Research Paper

Petrographic and Magnetic Fabric Investigation of the Tadaout-Tizi n'Rsas Dyke Swarms in the Eastern Anti-Atlas, Morocco

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Research Highlights

- Petrographic and structural study of the Tadaout-Tizi n'Rsas dyke swarms.
- Magnetic fabrics indicate the tectonic events that affected the Tadaout-Tizi n'Rsas dykes.
- Characterization of the variscan deformation and kinematic faults of Tadaout-Tizi n'Rsas anticline.

ABSTRACT

Located in the eastern part of the Anti-Atlas, the Tafilalet region shows numerous dykes and sills that crosscut the Paleozoic terrains. The magmatic structures (dykes and sills) of the Tadaout-Tizi n'Rsas (TTR) anticline is studied here, it located neighboring the main branch of the Anti-Atlas Major Fault (AAMF), known in this location as the Oumejrane-Taouz Fault (OJTF). The N20° to N60° trending dykes crosscut the Paleozoic formations (Ordovician to Devonian), whereas sills are injected into the Silurian and Devonian ones. The dyke swarms of TTR have been studied using the Anisotropy of Magnetic Susceptibility (AMS), petrographic study and structural analyses. The petrographic study of the TTR doleritic dykes shows a dominance of plagioclase feldspars, alkali feldspars, amphiboles, pyroxenes and biotite. The dykes contain also mesotype (natrolite), sphene (titanite), apatite, actinolite and pegmatitic enclaves of biotite, orthoclase feldspars and pelites. Concerning field works, they show the deformation of TTR dykes by the Variscan tectonics events, it is marked by the presence of displacements (strike-slip faults) and cleavages. The Magnetic Susceptibility (MS) measured on magmatic specimens show the dominance of ferromagnetic and paramagnetic minerals. The high values of MS in the dykes are due to the presence of hematite, amphibole, pyroxene and biotite. In addition their magnetic fabric, determined by our AMS study, allows us to reconstitute the tectonic event which affected the magmatic bodies. This one is characterized by a magnetic foliation and a NNW-trending lineation that reflect the Variscan shortening orientation.

Keywords : Eastern Anti-Atlas, Tadaout-Tizi n'Rsas, magmatic system, Anisotropie of Magnetic Susceptibility, Oumejrane-Taouz Fault

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1. Introduction

rock Magnetism, coupled with complementary methods, has long been applied to understand the modes of mineralization emplacements and the evolution of some ore deposits (Essalhi, 2009). Moreover, rock magnetism allows to evaluate the direction of fluid flow (Sizaret et al., 2006; Essalhi, 2009; Essalhi et al., 2011). Furthermore, several studies based on the analysis of rock magnetism using the AMS show the utility of this technique for determining the magma emplacement kinematics (Knight and Walker, 1988; Ernst and Baragar, 1992; Raposo and Ernesto, 1995). In fact, the kinematics of dykes emplacement, recorded in magmatic rocks, is determined by their magnetic foliation and lineation which contribute to understand the emplacement mode of these magmatic bodies (Bouchez, 2000; Féménias et al., 2004; Nkono et al., 2006). They can also give idea on their deformation (Chakir et al., 2007; Otmame et al., 2018). As well as, our study based on the AMS and structural field work to make a relative dating of magmatic bodies and to clarify the deformation that affected, with respect to the reactivation of the major faults that pierce TTR anticline.

The magmatic system of TTR anticline is located in the NW part of the rural commune of Taouz, about 40 km to the west of the Moroccan-Algerian international frontier. The magmatic system of this study is a part of the Tafilalet region ones. This magmatic system is injected in the Paleozoic formations folded by Variscan orogeny that shows polyphase tectonics with reactivation of paleofaults and creation of new major folds (Baïdier et al., 2008, 2016; Ait Daoud et al., 2020);

Tafilalet is a Moroccan region with a big mining vocation; since antiquity, it has been the site of a big lead-zinc production. Nowadays, the exploitation concerns mainly the barite ore bodies. The main vein fields of Tafilalet are M'Fis, Shayb Arras, Njakh, Bouizrane, Bou Mayz, Tijekht and TTR. Geographically, the majority of these vein fields are concentrated in areas with abundant magmatic activity (Pouclet et al., 2017; Ait Daoud et al., 2020).

Several studies have been carried in Tafilalet region. The oldest ones are the studies undertaken in the framework of the geological mapping of this area, corresponding to

1/200 000 map sheet of Tafilalet-Taouz (Destombes and Hollard, 1986) recently revised by Destombes, (2006). Numerous works have been consecrated to the litho-stratigraphic, pleontologic and sedimentological studies (Destombes et al., 1962; Destombes, 1963; Hollard, 1974a; Klug, 2001, 2007; Klug et al., 2009; Becker et al., 2018a, 2018b, 2018c; Klug and Pohle, 2018; Pohle and Klug, 2018). In addition, several tectonic and metallogenic works have been documented in many publications (Makkoudi, 1995; Baïdier et al., 2008, 2016; Essalhi et al., 2016, 2018; Ait Daoud et al., 2020; Saidi et al., 2020) and in the National Geological Mapping Program [Programme National de la Cartographie Géologique (PNCG)]. This national program produced several 1/50.000 scale geological maps, like Irara, Marzouga, M'Fis, Taouz and El Atrous (Álvaro et al., 2014a, 2014b, Benharref et al., 2014b, 2014a, 2014c). Also, some magmatic studies were recently performed in Tafilalet region, like publications of Pouclet et al., (2017, 2018) and Najih et al., (2018, 2019).

In this paper, AMS study was coupled with structural field works to define the deformation having affected the dykes of TTR and to relate the deformation with the Variscan tectonic evolution of the Eastern Anti-Atlas.

2. Geological Setting

Tafilalet region is situated at the easternmost border of the Anti-Atlas. Generally, the Moroccan Anti-Atlas consists of Precambrian basement covered by Paleozoic sedimentary sequence. Precambrian basement is exposed in several inliers oriented ENE-WSW (Choubert, 1943, 1947; Thomas et al., 2004; Gasquet et al., 2005, 2008). The most eastern Precambrian inliers are Saghro and Ougnat. However, the Precambrian basement are not limited at the two major inliers; they outcrop in the east part of Erfoud city (Gour Brikat and El Aness), and in the south-eastern border of Ougnat-Ouzina ridge in the Jbel Tazoult n'Ouzina (Destombes and Hollard, 1986). These Precambrian basements are covered by a series of folded Paleozoic sedimentary sequence (Paleozoic series, predominantly deposited in a shallow marine environment). The Ougnat-Ouzina ridge corresponds to a formation pile from Cambrian to Ordovician. Nevertheless, the Tafilalet and Maider basins, located to

Fig. 1. (a) Simplified geological map of the eastern Anti-Atlas. (b) Simplified geological map of the Tafilalet region, based on the compilation of five maps of the Moroccan cartographic program « Plan National de Cartographie Géologique, programme Tafilalet 2009 », (Álvaro et al. 2014a-b, Benharref et al. 2014a-b-c), with the works of Destombes and Hollard (1986), Baidder et al. (2016). Location of magmatic bodies: (A) west of Rissani, (B) north Erg Chebbi, (C) Widane Chebbi, (D) NE of M'Fis, (E) upstream of Ziz valley, (F) Douar Oum El Hadj, (G) Marzouga, (H) M'Fis, (I) eastern M'Fis, (J) middle of the Ziz valley, (K) Znaigui, (L) Tadaout, (M) Begaa, (N) eastern Taouz, (O) Jbel El Mraier. Blue rectangle indicates the study area.

the east and west of the ridge, respectively, consist of a set of formations ranging from Devonian to Carboniferous (Hollard, 1974b, 1981; Raddi et al., 2007) (Fig. 1a).

Paleozoic series of the eastern Anti-Atlas are affected by the Variscan orogeny. This later appear in the development of numerous folds and the reactivation of paleofaults (Soualhine et al., 2003; Robert-Charrue, 2006; Baidder, 2007; Raddi et al., 2007; Michard et al., 2008; Baidder et al., 2008, 2016; Álvaro et al., 2014b, 2014a; Benharref et al., 2014a, 2014b, 2014c; Soulaïmani et al., 2014; Ait Daoud et al., 2020). Several magmatic bodies (in the form of dykes, sills and laccoliths) intruded these series. During the Cambrian, the magmatic rocks were more developed in the south of the Ougnat inlier (Destombes and Hollard, 1986; Raddi, 2014) and between the Tafilalet and Maider basins in the Ougnat-Ouzina ridge, precisely in the Jbel

Tazoult n'Ouzina anticline (Destombes and Hollard, 1986; Benharref et al., 2014a, 2014b, 2014c; Baidder et al., 2016; Pouclet et al., 2018).

According to Destombes and Hollard (1986) (geological map of Tafilalet-Taouz, scale 1 :200 000), the Tafilalet province shows a large distribution of magmatic rocks located at the Ordovician, Silurian, Devonian and Carboniferous formations, but they don't present any indication of ages. However, recent publications about dykes and sills which cross the folded paleozoic series of the Anti-Atlas yielded an age of 200-195 Ma. The majority of these magmatic rocks follow the NE-SW direction faults, and are attributed to the Central Atlantic Magmatic Province (CAMP) events (Hailwood and Mitchell, 1971; Hollard, 1973; Sebai et al., 1991; Derder et al., 2001; Youbi et al., 2003; Silva et al., 2004; Verati et al., 2007; Chabou et al., 2010). However,

some new works present new results about the geochemical composition, petrographic and stratigraphic setting of these igneous rocks. Based on these works, the magmatic rocks of Tafilalet province have a sodic alkaline magma composition and intruded during the Famennian-Tournaisian and the early Visean (Álvaro et al., 2014b, 2014a, Benharref et al., 2014a, 2014b, 2014c, Pouclet et al., 2017, 2018). In the same way, Najih et al., (2018, 2019) confirm the geochemical affinity of these magmatic rocks, they attribute them a post-Visean and pre-Triassic age, precisely the late Permian (between $255 \pm 3\text{Ma}$ and $264.2 \pm 2.7\text{Ma}$) using the biotite $^{40}\text{Ar}/^{39}\text{Ar}$ and zircon U-Pb dating. The samples were collected in the Jbel Dboa laccolith in the core of the M'Fis anticline located at 14 km NE of the TTR anticline.

3. Magmatism of Tafilalet Region

The Cambrian series of Tafilalet show a Cambrian magmatic activity, limited in the Jbel Tazoult n'Ouzina massif (Pouclet et al., 2018). However, in other areas where the Cambrian series are exposed like Jbel Taklimt, Jbel Renneg and Jbel Tijekht for example, no magmatic outcrops have been observed (Destombes and Hollard, 1986; Benharref et al., 2014b; Baïdier et al., 2016).

According to several authors (Makkoudi, 1995; Álvaro et al., 2014a; Benharref et al., 2014c; Pouclet et al., 2017), the large concentration of magmatic bodies in Tafilalet region took place in the Middle Devonian to Lower Carboniferous formations (Fig. 1b). In Tafilalet sedimentary basin, the outcrop magmatic rocks are characterized by an important laccolith complex and many sills intruded in M'Fis upper Devonian formations (H in Fig. 1b), and by a system of sills, dykes and laccoliths in Znaigui Upper Devonian formations (K in Fig. 1b). In addition, a subvolcanic system is located at the vast reg in the eastern part of M'Fis (I and D in Fig. 1b) inside of the Lower Carboniferous formations. At the southern edge of Tafilalet basin, the magmatic activities are characterized by a sill system located in the Lower Visean strata in the eastern Taouz (N) and the Begaa sites (M in Fig. 1b).

At the north part of Tafilalet basin, the Widane Chebbi (C in Fig. 1b), Erg Chebbi (B in Fig. 1b) and Marzouga (G in Fig. 1b) sites show the presence of a laccolith system and sills. All of them took place in the Devonian and the

Lower Carboniferous formations (Benharref et al., 2014c; Pouclet et al., 2017). In addition, at the western part, several sites were the seat of an intense magmatic activity in the form of dykes and sills injected into the Ordovician, Silurian and Devonian formations in the ouest of Rissani (A in Fig. 1b), upstream of Ziz valley (E in Fig. 1b), Douar Oum El Hadj (F in Fig. 1b), middle of the Ziz valley (J in Fig. 1b), Jbel El Mraier (O in Fig. 1b) and Tadaout-Tizi n'Rsas the subject of this study area (L in Fig. 1b).

4. Materials and Methods

The methodology followed in this work consists of mapping, sampling and measuring the fracture system that affects the magmatic bodies of TTR. Thirty-six samples were sampled in two dykes (principal dyke and the dyke crossing the Ordovician formations) to prepare the thin sections for microscopic observation. The dyke crossing the Devonian formations has not been studied because of its advanced alteration.

Also, measurements of AMS were performed. The AMS technique consists of measuring the magnetic susceptibility (k) of a rock sample in different directions and defining the intensity and the direction of the three principal axes $k_1 \geq k_2 \geq k_3$ of the anisotropy of the magnetic susceptibility ellipsoid. The parameters of Jelinek, (1981) were used to characterize the AMS ellipsoid for each station (Table 1).

Sampling method consists of collecting oriented samples from the roof, the center and the walls of the two chosen dykes. Two techniques of sampling were adopted; the first one consists to extract cylindrical cores using a portable drilling machine (a gasoline-powered rock drill), and the second one consists of extracting oriented samples (hand-blocks) that were core drilled in the laboratory by a settled apparatus. Twenty-three samples coming from six sites were collected in two dykes (principal dyke and crossing Ordovician formations dykes) using the second method. Each drill core has been cut perpendicularly to the length into 2 or 3 specimens. AMS measurements were conducted on fifty-two standard size specimens with 25 mm-diameter and 22 mm high. The AMS measurements were carried out in low applied field of 300A/m ($\approx 0.38\text{ nT}$) using the Susceptometer Kappabridge KLY- 3S (AGICO) working in a weak alternating field in the magnetic laboratory of the

Table 1. AMS data and their associated parameters. L: lineation, F: foliation, T: shape parameter, P': degree of anisotropy, (k1, k2 and k3): axes of the AMS ellipsoid. Km: mean MS, D: declination. I: Inclination

Spécimen	L	F	P'	T	K1		K2		K3		Km (SI)
					D	I	D	I	D	I	
TZ1-1	1,003	1,004	1,007	0,203	116	41	274	47	16	11	22,23 E-03
TZ1-2	1,011	1	1,013	-0,919	160	46	328	43	64	6	17,71 E-03
TZ1-3	1,003	1,004	1,006	0,18	258	66	110	20	16	12	19,57 E-03
TZ2-1	1,006	1,006	1,012	-0,003	250	65	103	22	8	12	18,76 E-03
TZ2-2	1,013	1,007	1,02	-0,292	171	25	64	31	292	48	16,60 E-03
TZ2-3	1,002	1,007	1,01	0,514	179	12	81	35	284	53	9,63 E-03
TZ3-1	1,006	1,005	1,011	-0,13	173	4	80	35	268	55	18,76 E-03
TZ3-2	1,005	1,004	1,008	-0,13	2	6	95	30	261	60	19,41 E-03
TZ4-1	1,003	1,005	1,008	0,151	120	41	335	43	226	18	534,2 E-06
TZ4-2	1,001	1,005	1,007	0,599	344	101	241	20	52	31	641,4 E-06
TZ5-1	1,004	1,002	1,007	-0,255	205	64	335	18	71	19	538,3 E-06
TZ5-2	1,007	1,005	1,012	-0,17	356	26	122	51	252	27	548,8 E-06
TZ6-1	1,002	1,003	1,005	0,222	204	42	82	30	330	33	658,9 E-06
TZ6-2	1,002	1,007	1,009	0,531	141	76	289	12	20	70	640,0 E-06
TZ6-3	1,003	1,002	1,005	-0,268	259	83	147	2	57	6	683 E-06
TZ7-1	1,004	1,002	1,005	-0,406	355	58	157	31	252	8	608 E-06
TZ7-2	1,004	1,005	1,009	0,093	249	47	153	5	59	42	601,5 E-06
TZ8	1,001	1,003	1,003	0,671	222	33	359	48	117	22	535,8 E-06
TZ9	1,003	1,002	1,005	-0,133	30	34	203	55	298	3	345,4 E-06
TZ10-1	1,002	1,002	1,003	0,073	85	51	253	38	348	6	553,1 E-06
TZ10-2	1,003	1,001	1,004	-0,332	307	42	156	44	51	15	518,5 E-06
TZ11	1,004	1,006	1,01	0,138	352	19	84	6	191	70	495,7 E-06
TZ12-1	1,007	1,002	1,009	-0,486	120	17	23	22	246	61	517,7 E-06
TZ12-2	1,003	1,009	1,012	0,553	151	7	57	31	251	58	508,5 E-06
TZ13-1	1,004	1,004	1,008	0,018	260	0	350	31	169	59	21,01 E-03
TZ13-2	1,004	1,003	1,007	-0,131	184	42	323	40	73	22	20,83 E-03
TZ14-1	1,005	1,004	1,009	-0,098	185	46	329	38	75	19	23,84 E-03
TZ14-2	1,001	1,001	1,003	0,103	189	43	436	45	88	12	22,01 E-03
TZ15-1	1,007	1,004	1,011	-0,247	187	9	278	10	58	76	18,58 E-03
TZ15-2	1,005	1,005	1,01	-0,082	103	44	239	34	349	27	19,75 E-03
TZ15-3	1,003	1,003	1,007	-0,147	102	38	226	35	343	33	20,40 E-03
TZ16-1	1,012	1,012	1,024	0,38	336	6	241	41	73	49	24,47 E-03
TZ16-2	1,015	1,016	1,031	0,054	335	7	236	40	73	50	27,81 E-03
TZ17-1	1,007	1,003	1,01	-0,451	328	55	231	5	137	35	30,18 E-03
TZ17-2	1,009	1,004	1,013	-0,381	327	66	105	18	200	15	24,85 E-03
TZ17-3	1,009	1,002	1,011	-0,671	311	58	70	17	168	27	22,06 E-03
TZ18-1	1,016	1,018	1,035	0,039	198	14	298	36	90	51	25,19 E-03
TZ18-2	1,022	1,023	1,046	0,015	178	10	274	30	71	58	29,47 E-03
TZ19-1	1,024	1,022	1,047	-0,042	301	3	209	32	36	58	13,49 E-03
TZ19-2	1,026	1,024	1,051	-0,046	301	5	207	37	37	53	24,73 E-03
TZ19-3	1,009	1,013	1,023	0,175	301	13	198	44	43	43	20,02 E-03
TZ20-1	1,001	1,003	1,004	0,34	138	2	46	47	229	43	476 E-06
TZ20-2	1,003	1,003	1,006	0,143	220	39	2	44	113	20	518,7 E-06
TZ20-3	1,002	1,003	1,005	0,299	279	16	17	25	159	60	487,5 E-06
TZ21-1	1,022	1,016	1,038	-0,165	69	3	334	55	161	35	11,47 E-03
TZ21-2	1,004	1,006	1,011	0,189	245	3	335	2	102	87	9,166 E-03
TZ21-3	1,002	1,007	1,01	0,488	248	7	158	3	45	83	9,705 E-03
TZ22-1	1,009	1,01	1,019	0,087	169	24	278	36	53	44	9,569 E-03
TZ22-2	1,008	1,007	1,015	-0,02	253	0	343	17	163	73	8,947 E-03
TZ22-3	1,009	1,007	1,016	-0,133	73	7	339	26	176	63	8,166 E-03
TZ23-1	1,001	1,006	1,007	0,749	59	61	194	21	291	19	687,8 E-06
TZ23-2	1,002	1,003	1,004	0,161	224	7	345	77	133	11	690,7 E-06

The MS data and petrographic study has been coupled in this work to explain the obtained MS value. However, the AMS data and structural field works studies are associated in order to analyze the relationships between these magmatic bodies and the different deformation phases (at a larger regional scale with respect to previous works).

5.1. Description of TTR dykes

(Fig. 2). The dykes are located in three zones; (i) the principal dyke trending NE to ENE and dipping 70° to the southeast that took place on the right edge of the Ziz valley. This dyke follows the direction on OJTF branch that put the Ordovician formations into contact with the Middle-Upper Devonian ones (Figs. 3a-b). (ii) the dyke crossing the Ordovician formations located approximately 900 m westward of the principal dyke, it is trending $N15^{\circ}$ to $N20^{\circ}$ and dipping 50° to the southeast (Fig. 3b), and (iii) in the Jbel Aoufilale, at the northern limit of the study area, outcrops a dyke crossing the Upper Devonian formations with a NE-SW direction and dipping 70° to the north-west (Figs. 2, 3c, 4a-4c). Generally, the orientations of the studied dykes span from $N15^{\circ}$ to $N70^{\circ}$, with a dominance of the NE-SW direction, with thicknesses ranging from 1 m to 2 m (Table 2).

Fig. 3. Geological cross sections in the eastern part of the TTR anticline, showing the disposition of the magmatic bodies. (a) Principal dyke, putting together the Devonian and Ordovician formations, of the right bank of Ziz valley, (b) principal dyke and dyke crossing the Ordovician formations, (c) sills interbedded in the Silurian and Devonian formations, and dyke crossing the Devonian formations.

Table 2. Geometric characteristics of the studied dykes

Dykes	Thickness (m)	Direction (°)/dip
Principal dyke	2	NE to ENE , 70°SE
Dyke crossing the Ordovician formations	1.50	N10° to N20°, 50°SE
Dyke crossing the upper Devonian formations	1	NE, 70°NW

5.2. Petrographic characteristics

The TTR doleritic dykes are macroscopically similar; they all show a greenish color with oxidation marks and feldspar crystals. They also show centimetric phenocryst of orthoclase, biotite, pelitic fragments of the host, and rounded amygdaloid calcite (Figs. 4e-f).

The microscopic observation shows that these dykes have a microlite to microlite porphyry texture with rarely microgranular texture. They are composed of plagioclase feldspar, alkali feldspar, amphibole, pyroxene, sphene (titanite), apatite and biotite in the primary paragenesis,

and mesotype (natrolite), actinolite, hematite and calcite in the secondary paragenesis (Fig. 5). The plagioclase feldspar is the most abundant mineral in this facies. It appears in the form of elongated millimetric phenocrysts (c.5mm), more or less automorphic and it sometimes shows a fan form microlites. The plagioclase feldspar is occasionally altered and shows an elongated form (Figs. 5a, 5c-d, 5g-h, 5j-l). Towards the centre of the dyke, alkaline feldspar is increasingly abundant. It often appears as an elongated phenocrysts form (Figs. 5d, 5i). With two planes of cleavage, the amphibole (hornblende) is present in the form of small

Fig. 4. Magmatic bodies of TTR. (a & b) principal dyke, (c) dyke crossing the Ordovician formations, (d) dyke crossing the Devonian formations and (e & f) macroscopic appearance of dykes: biotite and orthoclase feldspar phenocrysts, and pelite enclaves in the dolerite matrix (coin diameter = 2 cm).

lozenges. In general, the amphiboles are altered into chlorite or transformed to iron oxides that follow the cleavage planes (Figs. 5b-5c, 5e). The pyroxene is not abundant; it appears automorphic, biotitized and chloritized (Figs. 5c-5d, 5f). The mesotype (natrolite) is a secondary mineral in this facies. It has a globular form and rarely has an elongated form. This mineral is colorless in the transmitted light with parallel nicols (PN) and with a white to gray color in the transmitted light with crossed nicols (CN). It shows a low relief and low refringence. The mesotype often shows small inclusions which seem to show a cleavage plane (Figs. 5g-i). The other secondary mineral is actinolite which is present in the elongated form, often

on feldspars and shows a greenish-blue color in CN and light green in PN, which reflects the effect of the alteration into the chlorite (Figs. 5a-b, 5d, 5g, 5k-l). Accessory minerals include sphene (titanite) with a high relief lozenge form and very apparent irregular cracking. It shows a yellowish-pink color in CN and uncolored in PN, and it is often altered into the chlorite (Fig. 5j). They also include grey-blue apatite which has an elongated form. It's present as inclusions in feldspars (Figs. 6a, 6d, 6g). The automorphic crystals of the biotite shows a reaction aureole with the alkaline feldspars. This means that the biotite is anterior to the alkaline feldspars (Fig. 5l). The ferromagnetic minerals (hematite and other iron oxides not identified in

Fig. 5. Microphotographs of TTR dykes (TL, nic. +). (a) elongated green actinolite and apatite crossing the alkaline feldspars and plagioclases. (b) chloritized amphibole with two 60° cleavage planes, actinolite and hematite. (c) chloritized pyroxene with perpendicular cleavage planes, chloritized amphibole and feldspar. (d) chloritized pyroxene in mesostasis aggregates of feldspar, actinolite, apatite, hematite and iron oxide. (e) zoom of (b). (f) zoom of (c). (g) mesotype surrounded by calcite. (h) globular mesotype, amphibole and feldspar. (i) elongated mesotype and calcite in the orthoclase feldspar enclave. (j) lozenge chloritized sphene with irregular cracks. (k) elongated actinolite crossing the feldspar. (l) biotite, actinolite and feldspar. Act: Actinolite, Ap: apatite, Am: amphibole, Bt: biotite, Cal: calcite, Fsp: alkaline feldspar and plagioclase, Hem: hematite, Ort: orthoclase feldspar, Mes: mesotype, Px: pyroxene, Sph: sphene, Oxy: iron oxide, TL: transmitted light, nic. +: crossed nicols.

transmitted light) often have a reddish-brown color. The hematite appears as veins or disseminated or as amygdaloids of calcite (Figs. 5b, 5d, 5h, 5k). Iron oxides have a nodule

structure reflecting the transformation products of biotite and amphiboles.

The TTR dykes contain, in variable quantities, a number

Fig. 6. Microphotographs of enclaves in TTR dykes. (a) Splint of biotite in an enclave of orthoclase feldspar. (b) mesotype in a pelite enclave. (c) chloritized biotite. (d) dolerite fragments and mesotype in orthoclase feldspar. (e) biotite and iron oxide in orthoclase feldspar. (f) enclave of calcite. Bt: biotite, Bt Chlo: chloritized biotite, Cal: calcite, Mes: mesotype, Ort: orthoclase feldspar, Oxy: iron oxide, Pel: pelite. (a, b, c, d & e): TL, nic. +; (f): TL, nic. //, TL: transmitted light, nic. //: parallel nicols, nic. +: crossed nicols.

of pegmatitic enclaves and rock fragments embedded in groundmass. These enclaves contain orthoclase feldspar, biotite, calcite and pelite coming from the hosted formations (Fig. 6). The orthoclase feldspar phenocrysts have centimetric size and a pink color. They often include biotite and mesotype (natrolite). The orthoclase feldspar crystals are altered, and shows fractures filled with iron oxides (Figs. 6a, 6d, 6e). In addition, the biotite phenocrysts have centimetric size and they are easily recognized. They appear in the form of ranges with a brown color, very paleochroic and sometimes chloritized inside the orthoclase

feldspar minerals, microcline and forming amygdaloids of micropegmatite with mesotype grains (Figs. 6a, 6e). Pelitic xenoliths are chloritized, oxidized and often show primary rock inclusions (Fig. 6b). In addition, the calcite xenoliths are essentially expressed as large automorphic to sub-automorphic crystals including grained or opaque minerals (Fig. 6f).

5.3. Magnetic fabrics study

5.3.1. Mean susceptibility (Km)

The observation of the MS values allows an evaluation

Fig. 7. Magnetic Susceptibility histograms. a) principal dyke, b) dyke crossing the Ordovician formations.

of the magnetic mineral content of the dykes. The histogram in (Fig. 7) shows the MS intervals for the two dykes. All the studied samples have a high and positive magnetic susceptibility more than 10^{-3} (SI), indicating a dominance of mineral with high susceptibility and therefore ferromagnetic minerals in both dykes.

The overall magnetic behavior of TTR dykes is controlled by: (i) the type and the quantity of contained magnetic minerals, and (ii) the effects of alteration of primary minerals to iron oxides.

5.3.2. Anisotropy of magnetic susceptibility

A number of parameters can be calculated to characterize the AMS ellipsoid, but the most widely used are (Tarling and Hrouda, 1993): the mean magnetic susceptibility (K_m), the anisotropy degree (P'), and the shape parameter (T). The volumetric MS averages and its associated parameters, as well as their graphical projection was done using Anisoft 5.1 AGICO program (Chadima and Jelinek, 2009) (Table 1).

5.3.2.1. P' - T diagram

The parameter $P' = \text{Exp} \left(2[(\ln k_1/k_m)^2 + (\ln k_2/k_m)^2 + (\ln k_3/k_m)^2] \right)^{1/2}$ defined by Jelinek (1981) was calculated for every sampled site of the studied dykes. P' describes the anisotropy degree of the magnetic fabric. It varies from $P'=1$ for an isotropic (i.e. spherical) AMS ellipsoid to infinity. The shape of the AMS ellipsoid is defined by the parameter $T = [\ln(k_2/k_3) - \ln(k_1/k_2)] / [\ln(k_2/k_3) + \ln(k_1/k_2)]$ (Jelinek, 1981). When $-1 \leq T < 0$ the AMS ellipsoid is defined as prolate (or linear) and as oblate (or planar) when $0 < T \leq +1$ (Jelinek, 1981).

The diagrams in Fig. 8 represent the degree of anisotropy (P') as a function of the shape parameter (T). In the principal dyke, there is a dominance of the "oblate" form of the AMS ellipsoid. This form indicates a dominance of the magnetic foliation and therefore planar structures compared to linear structures. However, the samples with negative T values cannot be overlooked, as they represent more than a third of the studied samples. The degree of anisotropy (P') is low since it is still less than 1.2 where the anisotropy can be linked to an intense tectonic episode. We can then affirm that the deformation is weakly expressed in this dyke (Fig. 8a).

For the dyke that outcrops in the Ordovician formations,

Fig. 8. Presentation of the shape parameter T as a function of the degree of anisotropy P' . a) principal dyke, b) dyke crossing the Ordovician formations.

the P' - T diagram reveals that the majority of studied samples have a negative value of shape parameter (Fig. 8b). The shape of the AMS ellipsoid is globally "prolate". A magnetic lineation is thus well expressed. The degree of anisotropy P' is generally low, indicating low anisotropy (the magnetic fabric is close to the sphere). This low value of P' indicates that the deformation is weak in this dyke.

5.3.2.2. Projection of the AMS ellipsoids: Magnetic foliation and lineation

As mentioned above, the magnetic fabric of the main dyke is dominated by magnetic foliation. This can be seen in the projection of the AMS ellipsoid axes. Also, we notice the dominance of a vertical magnetic foliation NNW-SSE trending at the site 2, in contrast to site 3 where the foliation is rather horizontal as well as oriented NNW-SSE (Fig. 9, sites 2 and 3). This foliation would reflect the preferential orientation of the magnetic grains, inherited from the late phase of the Variscan deformation. For the case of the dyke outcropping in the Ordovician formations, the magnetic lineation is better expressed (sites 4 and 6) than the foliation (site 5), and this may be related

Fig. 9. Stereographic projections of the AMS ellipsoid axes of the TTR dykes. Square: K1, triangle: K2, circle: K3.

to the observed shearing and very extensive alteration in this locality (Fig. 9).

5.4. Field structural observations

The WNW-ESE trending TTR anticline; has an Ordovician core. It is characterized by a long north limb and a short southern one (asymmetric fold). This anticline is affected by some kilometeric faults and by disharmonic folds. The eastern part of this anticline is limited by the ENE-trending fault (the OJTF), with the same orientation as the main dyke of the study area. Structural analysis of different faults along the TTR anticline shows three families of faults: the NE-SW family which is dominant and the ENE-WSW and NNE-SSW families which are less importance (Ait Daoud et al., 2020).

The reactivation of the ENE-WSW OJTF during the deformation is marked in the principal dyke that follows it. However, the OJTF reactivation is marked by a N60, 90° cleavage in the principal dyke located between the Ordovician and the Devonian formations (Fig. 10a). This post-setting up deformation is not only limited to the

cleavage. It is also marked by the presence of strike-slip faults (left lateral and right-lateral fault) crossing the magmatic bodies of the study area (Figs. 10b-e, 11). All of these faults are oriented NE-SW or ENE-WSW to E-W (Fig. 11). From a microscopic point of view, the deformation is recorded by the pegmatitic enclaves of the biotite (Fig. 10f).

In the study area, the movements observed in the ENE-WSW to E-W-trending faults are generally the strike-slip ones (right and left lateral), that are confirmed by the presence of horizontal striae in the mirror surface, and also the net displacement of the dykes (Figs. 10b-e, 11). These movements are probably expressed by the reactivation of these faults during the NW-SE and NE-SW main shortening stage of the Variscan orogeny.

6. Discussion

The eastern part of the TTR anticline exhibits a magmatic system hosted within the Paleozoic formations ranging from the Ordovician to Devonian. It is clearly obvious that

Fig. 10. Post-emplacement tectonic of the TTR magmatic rocks. (a) N60°, 90° cleavage in the dyke. (b, c) left-lateral faults, (d) striated (10°W) fault mirror in the hosted formation indicate the horizontal displacement of this N90° fault, (e) right-lateral fault, (f) microscopic view of deformed biotite (Bt) (TL, +). TL: transmitted light, +: crossed nicols.

these magmatic bodies are essentially distributed in the neighborhood of the major fault that delimited the TTR anticline to the east. This fault, called the OJTF, corresponds to the eastern branch of the AAMF. It should also be noted that this fault is followed by the magma flow that gave rise to the dykes in the study area.

From a petrographic point of view, the magmatic bodies of TTR are of three types: (i) doleritic basalts, (ii) lamprophyric dolerites, and (iii) camptonites (Benharref et

al., 2014b; Pouclet et al., 2017). However, and opposing to Benharref et al., (2014b) and Pouclet et al., (2017), we note the absence of olivine and ilmenite minerals and the presence of sphene, mesotype and actinolite ones in these studied dykes. In addition, the primary mineralogical paragenesis contains plagioclase feldspar, alkali feldspar, brown hornblende, biotite and apatite. Our petrographic study of the samples collected from the dykes shows the presence of ferromagnetic (hematite and other iron oxides),

Fig. 11. (a) Strike-slip faults affecting the TTR dykes. (b) left and right lateral faults, (c) E-W and (d) ENE-WSW left lateral.

paramagnetic (amphibole, pyroxene, biotite) and diamagnetic (calcite, feldspar) minerals. The existence of these minerals (mostly ferromagnetic) and the alteration of TTR dykes are responsible for the obtained high MS values.

The magmatic age of different outcrops of magmatic bodies in Tafilalet region is very difficult to resolve, because the field works combined with ASM data for the dykes of the TTR site (in this paper) are disaccords with the geochronological study in Jbel Dboa site; located at 14 km NE of the study area (Najih et al., 2019). This recent dating yields an age ranged between $255 \pm 3\text{Ma}$ and $264.2 \pm 2.7\text{Ma}$ using the biotite $^{40}\text{Ar}/^{39}\text{Ar}$ and zircon U-Pb dating (Najih et al., 2019). Nevertheless, many previous studies agree with our study and confirm the presence of Variscan deformation that affect some magmatic bodies in different area in Tafilalet (Makkoudi, 1995; Álvaro et al., 2014a,

2014b; Benharref et al., 2014b, 2014a, 2014c). According to these studies, magmatic bodies of Tafilalet are crossed and decaled by some accidents trending NE-SW, E-W, ENE-WSW right-lateral or vertical faults. These fault movements are related to the late and post Variscan tectonic event (Baidder et al., 2008, 2016; Ait Daoud et al., 2020). Our study confirms the last hypothesis that the dykes of our study area are affected by the Variscan deformation. Using the structural field work and AMS data, we confirmed that the dykes of the TTR are affected by numerous strike-slip faults trending E-W, ENE-WSW and NE-SW. Also, the degree of AMS (P'), despite its weakness, remains an indicator of the presence of the deformation recorded in these TTR dykes. In addition, the projection of AMS ellipsoids shows the presence of a magnetic foliation which reflects the preferential orientation

Fig. 12. Synthesis of the geodynamic evolution of TTR during the Variscan Orogeny.

of the magnetic grains, inherited from the late phase of the Variscan deformation.

Tectonic analysis of the collected data allowed us to distinguish the main deformation phases that the TTR anticline underwent (Fig. 12): (i) Eovariscan phase responsible for extensive tectonics confirmed by the presence of synsedimentary faults and slumps in the Devonian formations of the TTR. In addition we noted the presence of limestone strata with tamnopores along the OJTF. This deformation phase is responsible for tectonic tilting blocks in the whole Anti-Atlas (Baïdier, 2007; Baïdier et al., 2008). (ii) Neovariscan phase; is the primary shortening phase at TTR, it Namuro-Westphalian in age with a NW-SE to N-S direction of shortening. This deformation phase is firstly responsible for the fundamental folding of TTR. Second, is expressed by the left-lateral movements at the level of the major pan-African faults. The outstanding

example is the OJTF. This Neovarisc phase is also manifested by reverse movements on the NE-SW faults. (iii) Late Varsican phase is the second phase of the shortening affecting the TTR anticline; it is characterized by NE-SW to E-W compression. This phase dated as Stephanian-Permian, it responsible for the extensive and right lateral movements along the NE-SW faults. This extensive movement corresponds to zones of tectonic weakness that serve as receptacles for Pb, Zn, Cu and barite mineralization.

In our study area, the reactivation of the OJTF and other major faults during the Variscan events has a high importance in the deformation of these magmatic bodies. Moreover, the deformation recorded by these magmatic intrusions is related to the strike-slip movement of these faults during the Variscan shortening, and cannot be related to any other posterior deformation. The ENE to E-W-

directional left-lateral faults crossing the TTR are related to the late-Variscan shortening (Michard et al., 2008; Baidder et al., 2008, 2016; Ait Daoud et al., 2020). We confirm here that this fault crossed the doleritic dykes and all formations of TTR (Fig. 12). In addition, the clearly visible cleavage in these magmatic bodies confirms that they are deformed by the Variscan shortening.

Based on the work of Pouclet et al. (2017), Tafilalet intrusions are set up during an event of intra-continental extension, prior to the shortening phases of Variscan orogeny. In account to these data, we confirm that the age of the TTR dykes is limited between the surrounding Devonian terrains deposition and the Variscan shortening. This observation disagrees with a recently published work by Najih et al. (2019) which attributes a late Permian age to all the magmatic sites in Tafilalet (biotite $^{40}\text{Ar}/^{39}\text{Ar}$ and zircon U-Pb dating). This study concerns only the Jbel Dboa (site of dating samples). So, this result cannot be generalized on all magmatic bodies of Tafilalet. Based on these results and on the different studies exposed above, it is possible to propose that Tafilalet magmatism is set up during two episodes. The first episode is probably responsible for the emplacement of the TTR magmatic bodies, and can be related to the event prior to the Variscan shortening (present work). The second event is recorded in the early-rift magmatic activity in the late Permian (Najih et al., 2019).

Geochemically, the TTR site, especially the sills in the eastern part and the dyke on the right edge of the Ziz valley (principal dyke), show a higher melting degree (Pouclet et al., 2017). The geochemical study classifies the magmatic rocks of TTR in the basanite-hawaiite domain with a sodic alkaline composition (Benharref et al., 2014b; Pouclet et al., 2017). These magmatic rocks are different from the Anti-Atlas tholeiitic continental dolerites of Triassic/Liassic type (Hailwood and Mitchell, 1971; Hollard, 1973; Sebai et al., 1991; Derder et al., 2001; Youbi et al., 2003; Silva et al., 2004; Verati et al., 2007; Chabou et al., 2010).

In the Eastern Anti-Atlas, the Maider basin shows similar magmatic activities with numerous dykes, sills and laccoliths intruded in the Upper Devonian, Tournaisian and Lower Visean strata (Clariound, 1944). An example is the Mecissi volcanic system, which corresponds to a sodic alkaline gabbro rich in kaersutite and Ti-biotite, with

interstitial analcite (Salmon et al., 1986). The Mecissi gabbro is composed of plagioclase, clinopyroxene, biotite and titanomagnetite, with lesser quantities of amphibole, analcite, zeolite and prehnite. It has a doleritic texture, which shows that these gabbros share the same characteristics with the lamprophyric rocks of Tafilalet. Biotite K/Ar dating and paleomagnetic ages obtained by Salmon et al., (1986) give an age of 140 Ma to these gabbros, but they do not mention any deformation in the Mecissi volcanic system.

7. Conclusion

The magmatic bodies of TTR are part of a magmatic complex in Tafilalet region. The discovery of a new dyke in the study area enriches the petrographic and structural studies of these bodies. Petrographically, we note the presence of pegmatitic enclaves with bitotite, calcite, orthoclase feldspar and pelite fragments in the TTR dykes, as well as the appearance of new minerals discovered for the first time in Tafilalet area such as sphene and mesotype which reinforces the idea of magmatism with a sodic alkaline affinity.

The reactivation of the OJTF at the time of Variscan shortening generates a deformation posterior to the set-up of the TTR magmatic dykes. Firstly, these deformations are in the form of cleavage and strike-slip faults affecting the different magmatic bodies of the TTR site. Secondly, the AMS results confirmed the deformation by the dominance of magnetic foliation NNW-SSE trending that reflect the preferential orientation of the magnetic grains, inherited from the late phase of the Variscan deformation. We assume that these deformations cannot be, in any way, explained by late Permian, Triassic or Alpine tectonics, in particular the strike-slip movement marked along the NE-SW and ENE-WSW to E-W faults. The TTR magmatism has probably a pre-Variscan magmatic event.

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