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Inhomogeneous shearing related to rock composition: evidence from a major late-Panafrican shear zone in the Tuareg shield (Algeria)

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ABSTRACT

This study describes the deformation in zones affected by regional shearing, and its relation with local factors, in particular rock compositions. The Tihaliouine and Teg Orak plutons were emplaced close to a major shear zone of the Tuareg shield. Their magmatic to sub-magmatic fabrics were determined by using measurements of anisotropy of magnetic susceptibility; they are similar to those of some other late Panafrican plutons of the Tuareg shield. The eastern part of the Teg Orak pluton displays a coherent fabric with a subhorizontal lineation oblique to the 4°50 major shear zone located just to the east. This fabric is clearly related to shearing by a dextral strain-slip movement along the shear zone during magma crystallization. The fabric in the western part of the Teg Orak pluton and in the Tihaliouine massif presents much more scattered principal axes. It was much less affected by shearing along the shear zone. This difference strongly depends on the nature of the host-rocks: Granitic host-rocks around the Tihaliouine and the western part of the Teg Orak acted as a rigid block, protecting the intrusions from regional deformation, while basic plutonic and metamorphic host-rocks around the eastern part of the Teg Orak pluton had a more plastic behavior and transmitted the regional strain to the intrusion.

Introduction

The study of shearing in the vicinity of major shear zones is presently one of the major tasks that have to be carried out in order to understand the structural evolution of orogenic belts. It is becoming common to use fabric analysis in plutons (e.g. Pitcher & Berger 1972; Marre 1982; Paterson et al. 1998; Schofield and D'Lemos 1998) emplaced under transpressive regimes (e.g. Acef et al. 2003; Neves et al. 2003; Aurejac et al. 2004) to understand their emplacement. The visible effects of shearing in the rocks close to these shear zones can be explained by a combination of several key factors. One of these factors, often difficult to evaluate, is the mechanical behavior of the rocks, which depends in particular on their composition and petrofabric. The aim of this paper is to show the effects of shearing on rocks with different characteristics. The studied samples are from intrusions which outcrop in the same area within host-rocks of different compositions, and we use magnetic fabric analysis to compare the rheology of these intrusions according to the different nature of their host-rocks. The anisotropy of magnetic susceptibility (AMS) is a strong tool (e.g. Tarling & Hrouda 1993; Borradaile & Jackson 2004) to analyze emplacement conditions and deformation of intrusive bodies (e.g. Tarling & Hrouda 1993; Borradaile & Jackson 2004; King 1966; Hrouda et al. 1971; Borradaile & Kehlenbeck 1996; Pignotta & Benn 1999; Bouchez 2000; Tomezzoli et al. 2003; Henry et al. 2004).

In the Tuareg shield (Fig. 1a), the late Panafrican period was characterized by large displacements along mainly N-S mega-shear zones, which brought terranes of very different structural characteristics into contact (Black et al. 1994; Liégeois et al. 1994), and by the intrusion of numerous granitic plutons (Lelubre 1952). The magnetic fabric of all the late Panafrican plutons studied until now presents typical features due to shearing, such as a sub-horizontal mean lineation and an often vertical mean foliation. However, the constancy of the direction obtained for the principal susceptibility axes at the scale of a whole intrusion varies considerably, ranging

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from a very low scattering, for example in the Alous-En-Tides pluton (Henry et al. 2004), to a high scattering in other intrusions, for example the Tioueine (Djouadi et al. 1997) or In Tounine (Henry et al. 2006) plutons. Another difference is the strike of the mean orientation of the magnetic foliation, which is in some cases oblique to that of the closest shear zone, for example in the Tesnou massif (Djouadi & Bouchez 1992), but is almost similar to that of the shear zone in other cases, for example in the Tioueine pluton (Djouadi et al. 1997). The distance to the shear zone is clearly an important factor but may not to be the only one. The relative age of intrusion and shearing, as well as the petrographic facies of the pluton or of the host-rocks, could also have had a significant effect (Henry et al. 2007).

This is in particular the case for two neighboring late Panafrican plutons which outcrop at only slightly different distances from the shear zone, but were intruded within a basement composed partly of granites, diorites and gabbros (Afedafeda Panafrican synorogenic granitoids of the Iskel terrane) and partly of metamorphic rocks (Fig. 1b). The difference in rheology of the intrusions is already suggested by very different pluton shapes. The elongated shape of the Teg Orak massif suggests syntectonic emplacement, while the Tihaliouine pluton is almost perfectly circular and shows no evidence of being syntectonic. The late Panafrican plutons were not emplaced at very great depths, that is between 15 and 7 km, corresponding to 5.5 to 2.5 Kbars (Azzouni-Sekkal 1995).

Geological setting

The Tuareg shield acquired its present structure during the Panafrican orogeny (900–520 Ma) by amalgamation of some 23 terranes (Black et al. 1994). At the end of the Panafrican event, between 592 Ma and 519 Ma (Hadj-Kaddour et al. 1998; Paquette et al. 1998; Azzouni-Sekkal et al. 2003), massive alkaline to alkali-calcic post-orogenic plutons were emplaced throughout the Tuareg shield. The latest magmatic events, represented by high-level alkali-calcic to peralkaline plutons, occurred between 539 Ma and 519 Ma (Cheilletz et al. 1992;

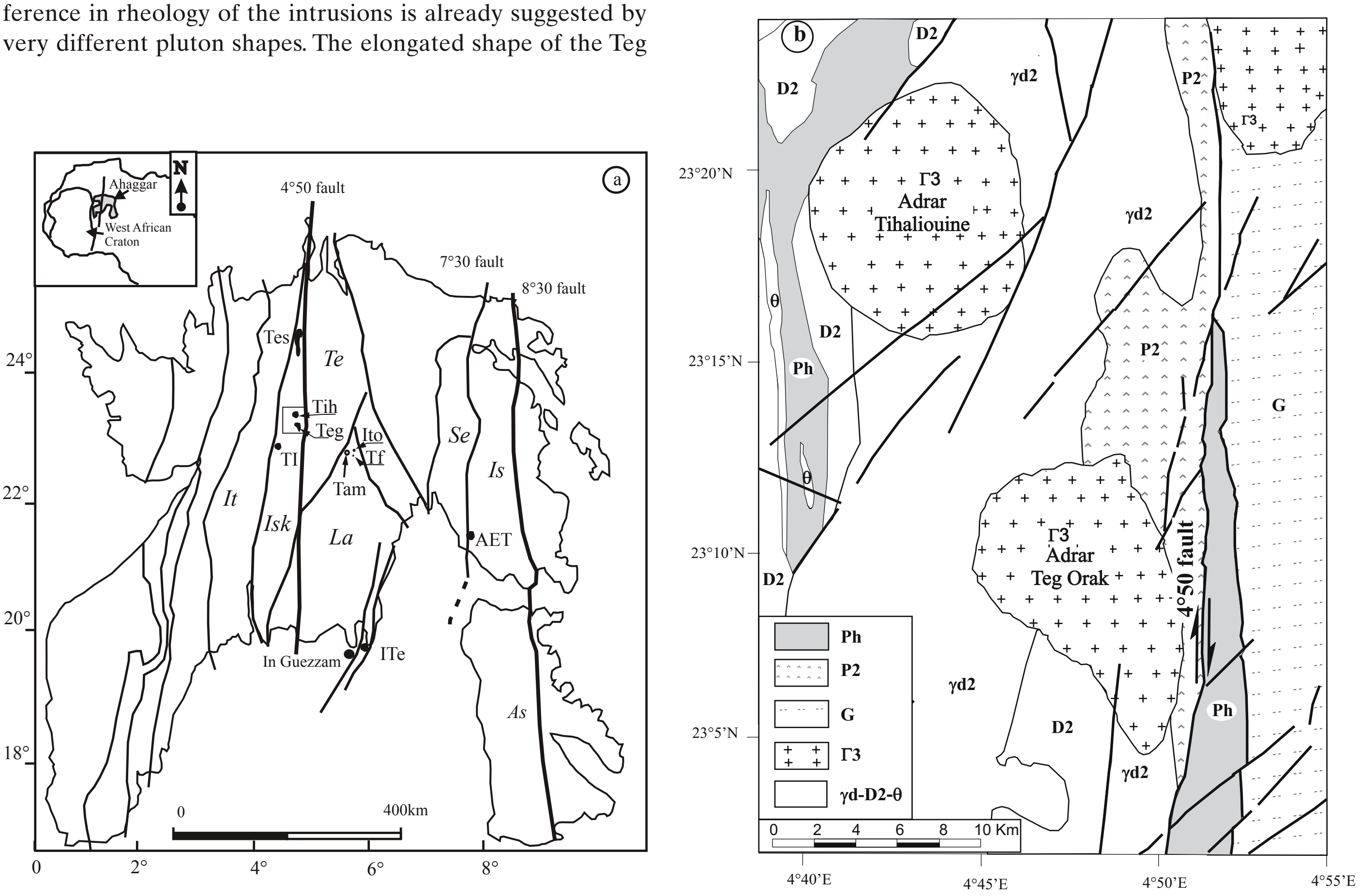

Fig. 1. a) General geological sketch map of the Tuareg shield showing the Taourirt plutons. Terranes of Assodé (*As*), Issalane (*Is*), Laouni (*La*), Serouenout (*Se*), Tefedest (*Te*), In Teidini (*It*) and Iskel (*Isk*). Tihaliouine (Tih), Teg Orak (Teg), Tesnou (Tes), Alous En Tides (AET), In Telloukh (ITe), Tioueine (TI), Tifferkit (Tf) and In Tounine (ITo) plutons. Tam: city of Tamanrasset.
b) Geological setting (Geological map "Tin Felki", 2002) of the studied plutons (Γ3): Ph: volcanites (rhyolite, dacite, tuff); P2: metamorphic rocks; γd2-D2-θ: Afedafeda syntectonic granitoids (γd2: granodiorite and granite, D2: norite, gabbro and diorite, θ: lentil of ultramafite); G: Gneiss and migmatites of the LATEA metacraton.

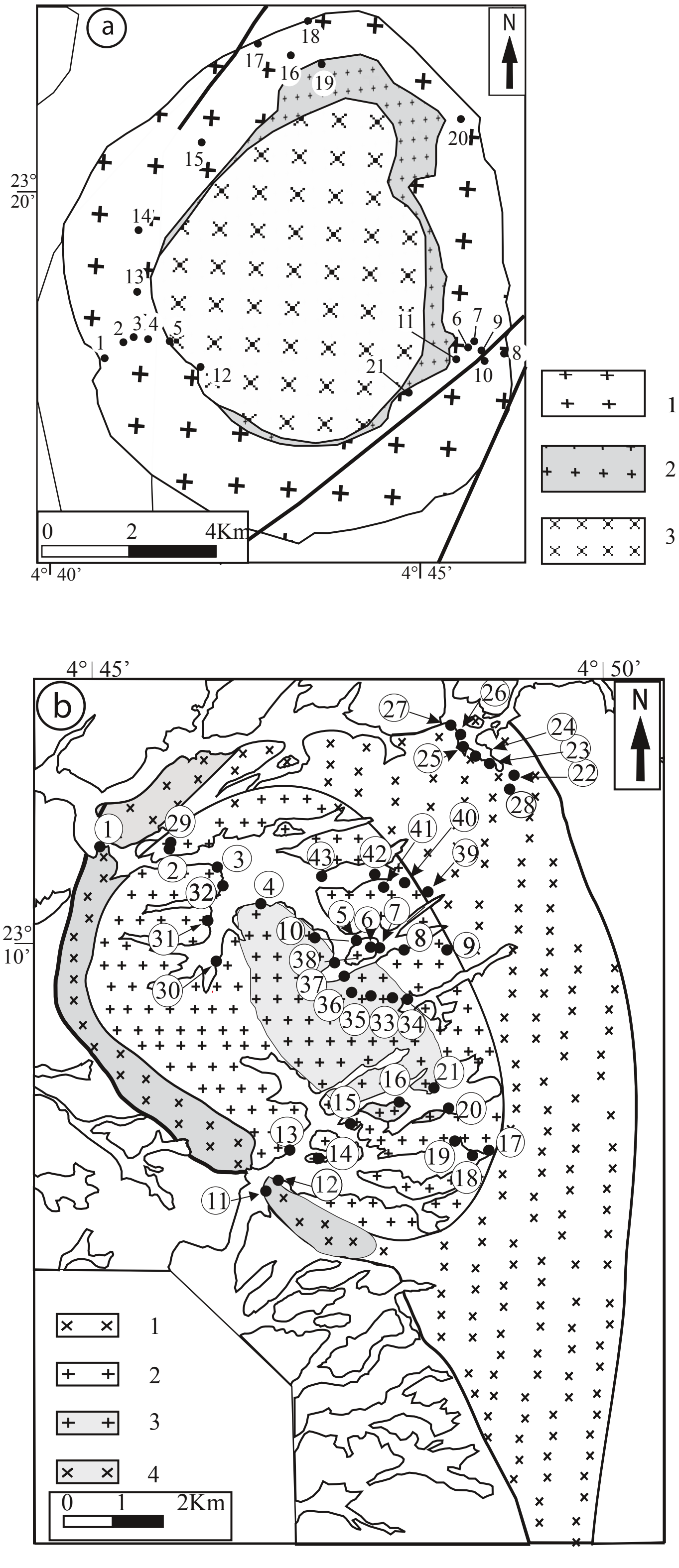

Fig. 2. Sampling sites: (a) in Tihaliouine pluton; (1) – Alaskite, (2) – Monzogranite of internal ring and (3) – Central monzogranite (Azzouni-Sekkal 1995, Azzouni-Sekkal et al., 2003). (b) in Teg Orak pluton; (1) – Alaskite, (2) – Syenogranite, (3) – Fine grain monzogranite and (4) – Coarse grain monzogranite (after unpublished field-map – Boissonnas 1960, personal communication).

Paquette et al. 1998; Azzouni-Sekkal et al. 2003), and were referred to as the "Taourirt" magmatism (Boissonnas 1974). Consequently to the reactivation of the N-S mega-shear zones by transtensional shearing (Liégeois et al. 2003), most of these plutons were emplaced (Fig. 1a) in the vicinity of shear zones, within the "Iskel" and "In Tedeini" terranes (west of the 4°50 N-S dextral shear zone) and within the LATEA (Liégeois et al. 2003) metacraton (east of the 4°50 shear zone). The Taourirt massifs are either clusters of plutons (e.g. the Imehellatene-Isseddiene and Tesnou complexes; Azzouni-Sekkal 1995) or single circular-to-elliptical (e.g. Tihaliouine; Azzouni-Sekkal 1995) or drop-shaped (e.g. Ta-n Ataram, Teg Orak; Boulfelfel 2000; Boulfelfel & Ouabadi 2000) isolated plutons, displaying a consistent N-S to N165° E elongation (Djouadi et al. 1997). The drop-shaped plutons are the closest to the 4°50 mega-shear zone. Most plutons are formed by several petrographic units, reflecting a possible multi-pulse emplacement (Azzouni-Sekkal 1995; Azzouni-Sekkal et al. 2003). For instance, this is the case of the Tihaliouine (3 units) and the Teg Orak (4 units) plutons.

The Tihaliouine pluton

This pluton is located about 10 km west of the 4°50 mega-shear zone (Fig. 1b). It has a slightly elliptical shape, outlined by an external ring of 1 to 2 km of width, where altitude reaches 1275 m in the south. The long axis trends N-S and has a length of about 12 km, and the short axis is about 10 km long. The inner area of the pluton forms a flat plain (mean elevation around 950 m) with recent deposits that surround small strongly weathered granitic inselbergs.

This pluton is made up of three main concentric units (Fig. 2a) (Boissonnas 1974; Azzouni-Sekkal & Boissonnas 1993): 1) in the central plain, a porphyritic monzogranite (Streckeisen 1976), 2) an internal half crown of medium-grained grey monzogranite that outcrops in the eastern part of the massif, around the central granite and 3) an external ring of red alaskite (leucocratic granite). For Azzouni-Sekkal (1995), emplacement occurred in two phases: the first intrusion gave the porphyritic granite and, by in situ differentiation on its border the grey granite; the alaskite was intruded in a second phase, favored by circular faulting related to the subsidence of the first intrusion.

The granite mineralogy includes quartz, rare amphibole, K-feldspar (perthitic orthose and microcline) and plagioclase (An_{11} to An_{17}) often fringed with albite and ferriferous biotite ($X_{Fe} \sim 0.67$). Accessory minerals are represented by fluorite, apatite, sphene, allanite and opaque minerals. The opaque grains (magnetite and variable amount of ilmenite) are rarely isolated and appear either in the form of skeletal figures or in xenomorphic zones in association with micas. The latter case suggests that they crystallized in sub-magmatic conditions. In the alaskite, the opaque minerals are rarer than in the other units. No clear shape preferential orientation of the main minerals was observed in the studied sites.

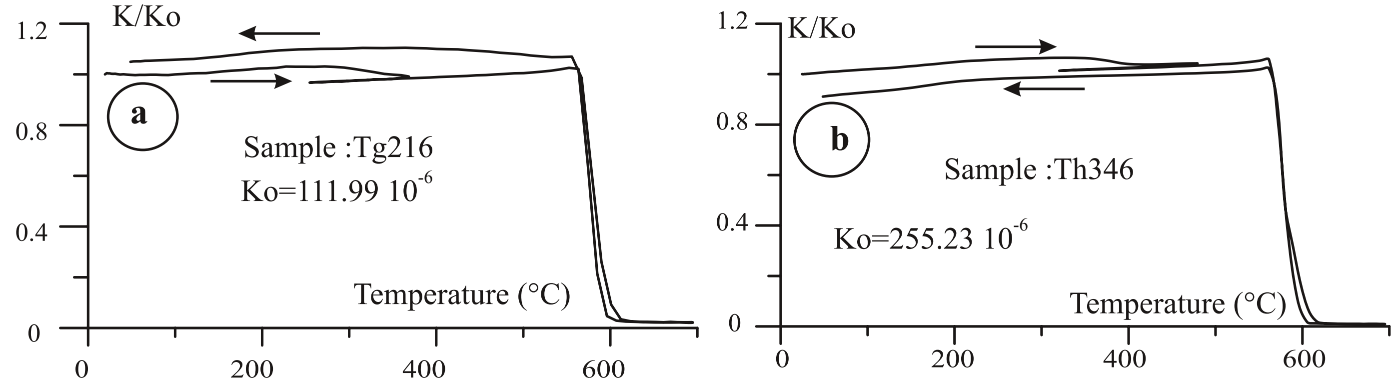

Fig. 3. Normalized thermomagnetic curves of samples from Teg Orak pluton (a) and Tihaliouine Pluton (b) with indication of the mean susceptibility (in SI) of the sample.

The Teg Orak pluton

This pluton is located about 8 km south-east of the Tihaliouine, just west of the 4°50 mega-shear zone (Fig. 1b). The eastern part of the massif is a high jagged ridge, reaching 1700 m, compared to about 900 m in the dry valleys crossing the western part. The pluton is drop-shaped and southwards-elongated parallel to the shear zone. This shape suggests that the pluton was still at a magmatic to sub-magmatic stage during a dextral movement along this fault. No clear shape preferential orientation of the main minerals is evident in the studied sites, but locally Boissonnas (1974) observed a rough preferential orientation of the large feldspars (oblique to the 4°50 fault). This likely represents a fluidality induced by dextral movements along the 4°50 fault during magma crystallization. The eastern border of Teg Orak also presents visible post-magmatic deformation with foliation parallel to the 4°50 shear zone (Boissonnas 1974). Rb-Sr geochronology dating provided an age of 519 ± 18 Ma, a Middle Cambrian age (Azzouni-Sekkal et al. 2003).

This pluton consists of a poorly fractionated suite of sub-alkaline affinity, ranging from monzogranites to syenogranites ($72\% < SiO_2 < 78\%$). It has a concentric structure (Fig. 2b), with four main petrographic units, which evolve increasingly from the core to the periphery, with: 1) a central elliptical core of fine-grained granite, 2) an intermediate ring of medium-grained granite, 3) a coarse-grained granite constituting the eastern border of the massif, and 4) a pink leucocrate granite (alaskite) forming the western border.

The primary mineral association includes: quartz, K-feldspar (perthitic orthose and microcline), zoned plagioclase (An_{15} to An_{24}) and ferriferous biotite ($0.56 < X_{Fe} < 0.92$). The biotite in the alaskite shows the highest values of X_{Fe}, since it is more ferriferous and less magnesian than in the other units. Accessory minerals include zircon, allanite, apatite and opaque minerals. The latter are often gathered in clusters of automorph magnetite. Ilmenite was observed only in one of the studied samples ($TiO_2 = 50\%$, $FeO = 37\%$, $MnO = 10\%$) from the intermediate ring. These rocks are often slightly altered with the development of epidote and chlorite.

Sampling

The Tihaliouine pluton displays a remarkable morphology, with an almost continuous circular thick external wall surrounding a flat plain. The granite of the central plain presents relatively few outcrops, most of them strongly weathered. Both its porphyritic nature and strong degree of weathering hamper studies of the anisotropy of magnetic susceptibility (AMS), and therefore this granite was not sampled. Accessible cross-sections through the external wall are limited to a few dry valleys. Sampling (21 sites; 160 samples) was then concentrated along these cross-sections and along the internal border of the external ring (Fig. 2a).

Access to the inner part of the Teg Orak is also restricted to a few dry valleys. Unfortunately, the eastern part of the pluton is not cut by such dry valleys. Sampling (Fig. 2b) was then conducted only along three dry valley systems, on the northern border (7 sites; 58 samples), in the south-western area (11 sites; 96 samples) and in the centre (25 sites; 195 samples).

Rock magnetism

Thermomagnetic analyses of low field magnetic susceptibility (K) were performed on a KLY3 susceptibility bridge with CS2–3 attachments (AGICO, Brno). Curves (Fig. 3) obtained for the different petrographic facies of both plutons have quite similar shapes, suggesting a similar type of magnetic mineralogy for all intrusions. Therefore, the variations in mean susceptibility within each pluton only reflect large differences in the concentration of the magnetic minerals. Curie curves indicate a weak mineralogical alteration during heating at about 300 °C. A sharp decrease of susceptibility at 580 °C is found in the curves from samples of both plutons, corresponding to the Curie temperature of pure magnetite

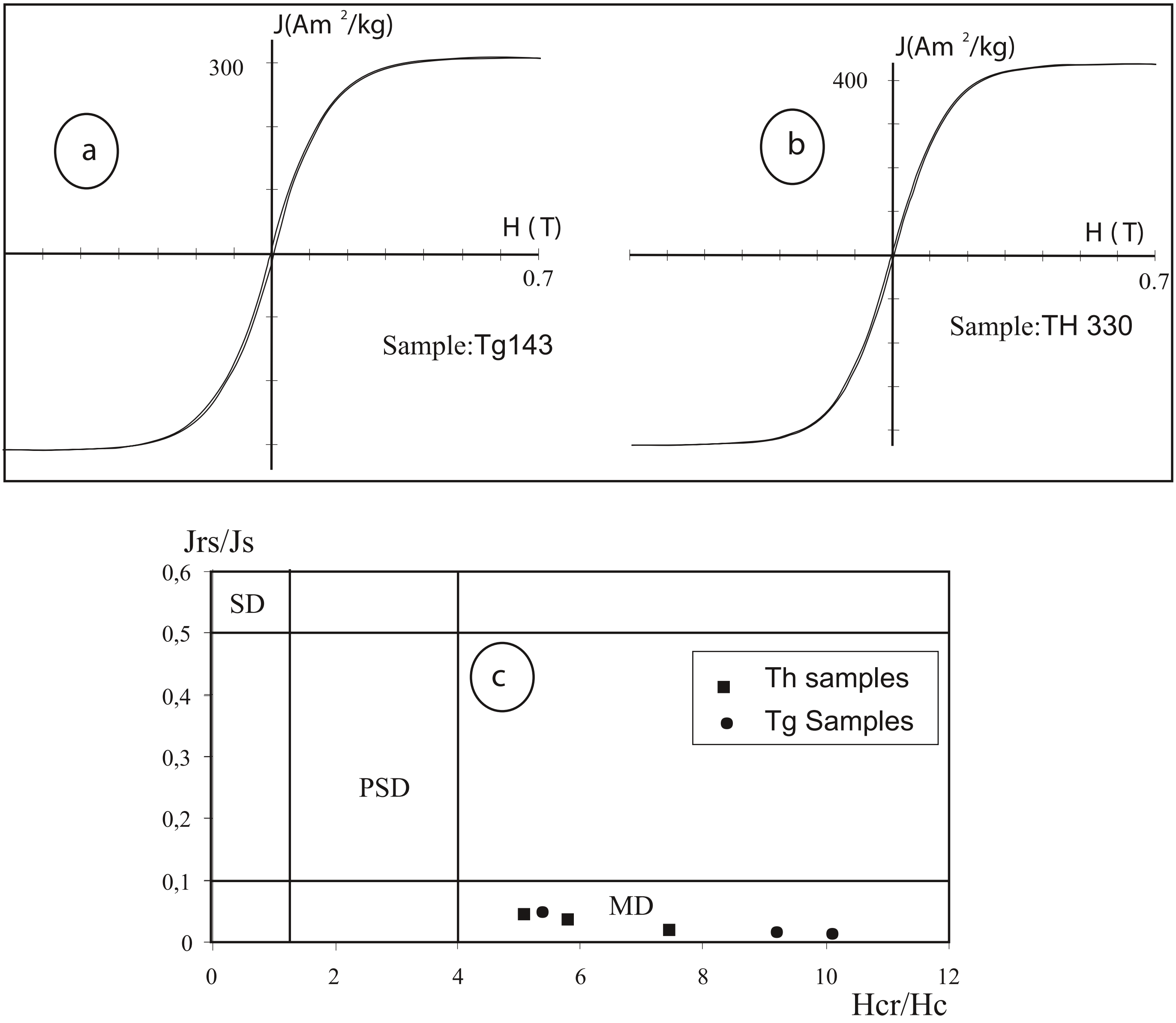

Fig. 4. Hysteresis loop of samples from Teg Orak pluton (a) and Tihaliouine pluton (b), corrected for the paramagnetism and (c) Day plot (Day et al., 1977) of the hysteresis parameters ratios of Tihaliouine (full squares) and Teg Orak (full circles) samples.

(Petrovský & Kapička 2006). The rectangular shape of the thermomagnetic curves and the absence of expressed Hopkinson peak immediately below the Curie temperature suggest that the magnetite is of large multi-domain (MD) grain size (O'Reilly 1984).

Hysteresis loops were made using a translation inductometer in an electromagnet capable of reaching 1.6 T. The curves obtained with samples from both plutons (Fig. 4a and b) suggest only the presence of magnetic minerals, with moderate coercive forces (saturation for about 0.3 T), such as magnetite. Ratios (Fig. 4c) of hysteresis parameters (Day et al. 1977) confirm that the magnetite grains have MD size. We can thus expect a normal magnetic fabric directly related to the shape of the magnetite grains (Potter & Stephenson 1988).

Magnetic fabric

AMS was measured using a KLY3 Kappabridge in low field. The Jelinek (1981) parameters P' and T were used to describe the magnetic fabric. Data for a group of samples were analyzed using normalized tensor variability (Hext 1963; Jelinek 1978), simple bootstrap (Henry 1997) and bivariate (Henry & Le Goff 1995) statistics. The three methods gave similar results. For bivariate statistics, weighting by precision parameter k related to measurement uncertainty was applied (Le Goff 1990; Le Goff et al. 1992). The magnetic zone axis was determined in order to obtain indications about the origin (stretching or planes intersection) of the magnetic lineation (Henry 1997).

Tihaliouine pluton

The mean susceptibility Km in 10^{-6} SI varies from 24 to 10 700 (mean value 1840) for the individual samples. The lowest values mainly correspond to the external border of the alaskite ring. The corrected degree of anisotropy P’ varies between 1.007 and 1.174 (mean 1.066) and the shape parameter T between –0.91 and 0.89 (mean 0.00). The highest P’ values correspond to oblate fabrics (Fig. 5a). The samples with the lowest mean susceptibilities have low P’ values. Table 1 lists the mean susceptibility and averaged AMS for the different sites.

The orientation of the principal axes between single specimens is quite scattered (Fig. 6, Tab. 1). However, despite this scatter and the limited number of studied sites, some broad tendencies appear. The maximum axes are mainly grouped around a vertical N-S to NNW-SSE plane, forming two slightly dominant clusters around vertical and horizontal directions. On the pluton scale (Fig. 6), the vertical direction appears to be the most important (i.e., maximum axis of the mean normalized tensor: D = 31° and I = 80°) and it is not significantly different from the poorly-defined magnetic zone axis (D = 12° and I = 68°). Most of the minimum axes are around a horizontal E-W to ENE-WSW direction, even in the north-western part of the pluton where the external contact trends NE-SW. On a map (Fig. 7), the magnetic foliation strikes however in some other sites parallel to that of the pluton border.

Teg Orak pluton

The mean susceptibility Km in 10^{-6} SI for individual samples is very variable, ranging from 8 to 9150 (mean value 2877). The lowest values (Tab. 1) have been obtained in the northern section, in coarse granite. Anisotropy degree P' has values (mean 1.074) from 1.021 to 1.283 and shape parameter T (mean –0.01) from –0.96 to 0.97 (mean site values on Table 1; Fig. 5b). Most of the principal maximum axes (Fig. 6) are well grouped around a horizontal NW-SE direction (maximum axis of the mean normalized tensor: D = 126° and I = 5°). A well-defined magnetic zone axis (D = 121°, I = 8°) coincides with this direction. Mean minimum axis is well-defined within each site, except in four sites where the fabric strongly prolate ($T < -0.40$). Minimum axes form two main clusters around a vertical NE-SW plane (Fig. 6). The well grouped maximum axes and girdled distribution of the minimum axes reflects the predominantly prolate shapes of the site mean ellipsoids.

On a map (Fig. 7), four different areas can however be distinguished. In the western area, the scatter of the principal axes is relatively high, part of the magnetic foliation striking more or less parallel to that of the pluton border or N-S. In all the other areas (in the central intrusion as well as

Table 1. Site, number of samples (N), declination (D) and inclination (I) of the principal maximum (Kmax) and minimum (Kmin) susceptibility axes, parameters P' and T (Jelinek 1981).

Tihaliouine

Site	N	Km (10^{-6} SI)	Kmax		Kmin		P'	T
			D (°)	I (°)	D (°)	I (°)		
Tih01	7	1065	146.6	42.9	255.8	19.5	1.039	–0.28
Tih02	6	94	35.4	79.0	223.3	10.9	1.042	0.14
Tih03	6	1796	185.2	5.6	275.9	6.7	1.084	0.40
Tih04	6	2382	164.2	10.4	256.7	13.2	1.090	0.23
Tih05	7	827	185.2	59.0	243	1.0	1.079	0.34
Tih06	8	1041	255.6	71.2	111.3	15.4	1.048	0.38
Tih07	8	1757	345.7	76.5	76.4	0.2	1.021	–0.06
Tih08	9	1565	38.4	74.9	271.3	9.2	1.050	0.11
Tih09	7	1926	178.3	20.0	69.5	41.7	1.036	0.01
Tih10	6	2401	180.0	8.5	273.5	19.9	1.032	–0.56
Tih11	8	2775	351.3	65.0	92.5	5.2	1.040	–0.27
Tih12	8	1619	154.8	23.9	64.1	1.5	1.070	0.56
Tih13	8	3252	175.3	35.3	269.6	6.1	1.067	0.12
Tih14	8	3601	165.9	9.4	260.5	26.1	1.053	0.09
Tih15	6	1624	87.1	30.3	284.1	58.6	1.041	0.44
Tih16	8	2964	99.0	65.0	351.9	7.8	1.061	–0.44
Tih17	7	38	331.2	43.7	88.2	25.5	1.007	–0.38
Tih18	8	159	339.6	72.5	189.6	15.3	1.031	–0.48
Tih19	12	2939	299.2	42.8	181.3	26.8	1.034	0.11
Tih20	8	3054	324.1	22.0	219	32.8	1.040	0.85
Tih21	9	726	13.2	17.7	118.6	39.6	1.058	–0.03

Table 1. (Continued).

Teg Orak								
Site	N	Km (10^{-6} SI)	Kmax		Kmin		P'	T
			D (°)	I (°)	D (°)	I (°)		
Teg01	7	21	130.7	24.4	229.2	17.9	1.029	–0.30
Teg02	8	5320	228.8	7.8	321.4	18.3	1.153	–0.03
Teg03	7	3406	0.1	9.7	258.8	49.1	1.043	–0.22
Teg04	8	3365	3.2	38.4	206.1	49.3	1.051	0.36
Teg05	8	2298	123.8	5.9	226.6	65.0	1.045	–0.23
Teg06	10	6011	312.6	6.2	212.1	59.2	1.096	0.10
Teg07	9	456	117.8	2.9	212.8	59.6	1.066	–0.43
Teg08	8	3149	307.0	5.4	212.4	40.2	1.052	–0.29
Teg09	8	4477	297.1	10.1	32.0	25.2	1.053	–0.84
Teg10	5	1877	130.9	5.5	223.6	26.4	1.042	–0.05
Teg11	11	122	82.4	55.8	289.7	31.2	1.044	–0.26
Teg12	7	541	358.1	79.5	177.0	10.5	1.061	–0.37
Teg13	8	3192	137.9	31.5	28.4	28.6	1.051	–0.17
Teg14	8	4198	124.2	19.0	15.6	42.8	1.044	0.30
Teg15	10	3793	143.4	16.7	18.4	62.4	1.059	0.05
Teg16	12	3328	135.1	12.4	29.1	51.4	1.065	0.40
Teg17	6	1767	135.3	11.5	30.3	51.9	1.074	–0.14
Teg18	8	4989	142.2	10.4	44.8	34.9	1.126	–0.45
Teg19	10	3388	125.0	9.1	27.1	40.6	1.071	–0.13
Teg20	9	3116	128.5	12.1	27.2	42.3	1.068	–0.06
Teg21	6	3183	127.4	10.0	25.1	50.5	1.059	–0.02
Teg22	8	627	314.2	51.3	192.3	22.9	1.054	0.18
Teg23	9	1842	296.4	13.1	205.2	4.9	1.069	0.02
Teg24	8	1401	288.6	5.5	196.3	22.5	1.071	–0.48
Teg25	8	1340	98.6	8.0	190.9	15.9	1.069	0.21
Teg26	9	925	115.2	3.3	206.5	21.5	1.062	–0.63
Teg27	4	1003	112.1	6.3	204.0	16.5	1.057	–0.37
Teg28	12	707	314.8	42.3	203.5	21.7	1.047	–0.46
Teg29	8	3289	221.1	4.3	311.9	10.9	1.094	0.12
Teg30	6	3885	160.1	2.1	250.4	10.1	1.050	–.022
Teg31	7	2741	154.4	15.2	253.6	30.6	1.032	0.26
Teg32	8	4104	358.3	8.9	257.1	51.4	1.046	0.05
Teg33	10	4327	309.3	0.8	217.7	63.5	1.078	–0.35
Teg34	8	2028	126.3	3.4	353.7	85.0	1.041	–0.80
Teg35	7	2665	137.9	2.3	240.1	79.2	1.053	–0.29
Teg36	7	3518	136.9	0.6	350.5	89.3	1.059	–0.56
Teg37	8	3642	144.6	6.0	242.7	53.2	1.067	–0.26
Teg38	8	3104	140.7	13.0	258.6	63.7	1.046	–0.27
Teg39	7	4821	301.6	4.1	208.2	39.1	1.078	–0.42
Teg40	9	3508	304.4	3.4	209.0	57.3	1.062	–0.23
Teg41	8	3482	308.4	0.1	218.3	48.5	1.060	–0.08
Teg42	8	4360	311.7	4.1	217.4	46.0	1.082	–0.36
Teg43	7	4737	150.5	5.4	254.6	68.9	1.058	0.02

in the other petrographic units), the magnetic lineation is very coherent throughout the pluton, except very close to the SW border. Although the minimum axes are distributed along a great circle whose pole is defined by the maximum axes, a bootstrap (Fig. 8) suggests that the minimum axes are grouped to the NE in the southwestern part of the pluton, are steeply dipping to the SSW in the central part, and are flat to the SSW in the northern part of the pluton. Therefore Kmin may correspond to a magnetic foliation of a local scale. The magnetic fabric is more prolate in the central area than in the other parts.

Evidence of brittle deformation

In all the studied area, NE-SW to ENE-WSW faults are important structures that affected the Taourirt plutons and the 4°50 shear zone. From the observed shift of the 4°50 shear zone by these faults (Geological map "Tin Felki", 2002), the latter were clearly dextral. In the northern, central and southwestern parts of the Teg Orak pluton, the NE-SW faults are characterized by brecciated zones, commonly several meters thick, that show strong silicification (e.g., in the Tihaliouine pluton, such a brecciated zone was observed only at one site

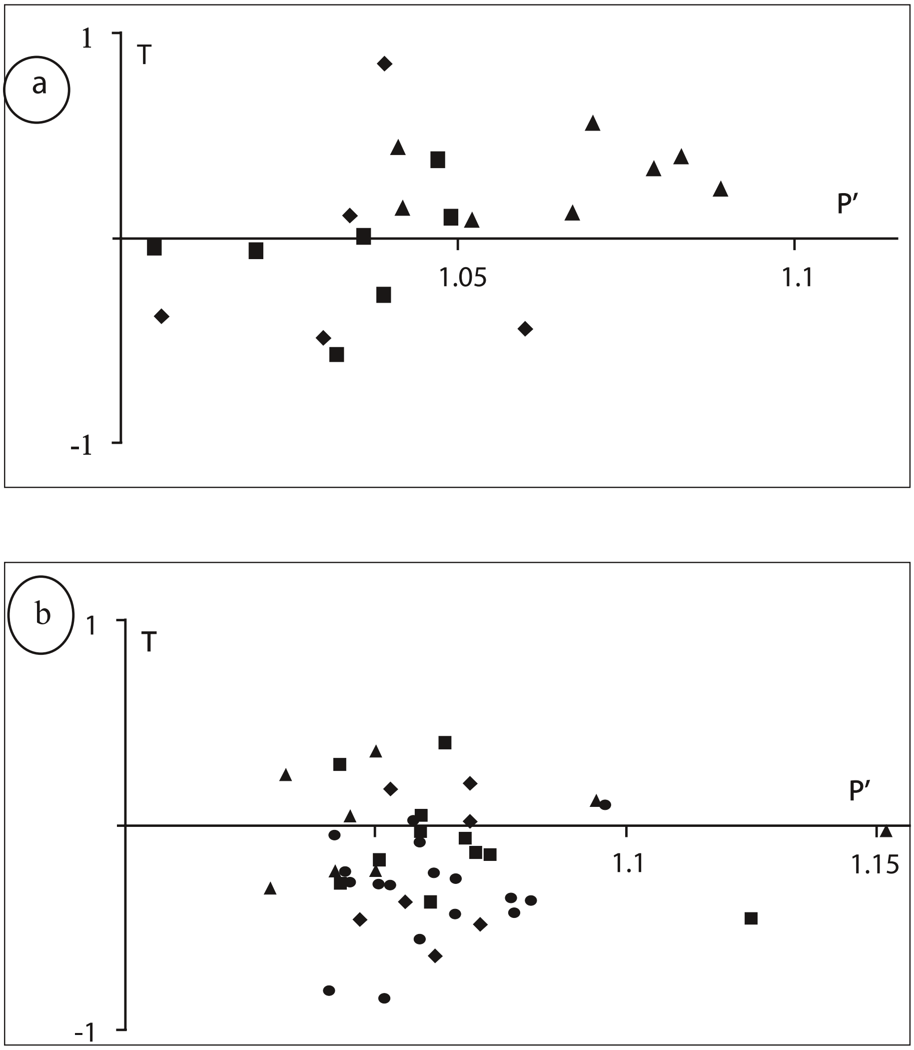

Fig. 5. P'-T diagram (Jelinek 1981) for sites of the northern (diamonds), western (triangles) and south-eastern (squares) parts of the Tihaliouine pluton (a) and for sites of the northern (black diamonds), western (black triangles), south-western (black squares) and central (grey circles) parts of the Teg Orak pluton (b).

on the western border). They often appear as moderate relief in the landscape. Observed fault planes are sub-vertical to SE to SSE-dipping. These fault zones were reactivated after the main silicification period, as indicated by the presence of fault mirrors with striations cutting the silicified breccias. The observation of the striation indicates reversed movements on the dipping planes. The compression direction inferred from this study is NW-SE to NNW-SSE and could correspond to sinistral movement of the 4°50 shear zone. The age of this event is unknown. However, the age of 482 ± 11 Ma obtained for Teg Orak only with samples with ^{87}Rb/^{86}Sr < 20 has been interpreted as related to fluid circulation during an early Ordovician slight reactivation of the main shear zones (Azzouni-Sekkal et al. 2003); this event could correspond to the compression in our plutons that is mentioned above).

Discussion

Magnetic fabric

The orientations of host-rock fabric and pluton magnetic fabric are unrelated. Host-rocks were therefore not significantly affected by internal deformation during and after emplacement of the Teg Orak and Tihaliouine plutons, except very close to the 4°50 shear zone (Boissonnas 1974). Intrusion did not occur at a very deep level of the crust.

With regard to the magnetic fabric of both plutons, two different zones clearly appear. The northern, central and south-eastern parts of Teg Orak (zone A) show a remarkably homogeneous fabric, while the western area of Teg Orak and the Tihaliouine (zone B) display a much larger scattering of the principal axes.

– Zone A corresponds to the elongated part of the Teg Orak pluton, suggesting syntectonic emplacement. The shape

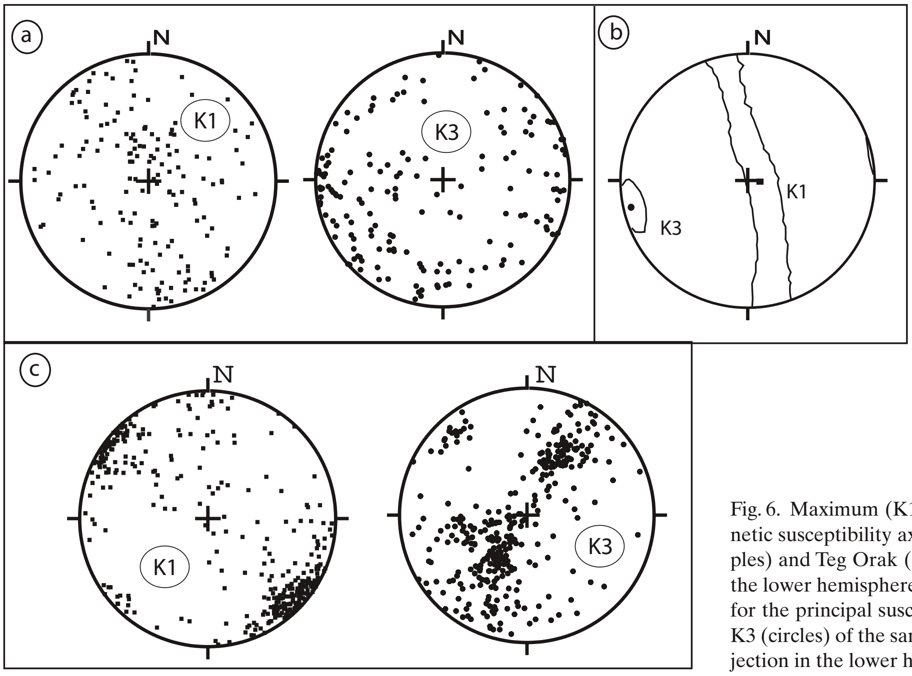

Fig. 6. Maximum (K1, squares) and minimum (K3, circles) principal magnetic susceptibility axes of the samples from the Tihaliouine (a – 160 samples) and Teg Orak (c – 349 samples) plutons (stereographic projection in the lower hemisphere). (b) Confidence zone at 95% from simple bootstrap for the principal susceptibility axes maximum K1 (squares) and minimum K3 (circles) of the samples from the Tihaliouine pluton (stereographic projection in the lower hemisphere).

of the site-mean ellipsoids is generally prolate and the lineation within this zone is entirely independent from the attitude of the internal contacts. In the studied sites, no visible preferred orientation of the main minerals is visible. The strike of the magnetic foliation, where it can be defined, seems however to be similar to the rough magmatic one observed locally in parts of the pluton by Boissonnas (1974). It is clearly different from the N-S post-magmatic one observed in the eastern border of the massif (Boissonnas 1974). In a late magmatic WSW-ENE vertical aplitic dyke (site Teg07, Table 1.) crossing the Teg Orak pluton, the magnetic fabric is not related to dyke orientation and is quite similar to the fabric measured in the neighboring sites of the pluton (Teg06 and Teg08, Table 1). The fabric in this zone is therefore not related to initial magma flow, even in the dyke, but has been acquired under strong compression during the last crystallization phases. The magnetic foliation, different in the northern, central and southwestern areas of the pluton, probably reflects the shape of the roof of the intrusion during these compressions.

– Zone B represents the part of Teg Orak that is not elongated and by the almost circular Tihaliouine pluton. Compared to zone A, the contrast in pluton shape also corresponds to different magnetic fabrics, which are generally oblate in shape. The orientation of the magnetic foliation, related to that of the pluton border and to that of the internal contacts in part of the sites, indicates a fabric reflecting the initial magma flow. In the Tihaliouine pluton, the external zone of the massif was emplaced during a second intrusion phase. The main cluster of sub-vertical principal maximum axes in this part could then reflect the ascending movement of the magma. There are, however, some sites in zone B giving more coherent data, suggesting that regional compression partly perturbed the initial fabric. In these sites, the magnetic foliation is often vertical and roughly N-S, and the P' values are mostly slightly higher than in the other sites. These sites correspond to the western border in the Tihaliouine pluton, which has therefore characteristics rather similar to those of zone A.

Regional implications

The emplacement of both plutons was favored by local distensions (e.g. Guineberteau et al. 1987; Tikoff & Teyssier 1992), probably related to movement along the 4°50 shear zone (Boissonnas 1974; Djouadi et al. 1997). Tihaliouine and the western part of Teg Orak were under almost the same conditions when new dextral displacement along the 4°50 affected this area during the sub-magmatic phases. Some sites show, however, a magnetic fabric with a roughly N-S vertical magnetic foliation. This is very similar to the mean fabric observed at Tioueine (Djouadi et al. 1997) and could indicate that, in zones not directly affected by shearing, a moderate E-W compression (perpendicular to the 4°50) slightly perturbed the fabric of the plutons. We can note that farther from the main shear zones, in other parts of the Tuareg shield (Tifferkit and In Tounine plutons, Henry et al. 2006), slight tectonic disturbances of the magnetic fabric were also attributed to displacements along secondary faults.

In contrast other parts of Teg Orak were subjected to strong compressions at the same time. In these areas, the magnetic fabric has strong similarities with those already observed in the Tesnou (Djouadi & Bouchez 1992; Djouadi et al. 1997) and Alous-En-Tides (Henry et al. 2004) plutons and in the In Telloukh dykes (Henry et al. 2007). In all these intrusions located

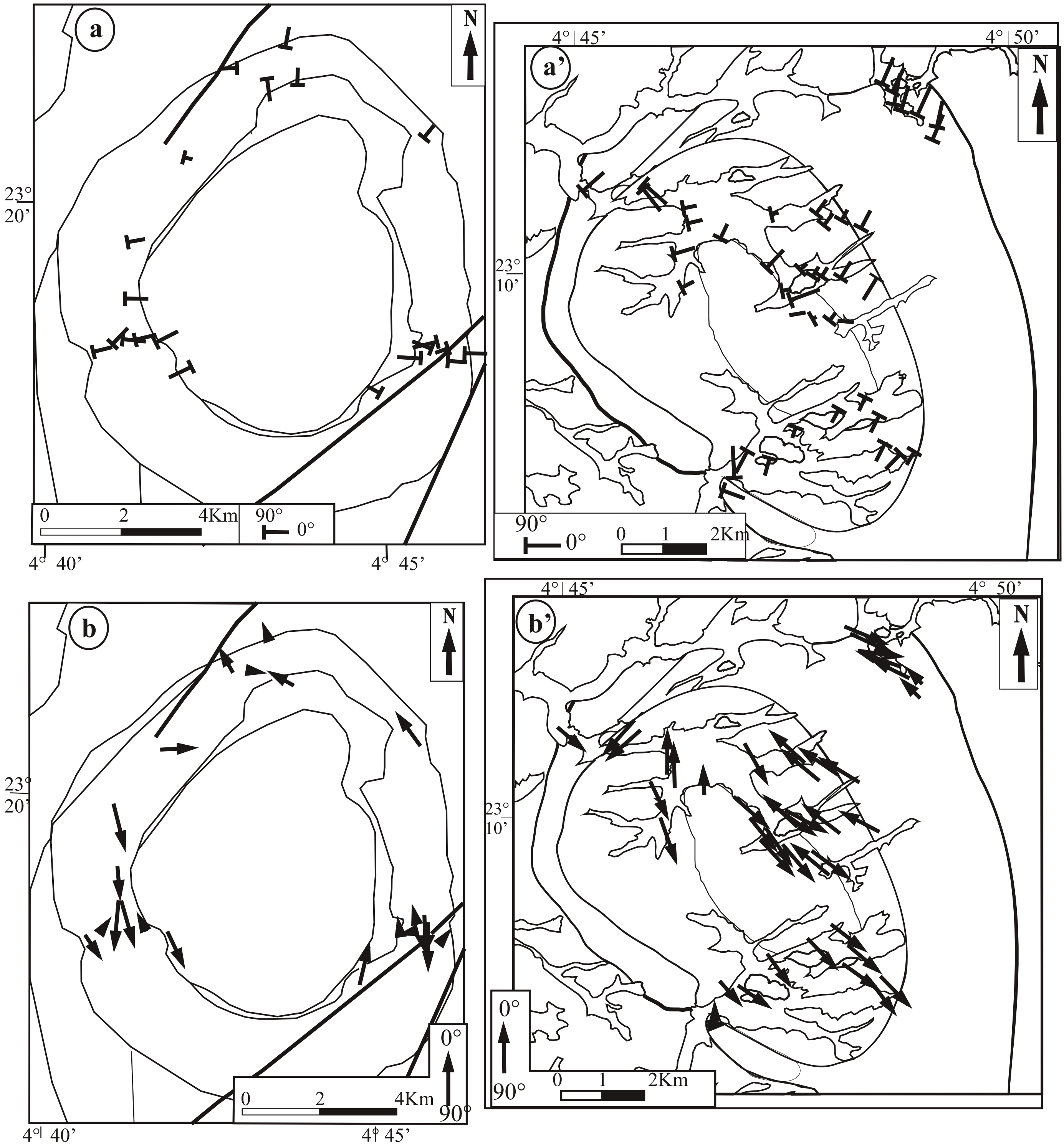

Fig. 7. Maps of the Tihaliouine (a, b) and the Teg Orak (a', b') plutons with the distribution of magnetic foliations (a, a') and magnetic lineations (b, b') measured in the studied sites.

along major shear zones of the Tuareg shield (4°50 and 8°30 shear zones and In Guezzam faults), the magnetic lineation is sub-horizontal and the strike of the magnetic foliation is different from that of the neighboring main shear zone, indicating a dextral movement of these major structures. It is then clear that in the entire Tuareg shield, emplacement and fabric-forming conditions of the late-Panafrican plutons are mainly related to the strike-slip movements along these structures.

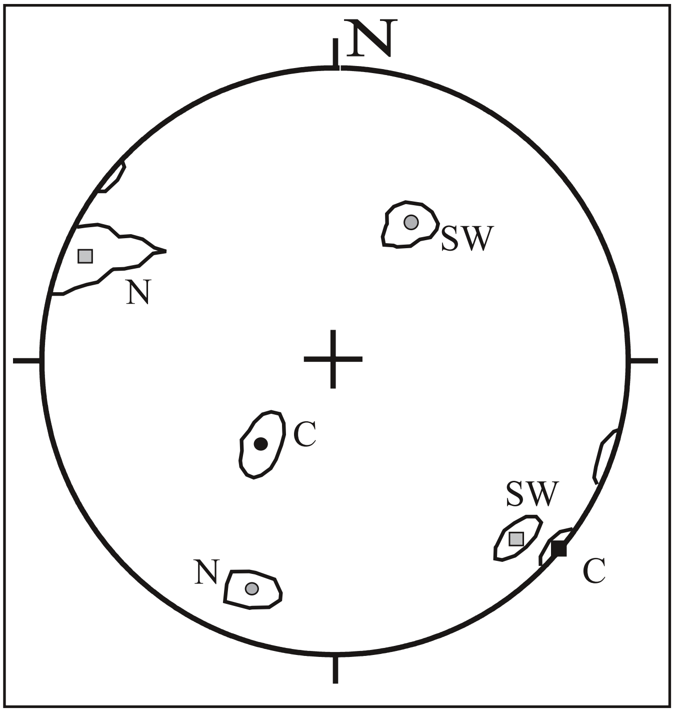

Fig. 8. Mean direction with 95% confidence limits determined from simple bootstrap for the principal susceptibility axes maximum (squares) and minimum (circles) of the sites from the northern (N – grey light, 58 samples), central (C – black, 195 samples) and south-western (SW – intermediate grey, 96 samples) parts of the Teg Orak pluton (stereographic projection in the lower hemisphere).

Relation with host-rocks characteristics

Magnetic fabrics clearly show that the country-rocks of these plutons correspond to two very different domains. Around zone B, rigidity "protected" the intrusions from almost all the external deformation. Zone A, on the contrary, was strongly affected by shearing related to strike-slip movements along the 4°50. It seems that there is almost no transition zone between these two domains. Their boundary does not correspond in the field to a visible major tectonic structure. Within the Teg Orak pluton, there is no change of the shape of the contact between the different granitic facies. South of the Teg Orak, this limit in host-rocks corresponds to the contact between granites to the west and diorites and gabbros to the east. North of the Teg Orak, the contact in host-rocks is between granites to the west and metamorphic rocks to the east. The Tihaliouine intrudes granitic host-rocks, except locally on its western border where host-rocks are volcanites, gabbros and diorites. The different rheologies of the granite intrusions in zones A and B therefore correspond quite well to the different characteristics of the host-rocks.

An interesting observation is that almost no breccias with faults mirrors, which indicate reactivation of the structures after silicification, have been observed in zone B. Evidence for reversed movement has been found on the contrary in numerous structures of zone A. The age of the reactivation of the NE-SW faults is unknown and could be Late Panafrican, early Ordovician as well as more recent. A difference of mechanical response to the stress field in zones A and B still apparently existed during this episode of brittle deformation.

Conclusion

Structural studies (granite rheology, brittle deformation) therefore clearly show in the Teg Orak – Tihaliouine region that granitic host-rocks acted as a rigid block, protecting the Taourirt plutons from the effect of regional deformation, while more basic plutonic rocks and metamorphic rocks had a more plastic behavior and transmitted the regional strain. Such a factor has therefore to be taken into account in the interpretation of structures in zones affected by regional shearing. Highly deformed rocks within apparently undeformed areas could often correspond to old weakness zones, in which a more plastic behavior was induced by previous fracturation and by appropriate lithology.

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REFERENCES

Acef, K., Liégeois, J.P., Ouabadi, A., and Latouche, L., 2003. The Anfeg post-collisional Pan-African high-K calcalkaline batholith (Central Hoggar, Algeria), result of the LATEA microcontinent metacratonization. Journal of African Earth Sciences 37, 295–311.

Auréjac, J.B., Gleizes, G., Diot, H. and Bouchez, J.L., 2004. Le complexe granitique de Quérigut (Pyrénées, France) ré-examiné par la technique de l'ASM: un pluton syntectonique de la transpression dextre hercynienne. Bulletin de la Société géologique de France 175, 157–174.

Azzouni-Sekkal, A., 1995. Pétrologie et géochimie des granites de types Taourirt. Exemple de Province magmatique de transition entre les régimes orogéniques et anorogéniques au Pan-Africain (Hoggar, Algérie). Mémoire du Service Géologique de l'Algérie 7. Edit. Service Géologique de l'Algérie, Alger, 288 pp.

Azzouni-Sekkal, A., and Boissonnas, J., 1993. Une province magmatique de transition du calco-alcalin à l'alcalin: les granitoïdes panafricains à structure annulaire de la chaîne pharusienne du Hoggar (Algérie). Bulletin de la Société Géologique France 164, 597–608.

Azzouni-Sekkal, A., Liégeois, J.-P., Bechiri-Benmerzoug, F., Belaidi-Zinet, S., and Bonin,B. 2003. The 'Taourirt' magmatic province, a marker of the closing stage of the Pan-African orogeny in the Tuareg Shield: review of available data and Sr–Nd isotope evidence. Journal of African Earth Sciences 37, 331–350

Black, R., Latouche, L., Liégeois, J.P., and Bertrand, J.M., 1994. Pan African displaced terranes in the Tuareg shield (central Sahara). Geology 22, 641–644.

Boissonnas, J., 1974. Les granites à structures concentriques et quelques autres granites tardifs de la chaîne panafricaine en Ahaggar (Sahara central, Algérie). Thèse, Centre de Recherches sur les Zones Arides, Série Géologie 16, 662 pp.

Borradaile, G.J., and Jackson, M., 2004. Anisotropy of magnetic susceptibility (AMS): magnetic fabric of deformed rocks. In Martin-Hernandez F., Lünenburg C.M., Aubourg, C. and Jackson, M. Eds, Magnetic fabric: Methods and application. Geological Society London, Special Publication 238, 299–360.

Borradaile, G.J., and Kehlenbeck, M.M., 1996. Possible cryptic tectono-magnetic fabrics in "post-tectonic" granitoid plutons of the Canadian shield. Earth and Planetary Science Letters 137, 119–127.

Bouchez, J.L., 2000. Anisotropie de susceptibilité et fabrique des granites. Comptes Rendus de l'Académie des Sciences, Paris, 330, 1–14.

Boulfelfel, N. E., 2000. Le Complexe plutonique du Teg Orak: Pétrographie, minéralogie et Géochimie (Fossé Pharusien-Hoggar Occidental). Magister Thesis, Algiers, 140 pp.

Boulfelfel, N. E., and Ouabadi, A., 2000. Le pluton granitique "Taourirt" panafricain de Teg Orak (Hoggar Occidental): caractéristiques géochimiques. Bulletin du Service Géologique de l'Algérie 11, 147–163.

Cheilletz, A., Bertrand, J.M.L., Charoy, B., Moulahoum, O., Bouabsa, L., Farrar, E., Zimmerman, J.L, Dautel, D., Archibald, D.A., Boullier, A.M., 1992. Géochimie et géochronologie Rb–Sr, K–Ar et ^{40}Ar/^{39}Ar des complexes granitiques panafricains de la région de Tamanrasset (Algérie): relations avec les minéralisations Sn–W associées et l'évolution tectonique du Hoggar central. Bulletin Société Géologique France 163, 733–750.

Day, R., Fuller, M., and Schmidt, V. A., 1977. Hysteresis properties of titanomagnetites: grain size and compositional dependence, Physics of the Earth and Planetary Interiors 13, 260–267.

Djouadi, M.T., and Bouchez, J.L., 1992. Structure étrange du granite du Tesnou (Hoggar, Algérie). Comptes Rendus de l'Académie des Sciences, Paris 315 II, 1231–1238.

Djouadi, M.T., Gleizes, G., Ferré, E., Bouchez, J.L., Caby, R. and Lesquer, A.1997. Oblique magmatic structures of two epizonal granite plutons, Hoggar, Algeria: late orogenic emplacement in a transcurrent orogen. Tectonophysics 279, 351–374.

Geological map "Tin Felki", 2002. Carte géologique de l'Algérie au 1/200 000 NF-31-XXIII, Service Géologique de l'Algérie, Office National de la Recherche Géologique et Minière.

Guineberteau, B., Bouchez, J.L., and Vigneresse, J.L., 1987. The Mortagne pluton (France) emplaced by pull apart along a shear zone: structural and gravimetric arguments, regional implications. Geological Society of America Bulletin 99, 763–770.

Hadj Kaddour, Z., Demaiffe, D., Liégeois, J.P., Caby, R. 1998. The alkaline-peralkaline granitic post-collisional Tin Zebane dyke swarm (Pan-African Tuareg Shield, Algeria): prevalent mantle signature and late agpaitic differentiation. Lithos 45, 223–243.

Henry, B., 1997. The magnetic zone axis: a new element of magnetic fabric for the interpretation of the magnetic lineation. Tectonophysics 271, 325–329.

Henry, B., and Le Goff, M., 1995. Application de l'extension bivariate de la statistique de Fisher aux données d'anisotropie de susceptibilité magnétique: intégration des incertitudes de mesure sur l'orientation des directions principales. Comptes Rendus de l'Académie des Sciences, Paris 320 II, 1037–1042

Henry, B., Djellit, H., Bayou, B., Derder, M.E.M., Ouabadi, A., Merahi, M.K., Baziz, K., Khaldi, A., and Hemmi, A., 2004. Emplacement and fabric-forming conditions of the Alous-En-Tides granite, eastern border of the Tin Serririne/Tin Mersoï basin (Algeria): magnetic and visible fabrics analysis. Journal of Structural Geology 26, 1647–1657.

Henry, B., Derder, M.E.M., Bayou, B., Ouabadi, A., Belhai, D., and Hemmi, A., 2006. Magnetic fabric of Late Panafrican plutons in the Tamanrasset area (Hoggar shield, Algeria) and structural implications. Africa Geosciences Review 13, 41–52.

Henry, B., Bayou, B., Derder, M.E.M., Djellit, H., Ouabadi, A., Khaldi, A. and Hemmi, A., 2007. Late Panafrican evolution of the main Hoggar fault zones: Implications of magnetic fabric study in the In Telloukh pluton (Tin Serririne basin, Algeria). Journal of African Earth Sciences 49, 211–221,

Hext, G., 1963. The estimation of second-order tensors, with related tests and designs, Biometrika 50, 353.

Hrouda, F., Chlupáčová, M. and Rejl L., 1971. The mimetic fabric in some foliated granosiorites as indicated by magnetic anisotropy. Earth and Planetary Sciences Letters 11, 381–384.

Jelinek,V., 1978. Statistical processing of magnetic susceptibility measured in groups of specimens. Studia geophysica et geodaetica 22, 50–62.

Jelinek, V., 1981. Characterization of the magnetic fabric of rocks. Tectonophysics 79, 63–67.

King, R.F., 1966. The magnetic fabric of some Irish granites. Geological Journal 5, 43–66.

Le Goff, M., 1990. Lissage et limites d'incertitudes des courbes de migration polaire: pondération, des données et extension bivariate de la statistique Fischer, Comptes Rendus de l'Académie des Sciences, Paris 311 II, 431–437.

Le Goff, M., Henry, B., and Daly, L., 1992. Practical method for drawing a VGP path, Physics of the Earth and Planetary Interiors 70, 201–204

Lelubre, M., 1952. Recherches sur la géologie de l'Ahaggar central et occidental. Bulletin du Service de la Carte Géologique de l'Algérie 2, 22.

Liégeois, J.P., Black, R., Navez, J., and Latouche, L., 1994. Early and late Pan-African orogenies in the Aïr assembly of terranes (Tuareg shield, Niger). Precambrian Research 67, 59–66.

Liégeois, J.P., Latouche, L., Boughrara, M., Navez, J., and Guiraud, M., 2003. The LATEA metacraton (Central Hoggar, Tuareg shield, Algeria): behaviour of an old passive margin during the Panafrican orogeny. Journal of African Earth Sciences 37, 161–190.

Marre, J., 1982. Analyse structurale des granitoïdes. BRGM Orléans, 80 p.

Neves, S.P., Araújo, A.M.B., Correia, P.B. and Mariano, G., 2003. Magnetic fabrics in the cabanas Granite (NE Brazil): interplay between emplacement and regional fabrics in a dextral transpressive regime. Journal of Structural Geology 25, 441–453.

O'Reilly, W., 1984. Rock and Mineral Magnetism. Blackie, Chapman and Hall edit, 220 pp.

Paquette, J.L., Caby, R., Djouadi, M.T,. and Bouchez, J.L., 1998. U-Pb dating of the end of Pan-African orogeny in the Tuareg Shield: the post-collisional syn-shear Tioueine pluton (Western Hoggar, Algeria). Lithos 45, 245–253.

Paterson, S.R., Fowler, T.K.Jr, Schmidt, K., Yoshinobu, A.S., Yuan, E.S. and Miller, R.B., 1998. Interpreting magmatic fabric patterns in plutons. Lithos 44, 53–82.

Petrovský, E. and Kapička A, 2006. On determination of the Curie point from thermomagnetic curves. Journal of Geophysical Research 111, B12S27, doi:10.1029/2006JB004507

Pignotta, G.S. and Benn, K., 1999. Magnetic fabric of the Barrington Passage pluton, Meguma Terrane, Nova Scotia: a two-stage fabric history of syntectonic emplacement. Tectonophysics 307, 75–92.

Pitcher, W.S. and Berger, A.R., 1972. The geology of Donegal: a study of granite emplacement and unroofing. Wiley Interscience, New York.

Potter, D.K. and Stephenson, A., 1988. Single-domain particles in rocks and magnetic fabric analysis. Geophysical Research Letters 15, 1097–1100.

Schofield, D.I. and D'Lemos, R.S., 1998. Relationships between syn-tectonic granite fabrics and regional PTtd paths: an example from the Gander-Avalon boundary of NE Newfoundland. Journal of Structural Geology 20, 459–471.

Streckeisen, A. L., 1976. To each plutonic rock its proper name, Earth Sciences Review 12, 1–33.

Tarling, D.H., and Hrouda, F., 1993. The magnetic anisotropy of rocks. Kluwer Academic Publishers, 232 pp.

Tikoff B and Teyssier C (1992) Crustal-scale, en-echelon "P-shear" tensional bridges: a possible solution to the batholith room problem. Geology 20, 927–930.

Tomezzoli, R.N., McDonald, W.D. and Tickyj, H., 2003. Composite magnetic fabrics and S-C structure in granitic gneiss of Cerro de los Viejos, La Pampa province, Argentina. Journal of Structural Geology 25, 159–169.

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