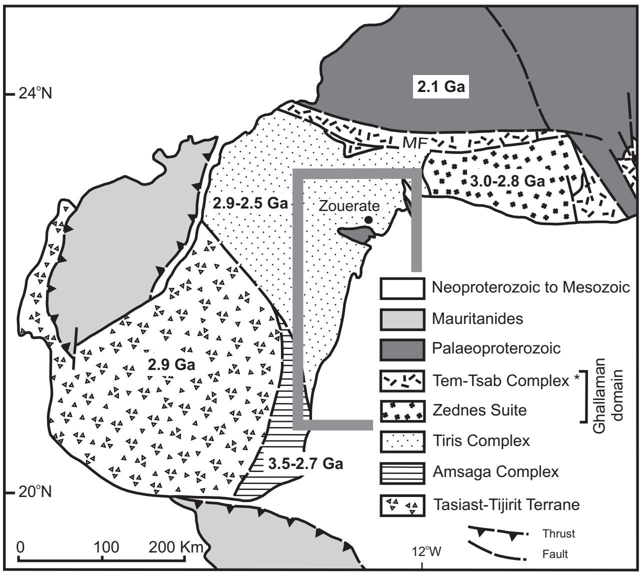
Neoproterozoic
to Mesozoic
Mauritanides
Panafrican
Palaeoproterozoic
Archaean



24°N
20°N
2.1 Ga
MF
3.0-2.8 Ga
2.9-2.5 Ga
Zouerate
2.9 Ga
3.5-2.7 Ga
Neoproterozoic to Mesozoic
Mauritanides
Palaeoproterozoic
Tem-Tsab Complex *
Zednes Suite
Ghallaman domain
Tiris Complex
Amsaga Complex
Tasiast-Tijirit Terrane
Thrust
Fault
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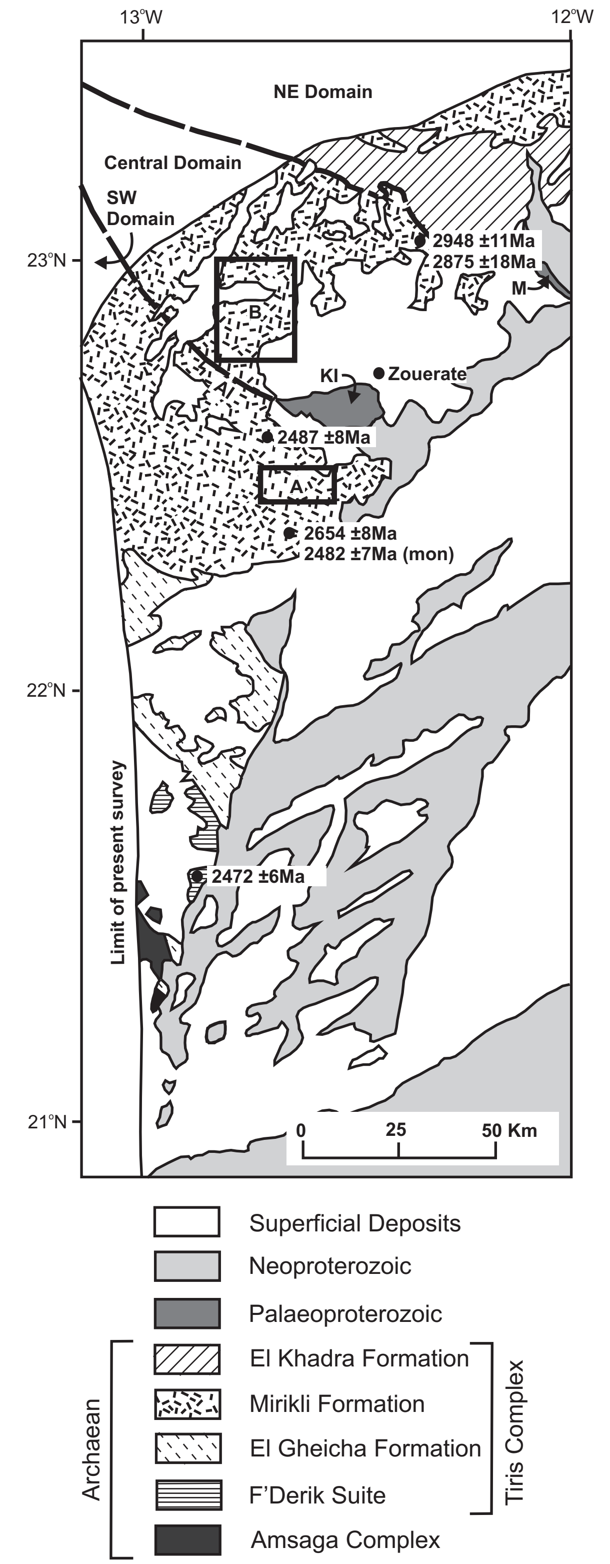
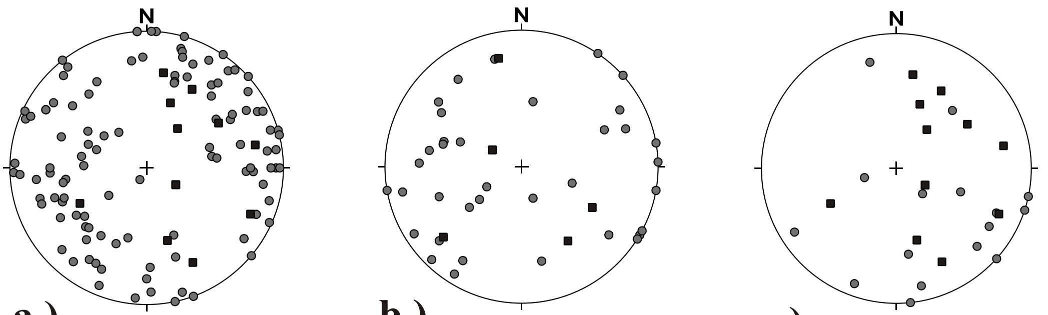
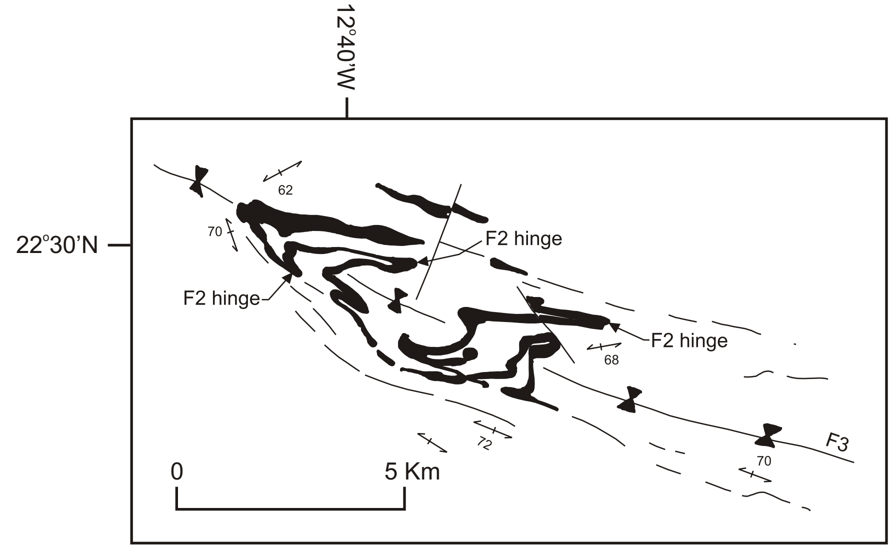
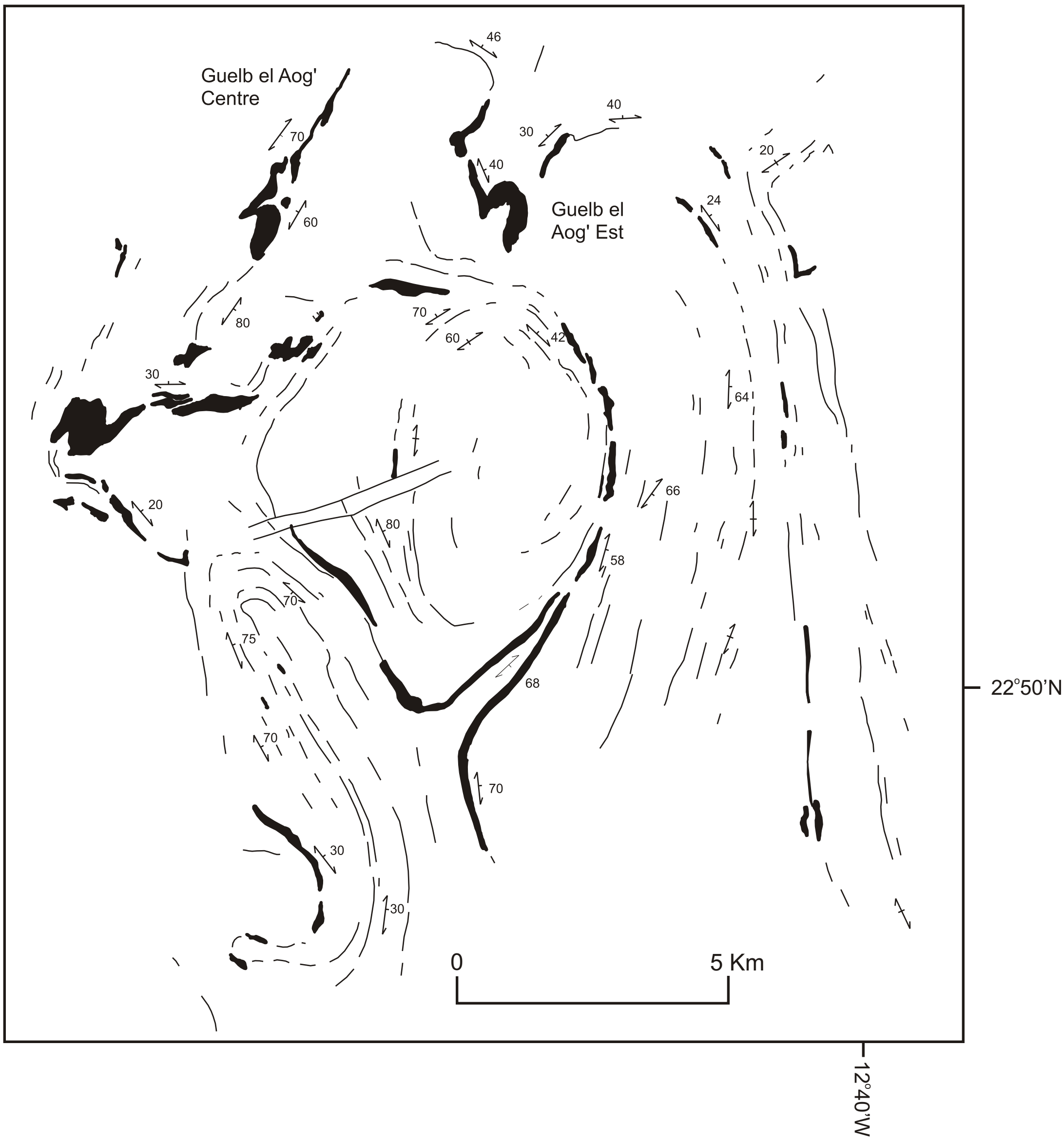
100
200 Km
12°W


13°W
12°W
NE Domain
Central Domain
SW Domain
23°N
22°N
21°N
B
A
KI
Zouerate
M
2948 ±11Ma
2875 ±18Ma
2487 ±8Ma
2654 ±8Ma
2482 ±7Ma (mon)
2472 ±6Ma
Limit of present survey
0
25
50 Km
Superficial Deposits
Neoproterozoic
Palaeoproterozoic
El Khadra Formation
Mirikli Formation
El Gheicha Formation
F'Derik Suite
Amsaga Complex
Archaean
Tiris Complex



a.) b.) c.)


12°40'W
22°30'N
62
70
F2 hinge
F2 hinge
F2 hinge
68
72
70
F3
0
5 Km



Guelb el Aog'
Centre
Guelb el
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46
40
30
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20
24
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60
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42
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64
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66
80
58
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75
68
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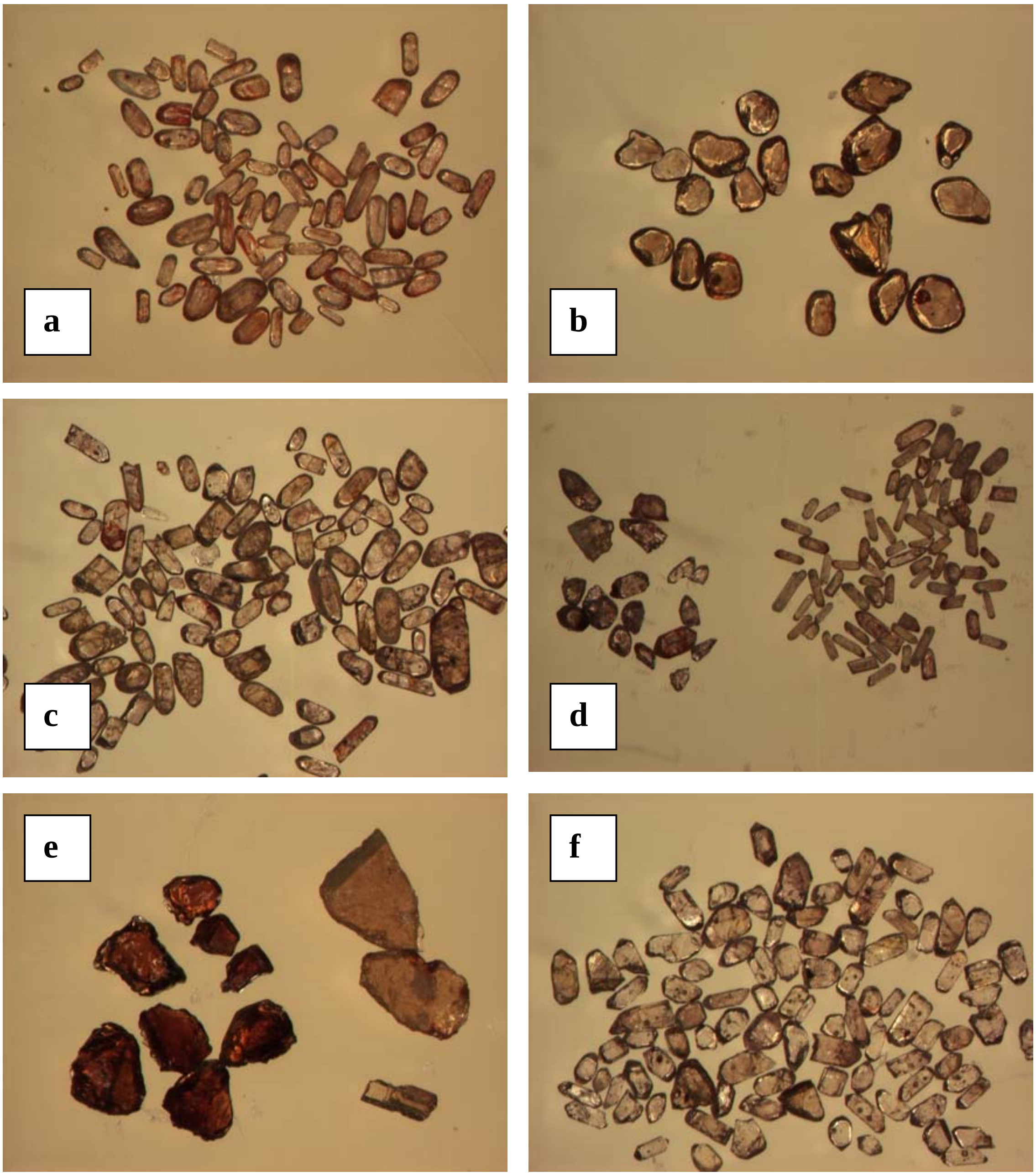
30
30
0
5 Km
22°50'N
12°40'W


a
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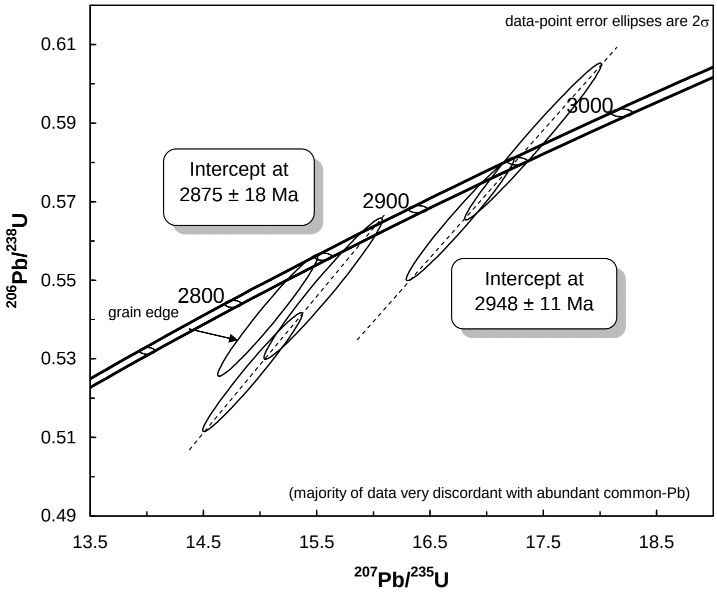
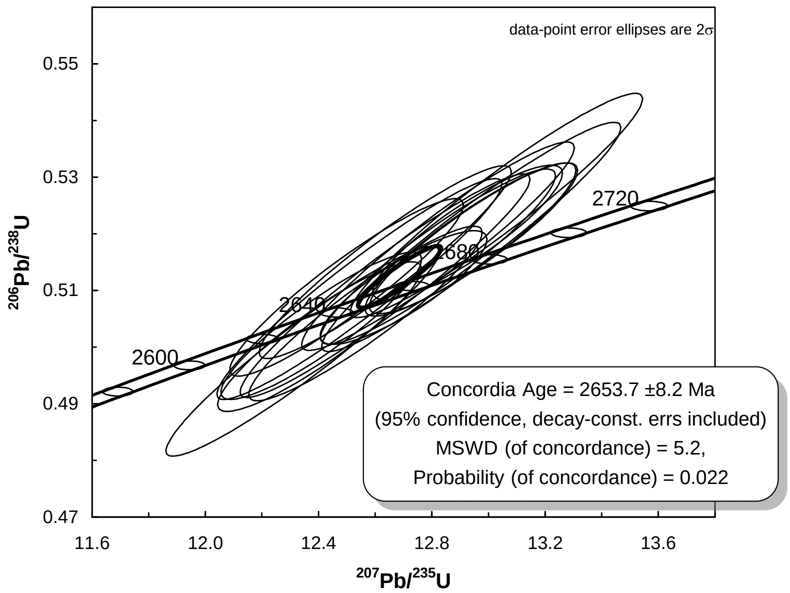
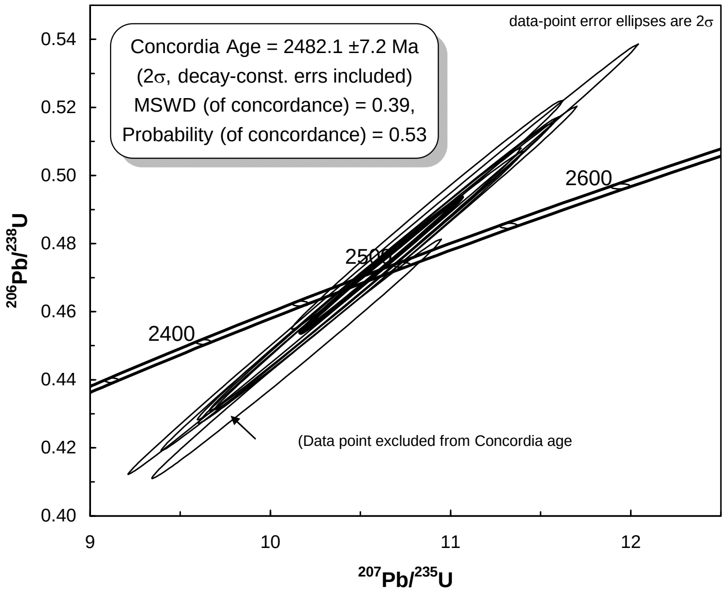
(a) 23120012



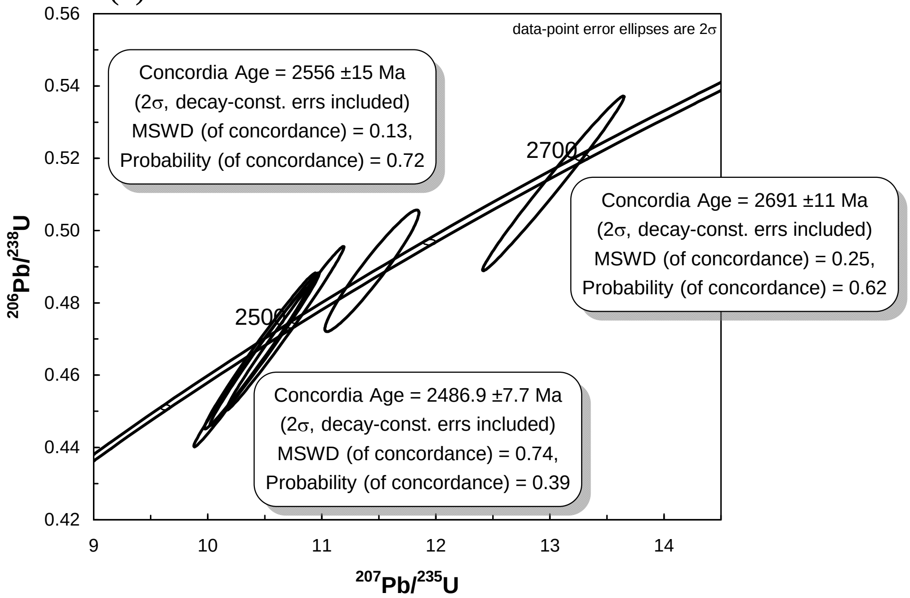
(b) 22120276 (zircon)



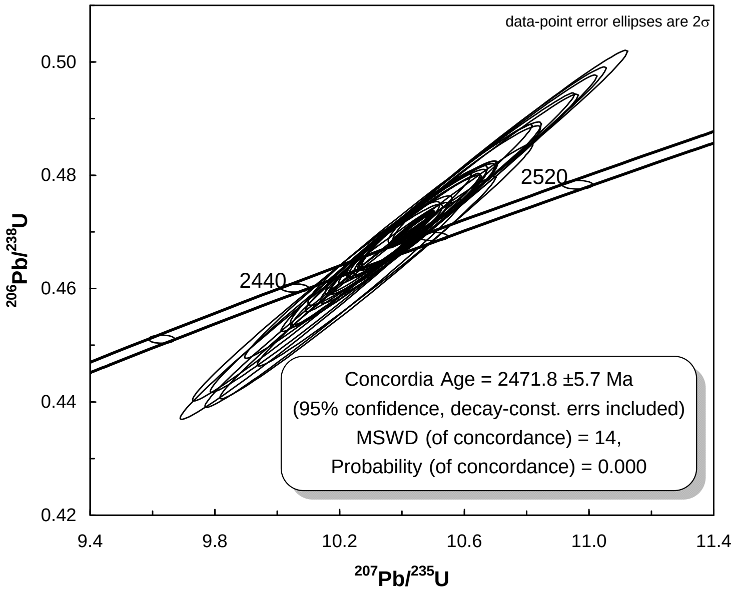
(c) 22120276 (monazite)



(d) 22120276



(e) 221200139



data-point error ellipses are 2σ
0.50
0.48
0.46
0.44
0.42
$^{206}Pb/^{238}U$
2520
2440
Concordia Age = 2471.8 ±5.7 Ma
(95% confidence, decay-const. errs included)
MSWD (of concordance) = 14,
Probability (of concordance) = 0.000
9.4
9.8
10.2
10.6
11.0
11.4
$^{207}Pb/^{235}U$