

The emplacement, geochemistry and petrogenesis of two central Morocco Hercynian granites. Geotectonic implications

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Abstract—New field, petrographic and geochemical data including REE, Rb-Sr, and K-Ar, are presented concerning the emplacement and petrogenesis of two calc-alkaline Moroccan Hercynian granites: the Zaër pluton and the Djebel Aouam stocks. Zonation in the Zaër pluton does not appear to result from simple fractional crystallization nor from hydrothermal alteration but is rather the diapiric intrusion of two interlocked bodies. REE geochemistry supports the interpretation that the biotite-granodiorite magma (301 ± 8.2 M.a.) and the Djebel Aouam stocks appear to have been derived by fusion of crustal materials with possible mantle contamination (Initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio = 0.70514). The second two-mica granitic magma (283.4 ± 6.2 M.a.) corresponds to a peraluminous granite ($1.22 < A/\text{CNK} < 1.33$) generated by fusion of continental crust including mature sedimentary materials (Initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio = 0.70836). These granites are compared to the Acadian granites of north Appalachian and classified in the «post-collision, uplift environment» type. An illustrative four step model presenting the generation and emplacement of these two granites together with the associated W-Sn-Pb-Zn-Ag mineralizations is proposed: (1) first magma generation, (2) first melt emplacement, (3) second melt emplacement, (4) late convective flow.

INTRODUCTION

In spite of a long history of field mapping and petrographic studies devoted to Moroccan granitic bodies, particularly Paleozoic central Moroccan plutons (Fig. 1a), little work has been done concerning their petrogenesis. Some of them offer opportunities to test recent petrologic models of the origin and emplacement of granites. Moreover, W-Sn mineralization is spatially associated with central Moroccan granitic bodies (Agard and Permingeat, 1952) and a better understanding of the magmatic evolution and mode of emplacement of granites will contribute to a better knowledge of W-Sn metallogenesis in that area and provide specific prospecting tools. Unfortunately, scattered and contradictory results have introduced some confusion about Moroccan granites, particularly in the context of plate tectonic models which permit significant correlations between North America and North Africa before the Atlantic opening (Schenk, 1971; Le Pichon and others, 1977; Matte, 1986). In effect, strong tectonic and geochemical correlations appear between the central Moroccan granites and the north Appalachian-Nova Scotia-Newfoundland mobile belt granites (Fairbairn, 1971; Kanes and others, 1973; Vogel and others,

1976; Bell and others, 1977; Albuquerque, 1977; Williams, 1978; Clarke and Halliday, 1980; Strong, 1980; Mahmood and Benani, 1984). Comparison of the origin and mode of emplacement of Moroccan granitic magmas may also provide new information about the constitution of the Hercynian chain in western Africa, north America and south western Europe. The aim of this paper is to present new geochemical data and updated published results from two granitic intrusives in central Morocco. The first is the zoned concentric Zaër pluton (Fig. 1 b), previously interpreted as a comagmatic sequence progressing by fractional crystallization from intermediate biotite granodiorite outward to the two-micas granite unit at the center by Mahmood and Couturié (1979) and Mahmood (1981, 1986), on the basis of petrographic and geochemical analysis. Recent structural data (Mahmood, 1985; Diot and Bouchez, 1986) clearly demonstrate the successive emplacement of the two magmatic bodies during a polyphase diapiric process. The second granite considered is the Djebel Aouam multiple intrusive stocks and dykes (Fig. 2) represented by a differentiated microtonalite to granite plutonic sequence (Agard and others, 1958; Cheilletz and Zimmermann, 1982).

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Among the features that justify the comparison of these two granitoid bodies is the fact that the biotite-granodiorite unit of the Zaër pluton appears to have roughly the same geochemical characteristics as the Djebel Aouam plutonic sequence. It is also true that in both occurrences, late-magmatic or hydrothermal alteration associated with W-Sn mineralization at the Zaër massif (Giuliani, 1984) and with W-Pb-Zn-Ag at the Djebel Aouam district (Agard and others, 1958; Cheilletz, 1983a, 1983b) affected the various granitoid rocks and may have modified primary magmatic trends and given rise to inaccurate petrologic interpretation. These secondary sub-solidus alteration processes are better expressed in the Djebel Aouam area (Cheilletz and Isnard, 1985) and will be used as a reference for interpretation of the Zaër geochemical data.

Similar geochemical analyses have been performed on the two granitic bodies: major and trace elements were determined along with Rb-Sr and K-Ar on the two massifs. We include some data on the Zaër massif by Mrini (1985). REE have been analyzed only from the Djebel Aouam stocks.

GEOLOGICAL FRAMEWORK AND PETROGRAPHIC DATA

The Zaër and Djebel Aouam massifs belong to a family of small to medium-sized granitoids that include the Zaër, Oulmès, Ment, Moulay Bou Azza, Achemeche, Djebel Aouam bodies that have intrude anchizonal to epizonal Paleozoic terranes in which they develop a hornblende-hornfels facies contact metamorphism (see Michard, 1976, for a general review). Stratigraphic correlations and Rb-Sr or K-Ar radiometric data indicate an age of 295-284 M.a., suggesting that the emplacement of these central Morocco granitoids occurred from Upper Carboniferous to Lower Permian, thus characterizing the Late Hercynian orogeny (Choubert and others, 1965; Cheilletz and Zimmermann, 1982).

Among these granitic bodies, the elliptical Zaër pluton (Fig. 1b) occupies a large 500 km² area at the western edge of the Moroccan Central Massif. It is NE-SW elongated, following the general trend of the Variscan fold axis of the region. These broad structural characteristics associated with the existence of discordant contacts and the lack of numerous country-rock xenoliths near the margin of the pluton, suggest that the principal mechanism of intrusion during the late orogenic phases was diapirism (Giuliani, 1982; Mahmood, 1985). Moreover, the general «S» shape of the pluton and the presence of foliated magmatic structures suggest the existence of

strike-slip faulting movements during diapiric emplacement.

The Zaër pluton exhibits a zoned concentric structure characterized by an outer biotite-granodiorite unit and a center two-mica granite unit (Fig. 1 b). Remote sensing interpretation and field observations (Giuliani, 1982) show sharp intrusive contacts between the two granitic units: in the southern part of the pluton, inclusions of the biotite-granodiorite unit are encountered in the two-mica granite, and in the northern part (Fig. 1 b) a two-mica aplitic dyke designated «Aïn Guernouch Forest Guard» intrudes the biotite granodiorite. A two-step intrusive mechanism is suggested for the emplacement of the two granitic units.

The outer unit can be divided into two facies with gradational contacts. The dark-colored rocks are tonalitic to granodioritic in composition, exhibit an equigranular to porphyritic texture, and contain quartz, plagioclase (An₁₅₋₃₅), biotite and interstitial

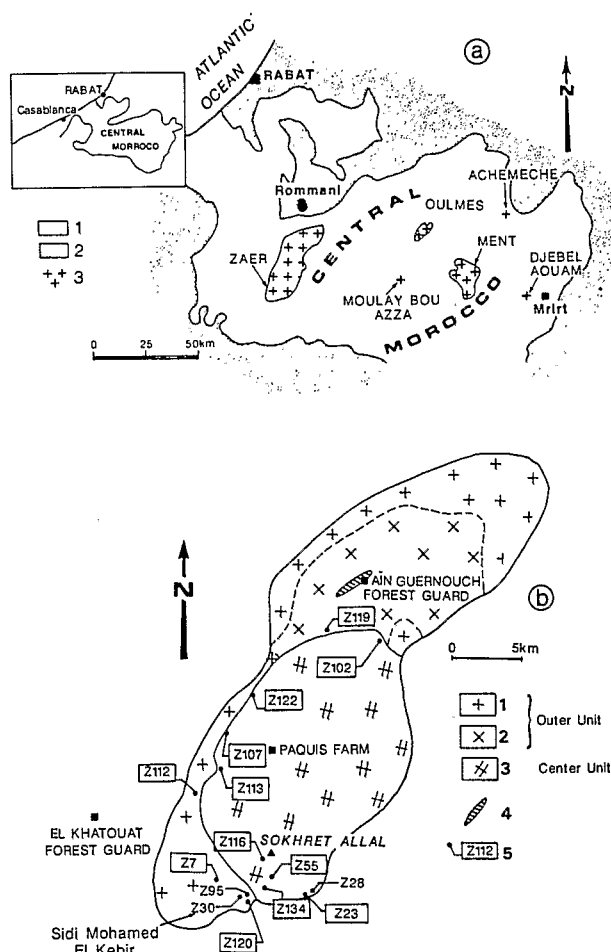


Fig. 1 -a) Central Morocco paleozoic area with the different granitic intrusives. 1 : Paleozoic terranes; 2 : post-Paleozoic terranes; 3 : Hercynian granites; b) Geological map of the zoned Zaër pluton. 1 : dark colored biotite granodiorite; 2 : light colored biotite granodiorite; 3 : two micas monzogranite; 4 : aplitic two micas granite of «Aïn Guernouch Forest Guard»; 5 : localization of the geochemical samples with Z112 = sample.

K-feldspar. A light-colored biotite-granodiorite in the northern part of the pluton is enriched in K-feldspar. Centimetric to metric fine-grained melanocratic enclaves of gabbroic to tonalitic biotite-hornblende-plagioclase-quartz-apatite-zircon-sphene assemblage are found in the biotite-granodiorite outer unit. The huge «Sidi Mohamed El Kebir» mafic enclave (Fig. 1 b) is of gabbroic composition; it is characterized by a diabasic assemblage of plagioclase (An_{40-60}), hornblende, and biotite. Minor reequilibration textures observed particularly at its border include pseudomorphing of primary pyroxene by actinolite and green hornblende.

The central unit is composed of a coarse-grained to locally aplitic quartz-plagioclase (An_{8-25})-biotite-muscovite-K feldspar and minor garnet and andalusite monzogranite assemblage.

Late magmatic-hydrothermal alteration phenomena have developed principally in the two-mica granite unit and have produced secondary sericitization (Mahmood, 1981, 1983; Giuliani, 1982) and K-feldspathization (Cheilletz and Giuliani, 1982). The phenomenon of replacement of quartz by K-feldspar in a granite that leads to unusually high volume % of total K-feldspar is known in Europe as K-episyenitization. Subsequent tin-tungsten mineralization is

emplaced along parallel quartz-vein networks in the two-mica granite unit (Giuliani, 1982, 1984) whereas copper-tungsten bearing skarns and lodes have formed at the northern edge of the biotite granodiorite unit (Agard and Ziegler, 1951). These post-magmatic phenomena are not the principal subject of this paper but will be taken into account in late geochemical and petrogenetic discussion.

The Djebel Aouam granitic stocks are located at the eastern edge of the Central Moroccan massif (Fig. 2). This important Pb-Zn-Ag mining district is characterized by Ordovician to late Mississippian schist-sandstone with minor limestone. These series are intruded by three granitoid stocks called «Mispickel», «Mine», and «Kaolin» (Fig. 2) all cross-cut by numerous dykes of microtonalite. The three stocks vary from granodiorite to granite and are biotite-bearing with quartz, plagioclase (An_{25-45}), and K-feldspar. Minor constituents are apatite, zircon, rutile, ilmenite, chlorite, scheelite, chalcocopyrite, and pyrite. The different stocks are fine to medium-grained with porphyritic tendency. No petrographic variation can be observed inside individual stocks; they appear homogeneous in composition. The three stocks contain xenoliths of metasedimentary rocks represented by fine-grained biotitic aggregates of biotite, muscovite, and alumino-silicate assemblages. The three stocks appear as individual intrusives along a north-south axis, so no chronological relationship between them can be determined. A cylindrical pipe-shaped morphology is clearly demonstrated for the «Kaolin» stock by intersections in underground mine workings from the upper 1200 m to the lower 657 m levels.

The emplacement of the granitoid stocks is accompanied by the development of a large biotitic alteration halo associated with tungsten mineralization in surrounding hornfels (Cheilletz and Isnard, 1985). This hydrothermal alteration episode may also affect plutonic rocks in the form of a quartz vein and veinlet network crosscutting restricted areas of the granites. This alteration phenomenon is also well revealed by geochemical analysis.

GEOCHEMICAL DATA

Major and trace elements

The chemical compositions of the main facies of the Zaër pluton (Table 1) present regular increase of SiO_2 from the dark granodiorite to the two-mica leucogranite. However, when plotted in the variation diagrams of Figs. 3 and 4a strong discontinuity in composition appear between the biotite-granodiorite facies and the two-mica granites. The biotite-granodiorite unit seems to present a continuous variation from dark to light

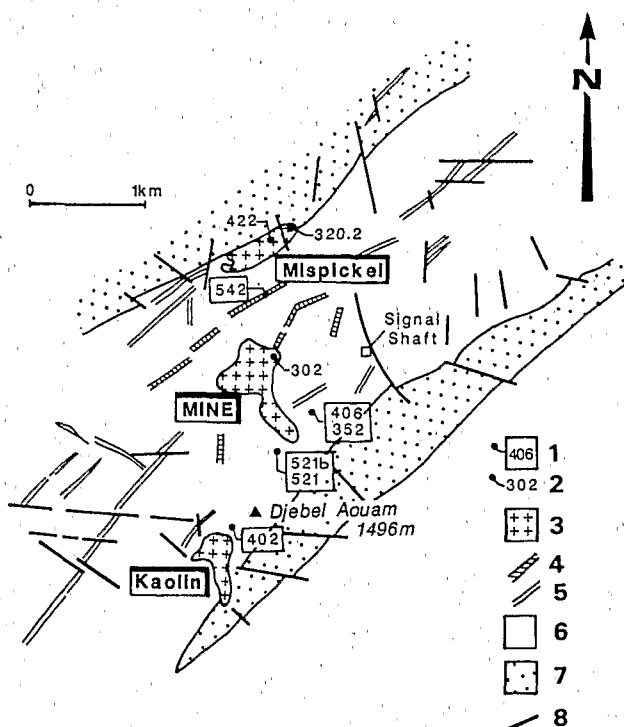


Fig. 2. Geological map of the Djebel Aouam area. 1: Drill hole or underground mining sample; 2: surface sample; 3: Aouam granitic stocks; 4: Microtonalite dykes; 5: Microgranite dykes; 6: Ordovician-Silurian schists and sandstones; 7: Upper Visean schists and limestones; 8: Fault.

Table 1. Chemical representative samples from Zaër pluton. Quantometric analyses from C.R.P.G., Nancy.

| | Biotite granodiorite unit | | | | Mafic enclave | Two micas granite unit | | | | |
|----------------------------------|---------------------------|--------|--------|-------|---------------|------------------------|-------|--------|--------|-------|
| | Z7 | Z95 | Z112 | Z119 | Z30 | Z23 | Z28 | Z102 | Z107 | Z113 |
| SiO ₂ | 67.13 | 60.48 | 68.85 | 70.47 | 48.46 | 76.15 | 72.70 | 77.07 | 73.38 | 71.54 |
| Al ₂ O ₃ | 15.62 | 17.17 | 15.67 | 15.21 | 17.50 | 13.83 | 15.21 | 12.64 | 13.94 | 4.96 |
| Fe ₂ O ₃ T | 4.17 | 5.88 | 3.58 | 2.71 | 8.68 | .37 | 1.16 | .94 | 1.55 | 1.90 |
| MnO | .07 | .1 | .07 | .05 | .12 | .02 | - | .02 | .05 | .05 |
| MgO | 1.60 | 3.17 | 1.34 | 1.09 | 8.04 | .01 | .05 | .13 | .2 | .44 |
| CaO | 2.95 | 4.49 | 2.24 | 1.82 | 9.36 | .32 | .92 | .46 | .65 | 1.08 |
| Na ₂ O | 3.74 | 3.47 | 4.02 | 3.52 | 5.06 | 4.1 | 3.70 | 3.26 | 3.31 | 3.39 |
| K ₂ O | 3.02 | 2.75 | 2.89 | 4.22 | .58 | 3.51 | 4.31 | 4.63 | 4.4 | 4.60 |
| TiO ₂ | .66 | 1.13 | .51 | .4 | 1.04 | .06 | .18 | .09 | .24 | .29 |
| P ₂ O ₅ | .16 | .33 | .20 | .01 | .24 | .21 | .19 | .36 | .15 | .24 |
| L.I. | .6 | 1.27 | 1.07 | .49 | 1.76 | .98 | .64 | .61 | 2.49 | .75 |
| Total | 99.92 | 100.24 | 100.44 | 99.99 | 98.84 | 99.56 | 99.26 | 100.21 | 100.48 | 99.24 |
| Ba ppm | 633 | 589 | 636 | 555 | 189 | 68 | 414 | 330 | 193 | 442 |
| Sr | 385 | 488 | 286 | 287 | 670 | 61 | 130 | 130 | 52 | 148 |
| Rb | 98 | 82 | 239 | 166 | 30 | 197 | 266 | 255 | 468 | 558 |
| CIPW NORM | | | | | | | | | | |
| Q | 22.04 | 13.10 | 24.95 | 25.45 | - | 36.56 | 30.98 | 37.52 | 33.89 | 29.53 |
| OR | 18.14 | 16.53 | 17.32 | 25.28 | 3.51 | 21.19 | 26.08 | 27.89 | 26.92 | 27.89 |
| AB | 34.05 | 31.65 | 36.54 | 31.97 | 28.09 | 37.53 | 33.94 | 29.78 | 30.70 | 31.16 |
| AN | 13.80 | 20.46 | 9.93 | 9.15 | 33.05 | .21 | 3.39 | - | 2.32 | 3.87 |
| HY | 8.57 | 13.60 | 6.64 | 5.37 | 28.09 | .31 | 1.42 | 1.24 | 1.90 | 2.87 |
| Mt | .74 | 1.04 | .63 | .48 | 1.54 | .07 | .21 | .17 | .28 | 2.87 |
| ILM | .93 | 1.60 | .72 | .56 | 1.48 | .09 | .26 | .13 | .35 | .41 |
| C | 1.34 | 1.23 | 2.58 | 1.69 | - | 3.57 | 3.61 | 2.51 | 3.28 | 3.37 |
| AP | .34 | .71 | .43 | - | .52 | .45 | .41 | .77 | .33 | .52 |
| Di | - | - | - | - | 10.33 | - | - | - | - | - |
| A/CNK | 1.06 | 1.02 | 1.13 | 1.12 | .82 | 1.25 | 1.22 | 1.13 | 1.21 | 1.19 |

coloured facies, differentiation readily compared to a calc-alkaline trend such as the Tuolumne intrusive series (Bateman and Chappell, 1979). The molecular ratio $Al_2O_3/(K_2O + Na_2O + CaO)$ is low from 1.02 to 1.12. According to the classification of Chappell and White (1974), these granodiorites present both I- and S-type characteristics. The corundum-hypersthene (CIPW norm) versus SiO_2 diagram shows a divergent relation between these two normative minerals (Fig. 3), a relationship ascribed by Cawthorn and others (1976) to the calc-alkaline series of various geotectonic provinces. However, the two-mica granites are basically more alkaline and aluminous. In the typological diagram of Fig. 4, they can be compared in their composition and differentiation trends to peraluminous associations. They present obvious S-type characteristics, including muscovite and alumino-silicate minerals, $A/CNK > 1.1$, normative corundum > 1 , and with tin-tungsten mineralization association. $Al_2O_3/(K_2O + Na_2O + CaO)$ is high and varies from 1.33 to 1.22 whereas normative corundum varies from 2.5 to 3.6.

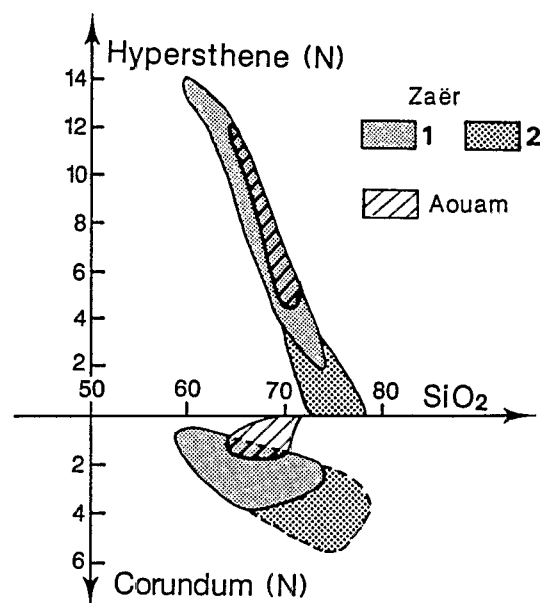


Fig. 3. Normative corundum or hypersthene versus SiO_2 (CIPW norm) for Zaër granites (33 samples) and Djebel Aouam (12 samples). 1, biotite-granodiorite unit; 2, two-mica granite unit.

Table 2. Chemical representative samples from Djebel Aouam granite stocks. Quantometric analyses from C.R.P.G., Nancy.

| | Minegranite stock | | | | Kaolin granite AM402 | Mispickel granite | | Microtonalite | |
|----------------------------------|-------------------|-------|-------|--------|-------------------------|-------------------|--------|---------------|--------|
| | AM302 | AM352 | AM406 | AM521b | | AM320.2 | AM422 | AM521 | AM542 |
| SiO ₂ | 70.54 | 70.29 | 70.00 | 69.91 | 68.85 | 68.24 | 69.40 | 66.74 | 63.91 |
| Al ₂ O ₃ | 14.11 | 13.76 | 15.01 | 14.88 | 14.68 | 14.51 | 15.23 | 15.81 | 16.05 |
| Fe ₂ O ₃ T | 2.90 | 2.77 | 2.61 | 2.57 | 3.17 | 3.53 | 2.65 | 4.45 | 5.80 |
| MnO | .02 | .03 | - | - | .06 | .06 | .01 | .04 | .07 |
| MgO | 1.00 | 1.06 | .87 | 1.19 | 1.26 | 1.37 | 1.25 | 1.85 | 2.43 |
| CaO | 2.03 | 1.81 | 2.40 | 2.09 | 2.12 | 2.79 | 3.15 | 3.55 | 4.49 |
| Na ₂ O | 3.34 | 3.46 | 3.65 | 3.39 | 3.48 | 3.19 | 2.98 | 3.78 | 2.71 |
| K ₂ O | 4.15 | 4.02 | 3.94 | 4.08 | 3.46 | 3.10 | 3.55 | 2.45 | 2.52 |
| TiO ₂ | .36 | .34 | .46 | .50 | .41 | .49 | .50 | .75 | .93 |
| P ₂ O ₅ | .05 | .03 | .18 | .09 | .14 | .16 | .16 | .11 | .26 |
| L.I. | 1.02 | 1.61 | .8 | 1.40 | 2.79 | 1.37 | 1.15 | .9 | 1.01 |
| Total | 99.52 | 98.18 | 99.92 | 100.10 | 100.42 | 98.81 | 100.03 | 100.43 | 100.18 |
| Ba | 652 | 578 | 696 | 564 | 653 | 745 | 448 | 567 | 682 |
| Sr | 185 | 167 | 215 | 206 | 180 | 272 | 273 | 312 | 349 |
| Rb | 198 | 156 | 163 | 189 | 184 | 175 | 241 | 155 | 329 |
| CIPW NORM | | | | | | | | | |
| Q | 28.17 | 28.09 | 26.65 | 27.52 | 27.83 | 28.59 | 29.20 | 23.36 | 23.37 |
| OR | 24.55 | 23.70 | 23.30 | 24.13 | 20.47 | 18.34 | 21.00 | 14.49 | 14.91 |
| AB | 28.23 | 29.24 | 30.85 | 28.65 | 29.41 | 26.96 | 25.19 | 31.95 | 22.90 |
| AN | 9.75 | 8.79 | 10.74 | 9.79 | 9.61 | 12.81 | 14.59 | 16.91 | 20.59 |
| Hy | 5.53 | 5.57 | 4.65 | 5.33 | 6.51 | 7.10 | 5.60 | 8.97 | 11.85 |
| Mt | .70 | .67 | .63 | .62 | .77 | .85 | .64 | 1.08 | 1.40 |
| ILM | .68 | .65 | .87 | .95 | .78 | .93 | .95 | 1.42 | 1.77 |
| C | .53 | .48 | .79 | 1.28 | 1.67 | 1.20 | 1.12 | .73 | 1.30 |
| AP | .11 | .07 | .39 | .20 | .31 | .35 | .35 | .24 | .57 |
| A/CNK | 1.02 | 1.03 | 1.03 | 1.06 | 1.07 | 1.05 | 1.06 | 1.03 | 1.04 |

Moreover, the two-mica granites present very high Rb/Sr, typically >>1.

None of the diagrams shows continuous differentiation trends between the granodiorite and two-mica granite units (Figs. 3 and 4). These specific geochemical characteristics cannot be ascribed to normal evolution by simple fractional crystallization in a single magma chamber. In European Hercynian granites, such geochemical discontinuities have been interpreted as polyphase magmatic reactivation in plutons, the later event possibly involving partial melting of the products of the earlier one (La Roche and Isnard, 1978). Such a process has been proposed for the Zaër massif (Giuliani, 1982).

Late-magmatic evolution or hydrothermal overprinting may be invoked to interpret such geochemical discontinuities between the two granitoid units. However, comparison with results from the Djebel Aouam stocks rejects such an hypothesis.

The chemical compositions of representative samples from the three main stocks and the microtonalite dykes in the Djebel Aouam district (Table 2), present a typical calc-alkaline composition and differentiation trend. The same mineralogical and chemical parameters are noted as in the

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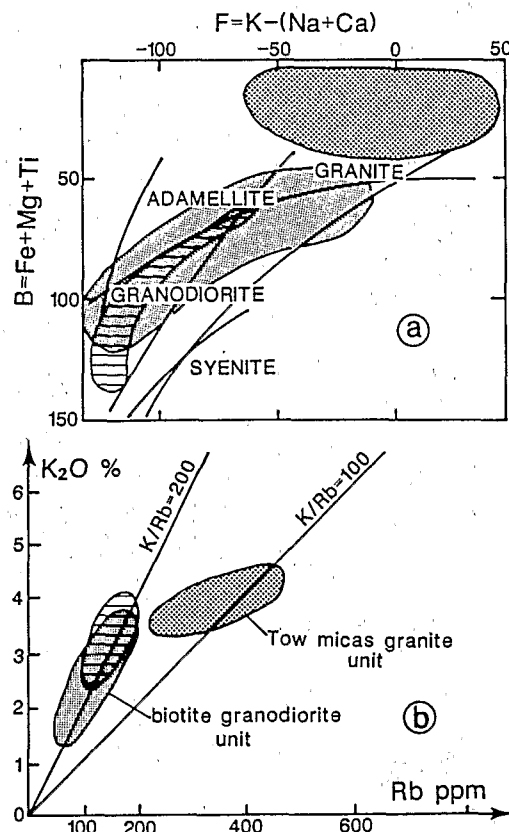


Fig. 4.

a) B/F diagram (Debon and Le Fort, 1983) showing the geochemical discontinuity between the biotite granodiorite unit and the two micas granite unit. b) The same discontinuity appears on a K₂O/Rb diagram. Same legend as in Fig. 3.

Zaër biotite granodiorite unit: $1.02 < A/CNK < 1.07$, $0.48 < \text{normative corundum} < 1.67$, normative hypersthene > 4.65 (Figs. 3 and 4). High tungsten content in some whole-rock analyses (Table 3) has been interpreted to result from hydrothermal fluid circulation and scheelite precipitation along mineralized microscopic veinlets. By contrast, normal W-Sn contents in the two Zaër granitic units (Table 3) suggest that no hydrothermal redistribution has occurred, hence the preservation of primary magmatic characters.

Analysis of the rare earth elements (REE) of samples from the Djebel Aouam plutonic rocks were performed on an ICP Jobin Yvon 48 P spectrometer (Govindaraju and others, 1976) which allows sensitivity of twice the chondritic abundance. The analytical results are in Table 4 and the chondrite-normalized REE distribution patterns are in Fig. 5. The three rock types analyzed, namely microtonalite, granodiorite, and granite, show constant characteristics. (1) The overall REE abundance is 45 to 60 times chondrite values; (2) the enrichment of light over heavy elements causes moderately fractionated patterns ($La/Yb=22-43$); (3) heavy REE appear weakly fractionated with respect to light REE, and (4) negative Eu anomaly appears. These features have been observed in many other typical calc-alkaline complexes, for instance the Acadian granites of Nova Scotia (Albuquerque, 1977; Muecke and Clarke, 1981), Western Corsica granites (Cocherie, 1984), and the Querigut plutonic association of the Pyrénées (Fourcade and Allègre, 1981).

For comparison, patterns of REE distribution in sedimentary rocks are presented (Fig. 5) for the North American Shale Composite (Gromet and others, 1984) and for the average greywacke (Haskin and others, 1968). The broad similarity of spectra between sedimentary rocks and granitoid samples from Djebel Aouam is striking except for the depletion in HREE in the latter. These results will be interpreted below.

Isotope geochemistry

a) **Rb-Sr.** Whole-rock Rb-Sr measurements have been performed on three samples from the biotite-

granodiorite Zaër unit and five samples from the two-mica granite (Table 5). Selected data by Mrini (1985) have also been used. The whole rock regression isochron ages are (Fig. 6) 301 ± 8.2 M.a. (initial $^{87}\text{Sr}/^{87}\text{Sr}$ ratio = 0.70514 ± 0.00009) for the biotite-granodiorite unit, and 283.4 ± 6.2 M.a. (initial $^{87}\text{Sr}/^{87}\text{Sr}$ ratio = 0.70836 ± 0.00055) for the two-mica granite. This result confirms the independence of the two main units of the Zaër pluton and the intrusion of these two distinct granites during the late Pennsylvanian of the Hercynian orogeny. This age is in good agreement with previous determinations on other central Moroccan granites. More dispersed values have been obtained for the different Djebel Aouam stocks (Table 6) probably because of hydrothermal alteration overprint. A reference isochron calculated for three samples from the Mine granite (Fig. 7) gives an age of 292.6 ± 36 M.a. with initial $^{87}\text{Sr}/^{87}\text{Sr}$ ratio = 0.7060 ± 0.007 . These initial $^{87}\text{Sr}/^{87}\text{Sr}$ ratio on Zaër and

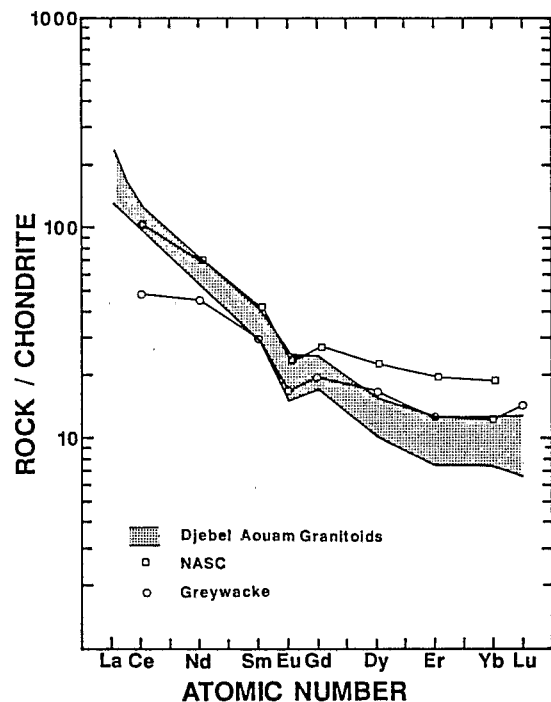


Fig. 5. REE patterns of granitoid rocks from the Djebel Aouam district compared with NASC (Gromet and others, 1984) and average greywacke (Haskin and others, 1968) values. Chondrite normalization values from Evensen and others (1978).

Table 3. Tin and tungsten contents of the granitoids from Zaër pluton and Djebel Aouam stocks.

| | ZAËR PLUTON | | DJBEL AOUAM STOCKS | | | | NORMAL GRANITES |
|--------|----------------------|----------------------|-------------------------------|--------------------------|------------------------------------|--------------------------------|-----------------|
| | Biotite Granodiorite | Two micas Granite | MINE Granite AM 406 AM 352 | KAOLIN Granite AM 420 | MISCKEL Granite AM 320.2 AM 422 | Microtonalite AM 521 AM 542 | |
| Sn ppm | 3.5 (8 samples) | 28.6 (11 samples) | - | - | - | - | 3 |
| W ppc | 0.6 (3 samples) | 1.8 (7 samples) | 30 3.7 | 53 | 11.6 14.7 | 102 1.7 | 1.5 |

Table 4. REE analyses of Djebel Aouam granitic stocks.

| | Mine granite | | Kaolin granite AM402 | Mispickel granite | | Microtonalite AM542 |
|--------|--------------|--------|-------------------------|-------------------|-------|------------------------|
| | AM302 | AM521b | | AM422 | AM521 | |
| La ppm | 32.14 | 38.79 | 37.48 | 33.24 | 52.06 | 52.96 |
| Ce | 61.31 | 69.53 | 63.91 | 61.51 | 80.83 | 78.03 |
| Nd | 26.32 | 27.86 | 25.22 | 25.74 | 33.62 | 32.57 |
| Sm | 4.68 | 5.32 | 4.63 | 4.48 | 6.35 | 6.29 |
| Eu | 1.09 | 1.01 | 0.97 | 0.88 | 1.30 | 1.48 |
| Gd | 3.86 | 4.22 | 3.56 | 3.52 | 5.07 | 5.07 |
| Dy | 2.83 | 3.30 | 2.54 | 2.64 | 4.00 | 3.27 |
| Er | 1.50 | 1.73 | 1.25 | 1.61 | 2.12 | 1.87 |
| Yb | 1.26 | 1.79 | 1.23 | 1.39 | 2.12 | 1.68 |
| Lu | 0.19 | 0.27 | 0.17 | 0.21 | 0.33 | 0.25 |
| Y | | 20.23 | | | 23.33 | |
| La/Yb | 25.55 | 21.67 | 30.47 | 25.25 | 25.56 | 31.49 |

Djebel Aouam intrusives are consistent with average granite values (Faure et Powell, 1972). Nevertheless, initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio are relatively higher for the Zaër two-mica granite unit than for the biotite-granodiorite unit and the Djebel Aouam stocks.

b) Because of the great sensitivity of K-Ar determination to alteration, K-Ar analyses were performed to test the accuracy of Rb-Sr results. K-Ar results on biotites from the Zaër biotite-granodiorite unit and muscovite from the two-mica granite unit (Table 7) give an average age of 282.7 ± 9.05 M.a., in good agreement with the Rb-Sr age of the younger granitic unit.

K-Ar results on biotite from both fresh and mineralized Djebel Aouam granites (Table 7) yield an isochron at 284 ± 2.3 M.a. (Fig. 7) close to the age of the Zaër granite determined by the same method. However, the K-Ar whole rock age (Table 7) is 268 ± 2.9 M.a., a lower number attributed to Ar loss by hydrothermal alteration. K-Ar results thus confirm that a hydrothermal event affected these two Hercynian central Moroccan granites at

280-285 M.a. That influence of hydrothermal circulation on the Rb-Sr system appears relatively more important for the Djebel Aouam stocks than for the two Zaër granitic units and is consistent with the importance of polyphased hydrothermal W-Pb-Zn-Ag mineralization that characterizes the Djebel Aouam district and with the dispersion of Rb-Sr values of the different Djebel Aouam granitic samples which prevents the calculation of a reliable isochron.

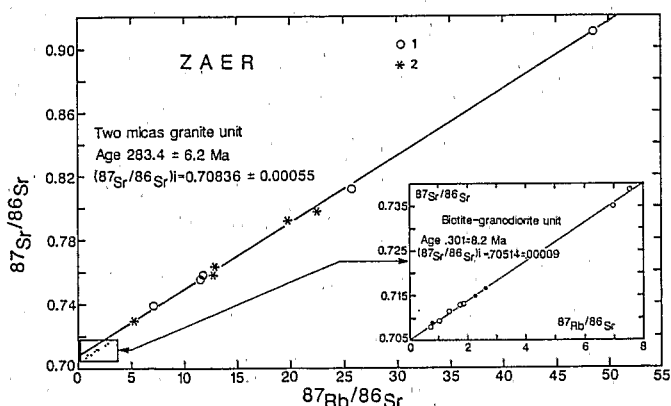


Fig. 6. Rb-Sr whole rock isochrons for the Zaër biotite granodiorite unit (MSWD = 3.8) and the two micas granite unit (MSWD = 3.1). Data from : 1 = M'Rini (1985); 2 = this study.

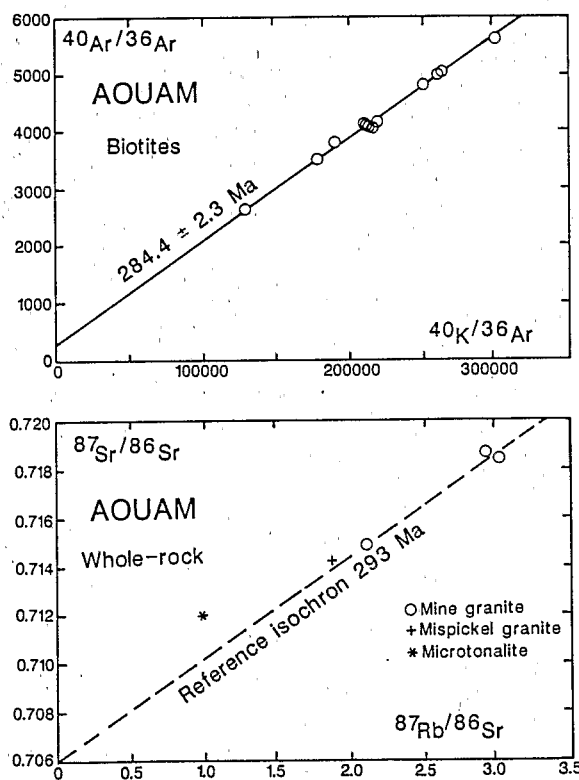


Fig. 7. K-Ar and Rb-Sr results on the Djebel Aouam district. Upper K-Ar data on biotites from plutonic and tungsten mineralization samples. Lower: Rb-Sr reference isochron at 293 Ma plotted for three «Mine granite» samples.

Table 5 - Analytical Rb-Sr whole rock analyses from Zaër granites. «Z» samples refer to Giuliani (1982) data. All Rb-Sr isotopic analyses used standard isotope dilution techniques employing a Thomson 206S mass spectrometer for Rb analyses and Cameca THN 206 for Sr analyses $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are normalized to $^{87}\text{Sr}/^{86}\text{Sr} = .1194$ and adjusted to E and $A = .7080$. $^{87}\text{Rb} = 1.42 \times 10^{-11} \text{ a}^{-1}$. «ZR» samples refer to Mrini (1985) data. The error on $^{87}\text{Rb}/^{86}\text{Sr} = 2\%$ and on $^{87}\text{Sr}/^{86}\text{Sr} = 1 \times 10^{-4}$.

| Sample n° | Rb ppm | Sr ppm | $^{87}\text{Rb}/^{86}\text{Sr}$ | $^{87}\text{Sr}/^{86}\text{Sr}$ |
|---------------------------|--------|--------|---------------------------------|---------------------------------|
| Biotite granodiorite unit | | | | |
| Z7 | 108 | 401 | .7820 ± .012 | .7089 ± .0003 |
| Z112 | 245 | 307 | 2.3102 ± .028 | .7149 ± .0004 |
| Z120 | 138 | 151 | 2.6564 ± .025 | .7165 ± .0003 |
| ZR10 | 103 | 402 | .743 ± .02 | .70802 ± .0001 |
| ZR1 | 113 | 310 | 1.05 | .70936 |
| ZR3 | 135 | 279 | 1.4 | .71149 |
| ZR4 | 156 | 251 | 1.78 | .71292 |
| ZR6 | 158 | 242 | 1.89 | .71310 |
| ZR8 | 312 | 128 | 7.05 | .73470 |
| ZR12 | 319 | 122 | 7.61 | .73828 |
| Two micas granite unit | | | | |
| Z23 | 208 | 47 | 12.9191 ± .498 | .7619 ± .0007 |
| Z55 | 400 | 58 | 20.1016 ± .686 | .7909 ± .0005 |
| Z102 | 262 | 141 | 5.3804 ± .121 | .7290 ± .0005 |
| Z107 | 353 | 80 | 12.8248 ± .286 | .7592 ± .0004 |
| Z116 | 385 | 49 | 22.7657 ± .777 | .7969 ± .0017 |
| ZR17 | 248 | 100 | 7.19 | .73903 |
| ZR15 | 306 | 76.3 | 11.7 | .75535 |
| ZR13 | 274 | 66.7 | 11.9 | .75761 |
| ZR14 | 390 | 43.8 | 26.1 | .81037 |
| ZR16 | 454 | 27.3 | 49.1 | .90535 |

Table 6. Analytical Rb-Sr whole rock analyses from Djebel Aouam granitic rocks. The experiments were made on a Cameca THN 206 mass spectrometer. Same standards and analytical errors as in Table 5.

| Sample n° | Rb ppm | Sr ppm | $^{87}\text{Rb}/^{86}\text{Sr}$ | $^{87}\text{Sr}/^{86}\text{Sr}$ |
|-------------------|--------|--------|---------------------------------|---------------------------------|
| Mine granite | | | | |
| AM 302 | 194 | 186 | 3.03230 | 0.718323 ± 0.000031 |
| AM 406 | 155 | 211.2 | 2.11935 | 0.714860 ± 0.000040 |
| AM 521b | 198.2 | 195 | 2.94186 | 0.718567 ± 0.000040 |
| Mispickel granite | | | | |
| AM 320.2 | 175 | 285 | 1.88395 | 0.714216 ± 0.000039 |
| Microtonalite | | | | |
| AM 542 | 329 | 397 | 0.99377 | 0.711947 ± 0.000028 |

Table 7 - Analytical K-Ar data from Zaër and Djebel Aouam granitoids. Constants used: $\lambda\beta = 4.962 \times 10^{-10}$ y; $\lambda\gamma = .581 \times 10^{-10}$ /y; $^{40}\text{K} = .01167\%$ K. Experiments are made on Thomson 205E modified mass spectrometer using analytical procedure developed in Zimmermann and others (1985). $^{40}\text{Ar}^*$ = radiogenic argon.

WR = whole rock, Bi = biotite, M = muscovite.

| Sample n° | Granitoid type or mineralization | Mineral | %K | $^{40}\text{Ar}^*$ 10 ⁻⁶ cc/g | ^{40}Ar atm | Age M.a. ± 2 |
|--------------------------------|----------------------------------|---------|------|---|-------------------------|------------------|
| Zaër Pluton | | | | | | |
| Z112 | Biotite granodiorite | Bi | 7.37 | 89.01 | 7.1 | 287.0 \pm 7.6 |
| Z116 | Two micas granite | Bi | 7.02 | 80.09 | 16.9 | 272.3 \pm 4.8 |
| Z116 | Two micas granite | M | 8.37 | 101.79 | 8.4 | 288.8 \pm .5 |
| Djebel Aouam Stocks | | | | | | |
| AM 302 | Mine granite | WR | 3.34 | 40.96 | 8.4 | 291.1 \pm 15.2 |
| AM 302 | Mine granite | Bi | 7.13 | 86.41 | 8.1 | 287.9 \pm 5.1 |
| AM 320-2 | Mispickel granite | WR | 3.16 | 36.42 | 13.0 | 274.9 \pm 20.1 |
| AM 320-2 | Mispickel granite | Bi | 6.48 | 80.02 | 6.2 | 293.0 \pm 3.0 |
| AM 349-a | Microgranite | WR | 3.34 | 36.61 | 14.5 | 262.4 \pm 3.6 |
| AM 338-1 | Microtonalite | WR | 2.40 | 26.73 | 10.5 | 266.3 \pm 4.6 |
| AM 385 | W lode | Bi | 7.10 | 86.18 | 5.9 | 288.4 \pm 3.1 |
| AM 484 | W lode | Bi | 5.46 | 65.44 | 5.5 | 285.0 \pm 3.8 |
| AM 339 | Stratiform W skarn | Bi | 7.65 | 91.80 | 4.6 | 285.3 \pm 3.0 |
| AM 368-a | Stratiform W skarn | Bi | 5.74 | 68.57 | 6.0 | 284.1 \pm 4.2 |

The preservation of primary magmatic geochemical and isotopic characteristics particularly in the two units of the Zaër massif will be used in the following discussion to develop a schematic model for the emplacement and petrogenesis of this granite.

DISCUSSION

Geochemical data including Rb-Sr measurements confirm structural evidence for the independent and successive emplacement of the two main units of the Zaër pluton. The earlier biotite granodiorite unit and the later two-mica granite unit are characterized by distinct initial $^{87}\text{Sr}/^{87}\text{Sr}$ ratio consistent with the forceful diapiric uprising of two non-cogenetic magmas. Composition variations between the two distinct units can be attributed neither to a single continuous fractional crystallization process nor to a hydrothermal alteration overprint during the cooling history of the magmas as suggested by comparison with the Djebel Aouam data. These composition variations are interpreted as having been inherited from source material and enhanced by differentiation processes. Initial $^{87}\text{Sr}/^{87}\text{Sr}$ ratio in the two-mica granite indicates derivation by fusion of continental crust including mature metasedimentary materials, as do the main petro-

graphic and geochemical characteristics (muscovite and alumino-silicate minerals bearing, low K/Rb and high Rb/Sr ratios).

The origin of the biotite-granodiorite magma is more complex, probably involving mantle participation with contamination and assimilation of crustal material. This hypothesis is confirmed by the existence of mafic enclaves in the biotite-granodiorite, such as the "Sidi Mohammed El Kebir" enclave in the Zaër granite and metasedimentary xenoliths in the Djebel Aouam stocks. However, REE abundances and distribution in the plutonic Djebel Aouam suite are not inconsistent with a partial melting of metasedimentary rocks origin. Indeed, we observe a broad similarity of NASC and greywacke REE spectra in granitoid rocks in the same geotectonic province as related previously for the Acadian granodioritic complexes of Nova Scotia (Albuquerque, 1977; Muecke and Clarke, 1981), and the Hercynian younger granites of Portugal (Albuquerque, 1978). The similarity of REE patterns in the Djebel Aouam granitoid rocks with those of hypothetical partial melts of metamorphic pelites, greywackes, or mixtures of both (Albuquerque, 1978), provides further evidence in favour of this hypothesis. The lesser abundance of heavy REE in granitoids relative to pelite or greywacke parent rocks suggest concentration of these

elements in residue rather than in melts; indeed, typical residual minerals like garnet, pyroxene, amphibole, or zircon present partition coefficients highly enriched in light REE (Kilinc, 1972). This model refers only to the acidic members of the Moroccan calc-alkaline plutonic association which is also characterized by basic magmatic units with mantle affinities that are well represented in the southern part of the Moroccan Hercynian chain, i.e. the Tichka massif (Termier H. and Termier B., 1971; Mrini, 1985). Therefore, the intermediate geochemical characteristics of the biotite-granodiorite of the outer unit of the Zaër massif and the Djebel Aouam stocks may be interpreted as the result of complex mixing of bimodal felsic and mafic fractions (Didier and Lameyre, 1969; Mrini and others, 1986).

Geotectonic implications

With reference to the general debate on the origin of the Variscan chain prior to the Atlantic opening, the main geochemical and structural characteristics of central Morocco plutonic massifs are closely comparable to those of the Acadian granites in the Appalachians, especially the New Hampshire, Maine, Nova Scotia and Newfoundland zones. In these areas, biotite-hornblende granites are associated with less abundant peraluminous two-mica granites (Strong, 1980). However, Acadian Appalachian magmatism at ± 360 M.a. does not appear well represented in the Moroccan part of the Hercynian chain where the main granitization activity at ± 310 -280 M.a. occurred during the final stages of collision between the African and Laurasian continental blocks (Matte, 1986). This eastward movement of the main plutonic activity during late Hercynian time does not imply the genetic dependence of granitization with a southeast dipping subduction-related process because of the lack of the principal structural and geochemical characteristics of Cordilleran-type calc-alkaline magmatism. The mixed I- and S-type geochemical signatures of the central Morocco granites, the lack of regional synmetamorphism, and the strong relationship of igneous diapiric uprising to strike-slip faulting (Arthaud and Matte, 1977; Cheilletz, 1983a), argue for their classification in the "post-collision, uplift environment" type of Pitcher (1982) that is well represented in the Caledonian chain. Within this general geotectonic framework, a schematic model can be proposed for the genesis and emplacement of the Zaër and Djebel Aouam granitic bodies.

The genesis and probable structural relations between the Zaër pluton and the Djebel Aouam stocks

Stage 1 (Fig. 8-1) first magma generation. According to the general geochemical characteristics and

the initial Sr ratio data, the first magma seems to have been derived by the fusion of lower crustal materials. Contamination by mantle-derived magmas is indicated by the presence of mafic enclaves.

Stage 2 (Fig. 8-2): first melt emplacement. The magma is emplaced in upper crustal levels along deep seated-fractures that are part of a regional shearing zone in Paleozoic terranes. The association of diapiric plutonism with major shear zones appears to be a common feature in the development of Hercynian orogeny and plutonism (Brun and Vigneresse, 1981). Melt crystallization proceeds from the margin to the inner zone of the granodiorite unit, a phenomenon that gave rise to the dark- to light-coloured granodioritic facies. Magmatic structures such as schlieren and the alignment of mafic enclaves were produced by flow during granite ascent and emplacement. At the same time, xenoliths of the country rocks were partially melted. This early granodiorite episode was accompanied by the emplacement of a first series of dykes and by the development of thermal metamorphism in the country rocks in an advancing thermal gradient zone. In other areas of this mobile continental belt, pockets of magma may have produced smaller stocks of granites like those of Djebel Aouam, Moulay Bou Azza (Mahmood and Bennani, 1984) or Achemeche (Sonnet, 1981).

Stage 3 (Fig. 8-3) : second melt emplacement. A second magma generation produced by partial melting of significant metasedimentary- component material, gives rise to peraluminous S-type granite, i.e. the two-mica granite unit in the Zaër pluton. Initial Sr ratio data reflect the change in source-magma components relative to the granodiorite unit and are consistent with the increase of metasediment contributions in the magma. Moreover, mafic enclaves are lacking in the two mica granite, but aluminous enclaves are very common. The emplacement of this second intrusion maintained the development of the thermal gradient. In the central Moroccan Massif, other peraluminous intrusives like the Oulmès granite (Termier and others, 1950), show characteristics similar to those of the Zaër two-mica granite. This second magma generation was accompanied by the emplacement of leucogranitic dykes intruding the first granodioritic unit. The "Aïn Guernouch Forest guard" aplite dyke of Zaër is related to these events.

Stage 4 (Fig. 8-4): late convective flows. A late convective flow system, probably involving both magmatic and meteoric fluids, produced locally restricted metasomatic alteration such as secondary sericitization and K-feldspathization and led to the development of mineral deposits; i.e. W-Sn lodes in the Zaër pluton and the stratiform tungsten skarn and the polymetallic W-Pb-Zn-Ag veins in the Djebel Aouam area. Other Central

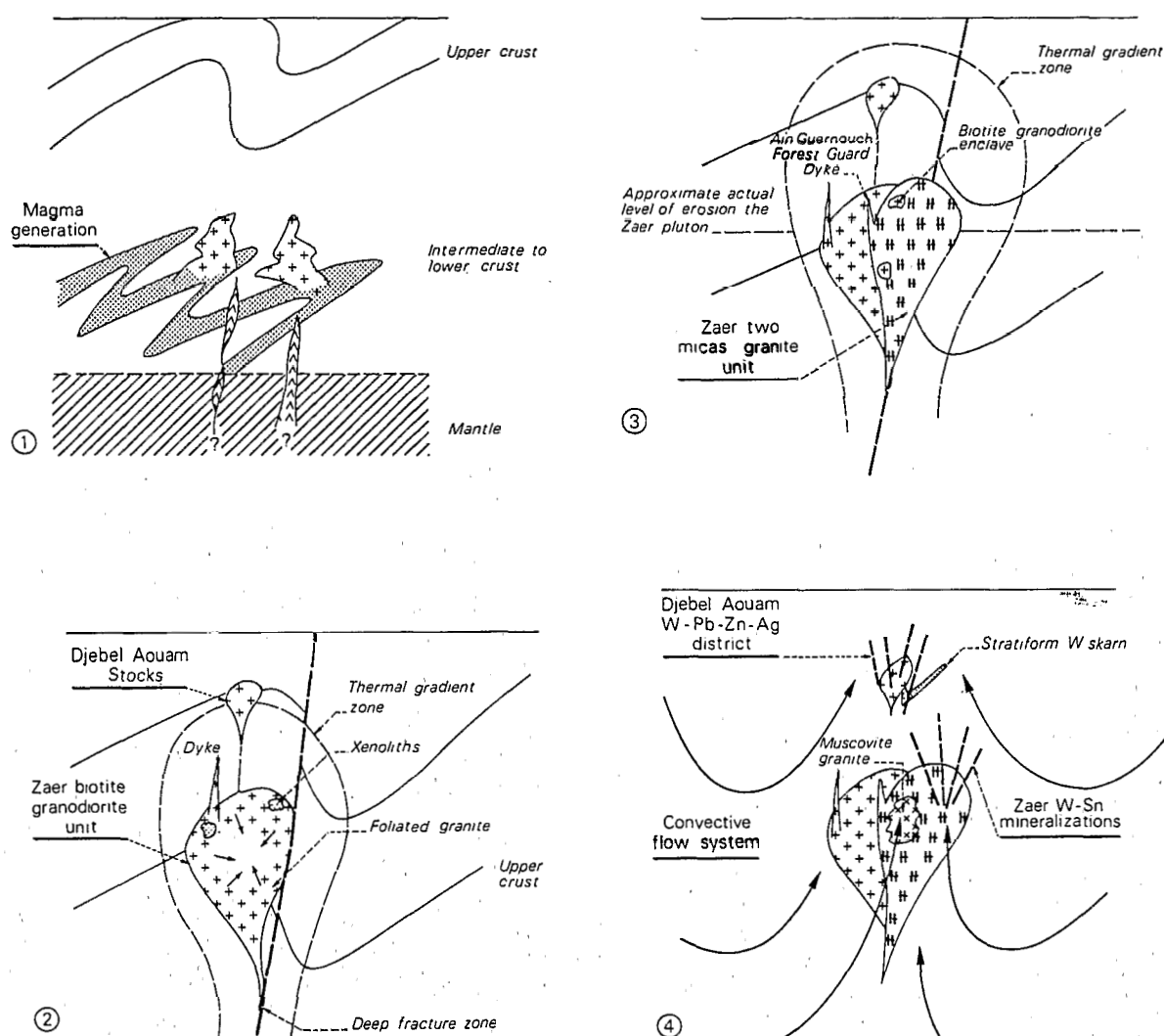


Fig. 8. Four step schematic model for the genesis of the zoned Zaër pluton and Djebel Aouam granitic stocks. See text for explanations.

Moroccan granites such as Oulmès and Achemeche also show well-developed endogene mineralizations. The model exposed here explains the widely recognized spatial and genetic connection of granite with W-Sn ore deposits.

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