THE CLASSIFICATION AND GENESIS OF THE GRANITOID INTRUSIONS OF THE EASTERN PART OF THE TIBESTI MASSIF (LIBYA) BASED ON REMOTE SENSING STUDIES

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Abstract
The northern part of the Tibesti Massif is built from Precambrian rocks which are metamorphosed in an amphibolitic facies. Due to varying resistance to weathering of the individual rock-types, the Lower Tibestian horizon forms a morphologically diversified outcrop which is 100 km long and 50 km wide. The identification of the various genetic types of intrusion has been done based on the cross-cutting relationship of the magmatic bodies within the complex intrusions. Type 1 - pre-tectonic or early-orogenic; type 2 - pre-shearing; type 3 - post-shearing; type 4 - post-tectonic. The outline of tectonic development of the Eastern Tibesti (base on a review of the existing publications on the geology of the region combined with results of a remote sensing analysis): The oldest, prekinematic intrusions were re-melted and deformed in later stages of tectonic-magmatic activity. Subduction of the oceanic crust took place towards the East, under the eastern part of Chadian-Awaynat craton. After orogenesis intensive and metamorphism granitoid intrusions penetrated the Lower Tibestian series. During the following subduction of the oceanic crust towards the West, this series was folded, metamorphosed and penetrated by calc-alkaline granitoids. The Lower Tibestian series was next subjected at that time to shearing and to, probable, clockwise, twist which resulted in deformation of the foliation and fold axes and also in rotation of the intrusive bodies. Several smaller phases of magmatic activity followed, with the youngest, the rhyolitic being of the lower Ordovician age.

Introduction
This work attempts to review what is known about the numerous granitic intrusions of eastern Tibesti (Fig. 1, 2). However, it should be emphasised, that owing to its inaccessibility and difficulties of climate and relief conditions (travelling is possible only along the valleys of intermittent rivers called wadis) the geological investigations in this area have not progressed much beyond the reconnaissance stage.

In the geological literature, this area has hitherto been described only in its regional context. Works concerning North Africa include Rogers et al. 1978, Black & Girod 1970, Ghuma & Rogers 1980. Works concerning the whole Tibesti include those of Wacrenier 1956 and Vincent 1963 while, at a local level, there are a few works concerning very small areas (e.g. List & Stock 1969). Studies carried out in the 1970s on the wider scale (Hunting 1974) were directed towards the delimitation of metal resources in the area but this included only a part of the area under review here.

The Authors present a working hypothesis concerning the genesis of the granite intrusions, emphasising their role in the structural evolution of this area. Where possible, remote sensing data were verified by data forthcoming from previous field studies in the area. They were also compared with previous models of the geology of Northern Africa in general and the Tibesti area specifically and also those of the magmatic and tectonic evolution of this area. No claim is made that our hypothesis concerning the different phases of intrusion applies to the whole of the Tibesti region but it is hoped that it will be accepted as a basis for wider scientific discussion and in the planning for further fieldwork.
Geographical setting

The area studied is situated in the southern part of Libya, near the Chad border (Fig. 1). It comprises the north-eastern part of the Tibesti Massif which is situated between 18°40′ and 19°10′ west and 22°00′ and 22°30′ north.

Geology and geomorphology of the area studied

The northern part of the Tibesti Massif is built from Precambrian rocks which are metamorphosed in an amphibolitic facies. According to Wacenier’s (1956) classification, it represents the Lower Tibestian horizon, which consists of gneisses, hornblende and quartzitic schists, quartzite and amphibolitic metavolcanics. These rocks are disposed in a number of narrow, isoclinal folds the axes of which trend NNE-SSW and NE-SW (Vincent 1963; List & Stock 1969). At the contact of metamorphic rocks with intrusions and close to tectonic dislocation zones the direction of foliation surfaces is often disturbed (Figs. 2,4 and 5,6).
Fig. 2. Scheme showing the main types of granitic intusions within the selected area between the escarpment and Kawr Graben

1 - metamorphic foliation; 2 - pre-tectonic or early tectonic intrusion, type I (gneisses, migmatites); 3 - pre-shearing intrusion, type II (calc-alkaline and alkaline granite); 4 - post-shearing intrusion, type III (alkaline granite); 5 - post-tectonic extrusion, type IV (rhyolite); 6 - Ordovician deposits (sandstone, conglomerate); 7 - tertiary and quaternary basalts; 8 - ring structure possibly related to intrusion of unkown type;

Due to varying resistance to weathering of the individual rock-types, the Lower Tibestian horizon forms a morphologically diversified outcrop which is 100 km long and 50 km wide. To the east, the area studied is bounded by a high morphological escarpment called the Dohan (Fig. 1,2) which is built from very thick clastic sediments of Ordovician age. These overlie the older strata with angular discordance. To the north and south, the Precambrian outcrops are covered by Tertiary basalts which form a wide plateau. The western boundary of the Lower Tibestian outcrop is cotermious with the eastern limb of a wide tectonic depression, the axis of which trends NNE-SSW. The bedrock is overlain by unconsolidated Tertiary sediments and modern
aeolian sands. This structure is referred to as the *Kawr Graben* (e.g. Hunting 1974).

The area studied is cut by two large meandering valleys (wadis) trending ESE-WNW. These are: *Wadi Oyurum*, in the northern part of the area and *Wadi Kawr* in the centre (Fig. 1).

**Methods of study**

The remote sensing analysis was carried out using black and white prints of Landsat TM satellite images (spectral band 4) which were rectified and elaborated by Hunting Technical Services. The images were taken in 1986 - the whole of sheet NF 34 v_c and part of sheet NF 34 y_a. These were at a scale of 1:250 000. Interpretation of aerial photographs was also carried out for selected areas. The photographs were black and white and at scales of 1:50 000 (Hunting 1974) and 1:90 000 (Libyan-Brazilian J.G. 1991). The photointerpretation was carried out using a mirror stereoscope. The final graphic elaboration of photointerpretation results was conducted using a PC computer.

**Identification of intrusions**

Recent denudation of the Precambrian bedrock has revealed many of the intrusions which outcrop on the drift-free terrain. Owing to the microrelief of their surface their borders are easy to identify (Hunting 1974, Hagedorn 1980, List & Stock 1969, Baegi 1996).

Some shallow magmatic bodies, the upper parts of which lie below the modern landscape, have been identified indirectly (Fig.2) from circular structures revealed on the satellite images. These structures are manifested by local, distinctive arrangements of concentric and radial fractures, anomalous segments of the drainage system and dislocations of foliation in the metamorphic rocks (Baegi, 1996). The circular structures may be regarded as the product of local stresses which accompanied the intrusions. This process was doubtless accompanied by hydrothermal and pegmatitic activities (Łuczicki & Bondarjenko 1974; Dadlez & Jaroszewski 1994).

**Geology of the intrusions**


The concentric magmatic bodies present in the area studied are composed from both calc-alkaline and alkaline granites (Roger *et al.*, 1978; Ghuma & Rogers 1980; List & Stock 1969; Hunting 1974). It is, therefore, important to try to distinguish these two types of rocks on the aerial photographs and satellite images.

Undoubtedly, a morphology of the outcrop surface is the main criterion in this identification. The calc-alkaline granites usually occupy trough-like depressions filled with drift deposits (Figs. 2,4,6,7) and usually covered with aeolian sands which severely hinder or make it impossible to study the bedrock (Hunting 1974). By contrast, the alkaline granites form positive landforms without any cover of recent deposits (List & Stock 1969; Hunting 1974; Hagedorn 1980). On the aerial photographs, the tone of the latter landforms is usually a bit darker than tone of the calc-alkaline intrusions.

Most of large intrusions represent polycyclic forms (Fig. 2,6,7) and, sometimes, the intrusions are quite complex (Fig.7).

It is presumed that diapirism also called “ballooning” was the main mechanism which controlled the form of the Tibesti Massif intrusions. This is suggested by their shapes, their relationship with the surrounding rocks and the interrelationship between individual intrusions. The ballooning process takes place in the following way: a granitoid body in the form of an interverted raindrop (a bubble) rises, piercing through and stoping the hot ductile country rock until a hydrostatic balance is reached. In many cases, this process is cyclic, because the “pathway
Fig. 3. Aerial photo and photogeologic interpretation showing intrusion type I
Legend (for Fig. 12 to 14): 1 - metamorphic foliations; 2 - faults and fractures; 3 - pre-tectonic or early-tectonic intrusion, type I; 4 - pre-shearing intrusion, type II; 5 - post-shearing intrusion, type III; 6 - post-tectonic intrusion type IV; 7 - Tertiary and Quaternary basalts; 8 - ring structure possibly related to intrusions;

Fig. 4. Landsat image and photogeological interpretation showing intrusion type II
"of the first bubble becomes a zone of local weakness. This is then exploited by other magmatic bodies which become detached from the main chamber (Dadlez & Jaroszewski, 1994; Ramsay 1989; Pons et al. 1992).

Genetic types of intrusions

Type 1. Prenectonic or early-orogenic types. These types have been identified on both the aerial photographs and satellite images from the chaotic photopattern surrounded by phototones showing the linear pattern associated with the outcrops of the metamorphic rocks (Fig. 3). The mosaic-like phototone within the intrusions may be caused by the differential weathering of the rocks present there. The contacts of the intrusions with their aureoles are often difficult to identify. Frequently, there is a gradual change from metamorphic rocks with clearly visible foliation to the intrusive centres which show a chaotic pattern. In some cases, owing to the cover of modern deposits, this contact is not discernible or it is represented by a tectonic surface (Fig. 3).

The intrusions are elongated parallel with the foliation of the metamorphic rocks (Fig. 2). Trends of faults and joints typical for them are rarely observed. In terms of morphology, they are little different from the country rocks. This may indicate the extent to which the country rock has become incorporated into the ascending magma bubbles. If they were intrusions of granodioritic nature, they have later been changed into gneisses or migmatites owing to repeated melting in the successive phases of magmatism.

Type 2. Pre-shearing types (described as syntectonic types by Modrzejewski & Wojciechowski, 1980). Intrusions of this group have been generally recognised as syntectonic (List & Stock, 1969; Hunting 1974). They are easily distinguished from the metamorphic series. In the landscape morphology they usually form depressions which are filled with recent aeolian sands. They usually represent calc-alkaline granites but intrusions of alkaline granites may also take this form. The latter form positive landforms. The shape of these bodies is ellipsoidal or elongated and their relationship to the country rocks is similar to that of calc-alkaline granites which form the depressions (there are rare cases of foliation cross-cutting but, normally, the foliation is simply deformed).

The pre-shearing granitoid bodies (type 2) have a nonuniform, concentrically variable structure. They have well-developed zones of contact with surrounded rocks which are often hornfelsed (Hunting 1974). Foliation around these intrusions is usually deformed in a distinctive manner (Figs. 2, 4, 6, 7). Analysis of the tectonic relationship of the pre-shearing intrusions to the country rocks suggests that their origin was coeval with the orogenesis of the Lower Tibestian series; they are the result of penetration of granitic magma as diapirs into metamorphic rocks. Such a model of the origin of syntectonic intrusions have been described by List & Stock (1969), Ramsay (1989) and Pons et al. (1992). The whole process probably took place in conditions of locally increased temperature which is evidenced by wide contact changes at the boundary with metamorphic rocks. These changes are seen as deformations of relatively ductile metamorphic rocks around intrusion bodies and a concentric deformation within the intrusions (slow cooling).

After orogenesis, a network of regional, anastomosing, ductile zones of shearing (probably with a clockwise sense of development) was produced (Fig. 2). This may be identified on both the Landsat images and aerial photographs from the s-c megastructures and distortion of the metamorphic foliation along dislocation surfaces which originated due to ductile displacement. During this movement, the behaviour of intrusion was rather more brittle than the ductile deformation in the surrounding rocks, which led to a clockwise rotation of these bodies and determined the origin of characteristic foliation distortion at the contacts with the intrusions (Figs. 2, 4, 6, 7). A similar type of deformation is well known from observations of sheared ductile metamorphic rocks (mainly eyed-gneisses and mica-slates) both at a micro and macro scale and described as "sigma" and "delta" rotation eyes (e.g. Ramsay & Huber 1983, 1987; Cymerman 1989; Dadlez & Jaroszewski 1994). It has also been observed at a larger scale, for example in the
granite intrusions of Africa (Pons et al., 1992). The distribution of stresses associated with clockwise shearing (where δ, was vertical) is probably also responsible for the set of tensional fractures within the intrusion, which were later developed as veins.

**Type 3. Post-shearing types** ("post-tectonic" in the terminology of Modrzejewski & Wojciechowska, 1980). Hitherto these intrusions have been described as post-tectonic (List & Stock, 1969; Hunting, 1974). On satellite images these intrusions are seen as circular landforms with positive relief and their phototone is quite different from that of the metamorphic rocks (Figs. 2,6). A uniform phototone and a chaotic, fine grained photopattern suggest no great petrological differentiation within the intrusion. The foliation at the contact zone is usually discordant. A lack of tectonic structures associated with shearing (deformed foliation, traces of rotation) suggests that these bodies originated after the shear movements had finished. The origin of these intrusions was probably also associated with diapirism but with some melting of the country rocks. A poorly developed contact zone, lesser deformation of the foliation and several instances of its destruction at its contact with the granite suggest that the intrusion had a relatively lower temperature and more brittle behaviour than that of the surrounding metamorphic rocks. These intrusions probably originated in the last phase of the development of the Tibesti Massife, i.e. after the main phase of tectonic activity had ceased.

**Type 4. Post-tectonic types.** These are restricted to the central part of the area studied. Both on the satellite images and aerial photographs, they have a distinctive, very light, uniform phototone.
Fig. 6. Aerial photo and photogeological interpretation showing intrusion type III and its relationship with intrusion type II.

Fig. 7. Aerial photo and photogeological interpretation showing composite intrusion formed of intrusive bodies type II and III.
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(Figs.2,5). In stereoscopic image, they are seen to form positive landforms. They are circular structures, often elongated along the foliation direction. Their contact with the surrounded rocks is discordant (Fig. 5). They are built from rhyolites which are probably of lower Ordovician age (Hunting 1974). Their shape, which is concordant with the foliation direction, results from the accommodation of the liquid magma to the existing structural arrangement. These rocks are generally recognised as the final stage of pan-African magmatic activity in the area studied.

Succession of intrusions

The identification of the various genetic types of intrusion has been done based on the cross-cutting relationship of the magmatic bodies within the complex intrusions. The interrelationship of types 2 and 3 is seen on Fig. 6, where almost 70% of the older, granitic, calc-alkaline intrusion body has been replaced by a new structure probably comprising alkaline granites. A deep zone of weakness responsible for these intrusions was again reactivated in the Tertiary, when basalts were generated.

Fig. 7 shows the largest intrusion in the area studied. It consists of several smaller, multiple intrusions of calc-alkaline granites intersected by many pegmatite veins which probably originated as a result of a clockwise shearing. These granites are discordantly intersected by the alkaline intrusions (a darker phototone, positive relief) and small developments of Tertiary volcanics. It is probable that, after the field studies, this picture will be considerably refined.

Outline of the structural evolution

The outline of tectonic development of the eastern Tibesti, has been based on a review of the existing publications on the geology of the region combined with remote sensing analysis. Recognition of the individual stages has been based on the pan-African structural evolution of the Hoggar, as elaborated by Żaba (1991, 1992 a,b). This seems to be not unreasonable, for it is widely believed that these two areas have had a more-or-less identical history.

1. The early-pan-African or pre-pan-African stage. The oldest, prekinematic intrusions originated during the sedimentation and later orogenesis of the original sedimentary and volcanic rocks of the Lower Tibestian series; these were then re-melted and deformed in later stages of tectonic-magmatic activity. In the Tibesti area they are represented by type 1 pre-tectonic intrusions. Similar rocks are known from the northern part of Eastern Desert of Egypt where they are dated at 700-950 m.a. B.P. (Rogers et al. 1978; Ghuma and Rogers 1980), corresponding to the pre-collision pan-African orogenic cycle of Żaba (1991).

2. The early-pan-African subduction stage. Subduction of the Earth’s crust took place towards the east, below the eastern part of Chadian-Awaynat Craton. An intensive orogenesis and metamorphism of the Lower Tibestian series took place at this time. Then, granitoid intrusions (most of which were calc-alkaline /type 2 - pre-shearing/) penetrated this series. This process occurred about 750-600 m.a. B.P. (Ghuma & Rogers, 1980; Rogers et al. 1978). It seems possible to correlate this stage with the subduction along the edges of the east-African Craton in the Hoggar area, where intrusions of similar petrographic composition are present (the D1 deformation phase of Zaba, 1991, 1992a, b). The intrusions of this stage also have equivalents in Egypt (the Synorogenic Plutonites of El Shazly 1977).

3. The subduction and late-pan-African collision stage. A subduction of the oceanic crust towards the west, under the western part of East-African Craton then took place (Rogers et al., 1978). The Upper Tibestian series became folded, metamorphosed and penetrated by calc-alkaline granitoids, such as the Bin Ghnema batholith, dated at 550 m.a. B.P. (Fullagr 1980; Ghuma &
Rogers 1980). The Lower Tibestian series was subjected at that time to shearing and to a probable clockwise twist which resulted in deformation of the foliation and fold axes and also in the rotation of the intrusion. This stage of deformation may be correlated to the D3 stage - the late African collision of the Hoggar, where clockwise shearing zones also took place (Zaba 1991, 1992a,b). Intrusions described as the type 3 - post-shearing (post-tectonic - List & Stock 1969) show neither traces of deformation nor of regional stress conditions during their origin. Indeed, this stage may have comprised several smaller phases of magmatic activity. One of the youngest of them may have been the rhyolite intrusions of lower Ordovician age.

References


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**Streszczenie**

Rozpatrywana część masywu Tibesti zbudowana jest ze zmetamorfizowanych w facji amfibolitowej skał prekambryjskich. Na omawianym obszarze piętro *Lower Tibestien* tworzy urozmaicony morfologicznie (w zależności od odporności na wietrzenie poszczególnych typów skał) obszar wychodni o długości 100 km i szerokości 50 km. Dokonano rozróżnienia typów genetycznych intruzji w oparciu o wzajemne nastąpię ciał magmowych w obrębie intruzji wielokrotnych i złożonych (przecinanie starszych ciał przez młodsze): TYP 1 - pretektoniczne lub wczesnoorogeniczne; TYP 2 - przedœciŒciowe; TYP 3 - poœciŒciowe; TYP 4 - posttektoniczne. Przedstawiono etapy tektonicznego rozwoju wschodniego Tibisti opracowane w oparciu o regionalne prace dotyczące panafrykaeskiego rozwoju północnej Afryki w powiązaniu z obserwacjami teledetekcyjnymi. Tworzenie się najstarszych intruzji zachodziło podczas sedymentacji, fałdowania pierwotnie osadowych i wulkanicznych skał serii *Lower Tibestien*. Intruzje te były przetapiane i deformowane w czasie późniejszych etapów aktywności tektoniczno-magmowej. Zachodząca w kierunku wschodnim subdukcja skorupy oceanicznej, pod wschodnią część kratunu wschodnioafrykańskiego prowadziła do intensywnego fałdowania i zmetamorfizowania serii *Lower Tibestien*, a następnie wniknięcia intruzji granitoidów w przewadze wapniowo-alkalicznych. Kolejny etap subdukcji skorupy oceanicznej w kierunku zachodnim, pod zachodnią część kratunu wschodnioafrykańskiego prowadził do poddawania ściśnianiu serii *Lower Tibestien* o przypuszczalnie prawoskrótnym zwrocie. Powodowało to deformacje foliacji i osi fałdów oraz rotowanie intruzji. W etapie ekstensji pokolizyjnej dochodzi do wniknięcia granitów alkalicznych tnących niezgodnie skały metamorficzne jak i starsze intruzje. Etap ten mógł się składać z kilku drobniejszych faz aktywności magmowej. Jedną z ostatnich mogło być powstanie w dolnym ordowiku skał riolitowych.

**Bibliografia**


