Epigenesis versus syngenesis: a contribution to the debate based on the stratiform tungsten skarn mineralizations of Djebel Aouam, central Morocco[1]

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With 6 figures

Abstract. Stratiform scheelite-biotite banded mineralizations in the polymetallic W-Pb-Zn-Ag district of Djebel Aouam, central Morocco, are interpreted as skarn bodies resulting from a two-stage process: (1) Metamorphic reactions in interbedded pelitic and impure limestone layers produce a characteristic zonation by cation exchange; (2) Later infiltration of hydrothermal fluids causes the replacement of the previously constituted calc-silicate layers and the formation of the stratiform tungsten mineralization. This stratiform skarn development occurs away from the granitic contact.

Introduction

Recent studies by European geologists have emphasized the role of syngenetic processes to explain the formation of stratiform tungsten ore bodies (e.g. Höll et al. 1972, Maucher 1976, Beziat & Tollon 1976, Noronha 1976, Arribas 1979, Saavedra 1982). The stratiform appearance of some mineralized occurrences may, however, have resulted from the replacement of sedimentary layers by the epigenetic infiltration of fluids (Guitard & Laffitte 1958, Sonnet 1981, Derré et al. 1986).

The stratiform tungsten mineralization recently discovered in the Djebel Aouam W-Pb-Zn-Ag polymetallic district of central Morocco resulted from an infiltrational process involving ascending hydrothermal fluids (Cheilletz 1983b) and represents a new type of tungsten mineralization in Morocco. The calcareous character of the sedimentary layers supports the classification of these scheelite occurrences as tungsten skarn.

Skarns may be broadly interpreted as resulting from the silification of carbonate rocks but within the term "skarn" many complex geological features are often included. Phan (1969), Bartholomé (1970), Zharikov (1970) and Einaudi et al. (1981) have distinguished two main groups:

(1) Skarns resulting from metamorphic recrystallization of impure carbonate rocks referred to as "calc-silicate hornfels" or "skarnoid" (Zharikov 1970), and skarns resulting from the reaction between rocks of contrasted lithology, such as schists and interbedded calcareous shales or carbonate-bearing rocks which produce by diffusion processes "calc-silicate bands" (Vidale 1969, Thompson 1975, Kerrick 1977).

(2) Skarns localized at the contact of magmatic intrusions and resulting from the replacement of carbonate rocks by hydrothermal fluids of diverse origins. The main process involved in these metasomatic reactions is an infiltration of fluid, and the resulting skarn is referred to as an "infiltrational metasomatic skarn" (Korzhinski 1968, Fonteilles 1978).

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The hydrothermal fluids play an important role in transporting and redistributing metals and other components into skarn deposits. Finally, skarn formation appears to be the convergence of an evolving process (Meinert 1983) which combines an initial isochemical metamorphism (stage 1), and a later multiple hydrothermal fluids circulation responsible for metamorphism and high-temperature mineral crystallization (stage 2). This second stage ends with retrograde alteration as temperatures decline. The importance of the Djebel Aouam tungsten skarn is that it shows clearly the superposition of these two stages: Metamorphic recrystallization of interbedded calcareous and schist-sandstone series, plus hydrothermal infiltration by mineralizing solutions unaffected by later folding or metamorphic remobilization. The underground mining of Pb-Zn-Ag mineralization by the Société Minière du Djebel Aouam (SMA), permitted access to, and the observation of several levels of the tungsten mineralization.

Geological setting

The Djebel Aouam tungsten deposit occurs within the W-Sn-Mo Moroccan province related to post-tectonic Hercynian granitoids (Agard et al. 1980). The Djebel Aouam district constitutes a noteworthy example of a palaeogeothermal system resulting from the emplacement of small granitoid stocks and involving polyphase hydrothermal circulation (Fig. 1). The mineralizations are divided into three main groups on the basis of chronological relationships and mineralogical paragenesis:

(1) Scheelite-skarns, including the stratiform skarn occurrences described in this paper.

(2) Quartz-scheelite-wolframite lodes and veins (Cheilletz 1984);

(3) Pb-Zn-Ag lodes (Agard et al. 1958) mined since 1955; production 300,000 t Pb, 30,000 t Zn and 600,000 kg Ag; reserves 120,000 t Pb, 32,000 t Zn (SMA estimation 1984, Figs. 1 and 2).

The Djebel Aouam district is located at the eastern edge of the central Morocco Palaeozoic ridge. Palaeozoic sediments ranging in age from Ordovician to Upper Visean are characterized by an alternation of schists and sandstones with a prominent quartzite bed at the Ordovician-Silurian boundary (Fig. 2). The series has been affected by at least two tectonic phases, the second one being responsible for the folding, vertical straightening, and tectonic slicing of the sedimentary layers.

Three Hercynian granitoid stocks (281 ± 2 Ma by the K-Ar method, Cheilletz & Zimmerman 1982), called "Mispickel", "Mine", and "Kaolin", intruded the sedimentary series and are crosscut by numerous microtonalite dykes. The Kaolin stock is crosscut by the largest Pb-Zn-Ag lode associated with an intense argillic alteration. Magmatic bodies are emplaced at a relatively shallow level ($\simeq$ 6 km, Termier et al. 1950) producing a contact metamorphic halo characterized by the development of biotite-cordierite spotted hornfelses in pelitic sediments. The existence of rare andalusite – sillimanite – K-feldspar assemblages in hornfelses along the granite contact gives a maximum temperature of 650°C for a 2 kb lithostatic pressure (Evans 1965) in the surrounding Palaeozoic formations at the time of magmatic intrusions. Upper Visean limestones were converted to marble and massive garnet-pyroxene skarn bodies, whereas Silurian and Devonian interlayered pelitic-impure limestone sequences (Fig. 3) produced calc-silicate bands containing the stratiform tungsten skarns studied here. This thermal metamorphic effect was followed by the development of a superimposed biotitic hydrothermal metamorphism (Cheilletz & Isnard 1985) along a system of stockwork-like veinlets distributed along the N-S axis of the three granitic stocks (Fig. 1). These hydrothermal circulations were the cause of the tungsten mineralization.

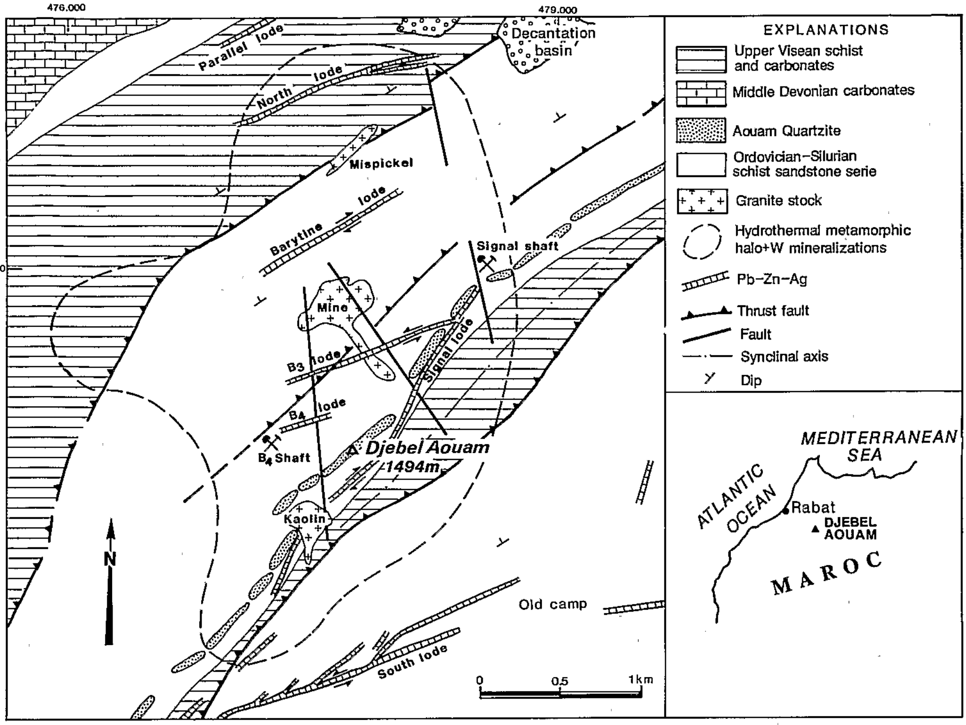

Fig. 1. Geological and mining sketch map of the Djebel Aouam district in central Morocco (modified after Agard et al. 1958). The tungsten mineralizations (lodes and skarns including the stratiform skarns described in this paper) are scattered inside the hydrothermal-metamorphic halo.

The emplacement of granitic stocks and subsequent hydrothermal metamorphism and mineralization appear to be controlled by a major E-W strike-slip fracture (Cheilletz 1983a) related to late Hercynian wrench faulting in northwestern Africa (Arthaud & Matte 1977). The dextral and subsequent sinistral movement along this fracture governs the geometrical disposition of respectively the W and Pb-Zn-Ag mineralizations.

Stratiform tungsten skarns

The stratiform tungsten skarns at Djebel Aouam are characterized by an elongate lenticular shape and are concordant with the bedding (Fig. 2). They occur in underground mining workings as lenses, about 250 metres high and 200 metres in horizontal extent, in the area between the Mine and Kaolin granites from approximately the 1057 m level; their frequency increases downwards. Two main strata are present at the bottom of a marked quartzite unit beneath the Djebel Aouam summit. Rough economic estimations give a 0.2–0.3% WO_3 grade for a 3 m scale sampling. The origin of the stratiform tungsten skarn ore bodies of the Djebel Aouam might be explained by either of two different hypotheses:

(1) Synsedimentary tungsten concentrations (syngenetic model) remobilized during the thermal and hydrothermal metamorphic events related to the granite stock emplacement. A lithogeochemical study of pelitic and carbonate layers outside of the metamorphic halo shows the lack of any tungsten anomaly (67 samples, average tungsten content 1.6 ppm, $\sigma = 2.1$) and makes this model untenable.

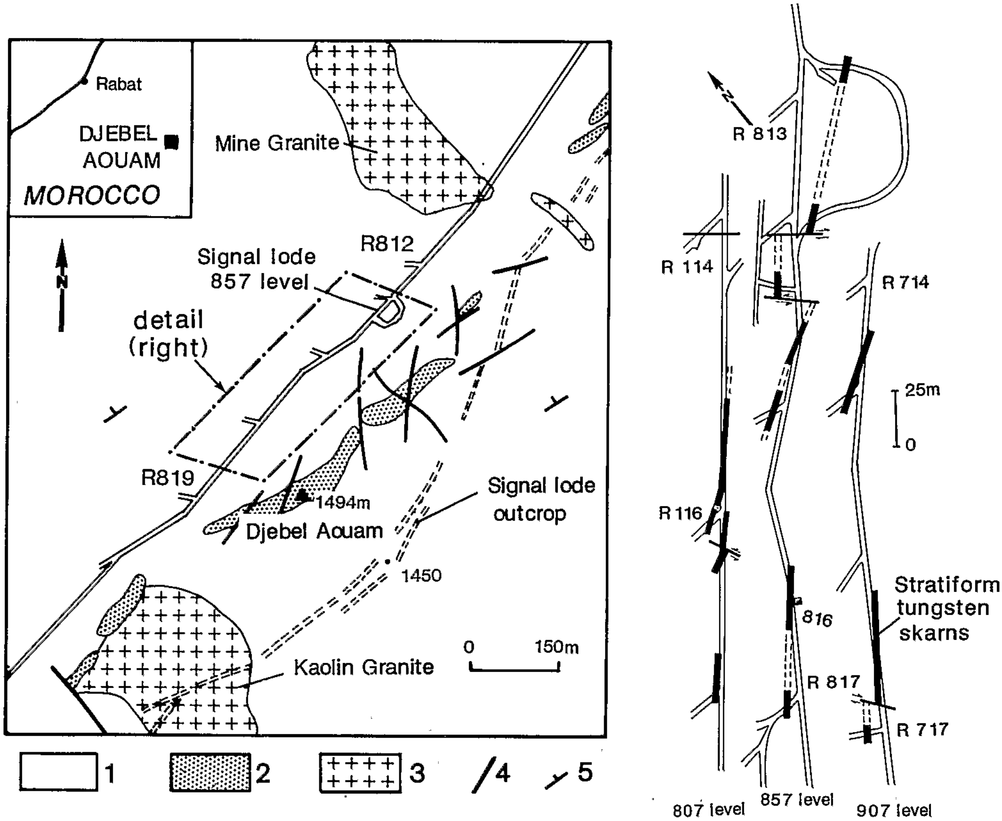

Fig. 2. Mining framework of the scheelite-biotite stratiform skarns of the Djebel Aouam district. 1, undifferentiated metamorphosed Palaeozoic series; 2, Ordovician-Silurian quartzite; 3, granites; 4, fault; 5, strike and dip of Palaeozoic series. Two mining levels of the Pb-Zn-Ag Signal lode vein are indicated (outcrop and 857 level). R812: crosscuts in the 807 and 907 levels (recorded by A. Cheilletz and SMA Geological Service).

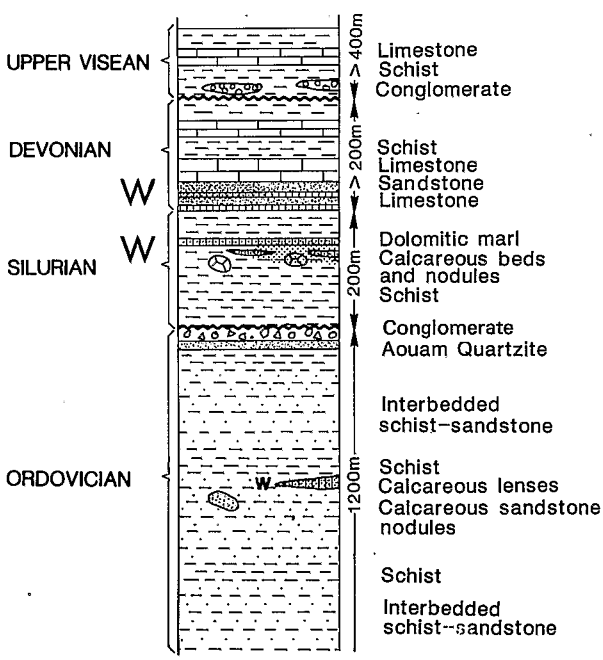

Fig. 3. Lithostratigraphic column of the Djebel Aouam Palaeozoic formations (after François et al. 1986) showing the position of the tungsten stratiform skarns (W).

(2) Epigenetic tungsten concentrations developed by partial replacement of the sedimentary series. This model can account for the zoning and nature of stratiform tungsten mineralization (Fig. 4) by use of a two-stage mechanism (Fig. 5). The first stage is related to the thermal metamorphic episode which gives rise to the zoned calc-silicate bands in interlayered pelitic-calcareous sedimentary series, while the second stage involves the infiltration of mineralized solutions and partial replacement of calc-silicate layers during the hydrothermal metamorphic episode. "skarn 1" and "skarn 2" refer to these two successive stages. Two types of infiltration skarn 2 can be distinguished: A "stratiform skarn" where replacement occurs parallel to the skarn 1 zonation planes, and a "vein skarn" related to vein filling by fluids percolating across the zonation planes of skarn 1 (Fig. 4).

Skarn 1 petrogenesis

Discontinuous levels of argillaceous limestones and dolomitic marls interlayered with black pelites (Fig. 3) characterize the Silurian – Lower Devonian units (François et al. 1986). Skarn 1 developed mainly in these series during the thermal metamorphic episode by reaction between contrasting lithologies with the formation of a metasomatic zonation. The mineralogical zoning is as follows (Fig. 5):

(Z1) metapelite zone – quartz, biotite, andalusite, cordierite, muscovite, K-feldspar, plagioclase, ilmenite;

(Z2) feldspathic hornfels zone – quartz, biotite, plagioclase, actinolite, ilmenite, sphene;

(Z3) feldspathic zone – plagioclase An_{80-100}, ilmenite, sphene;

(Z4) amphibole-pyroxene zone – quartz, actinolite, salite-ferrosalite, plagioclase, K-feldspar, ilmenite, sphene.

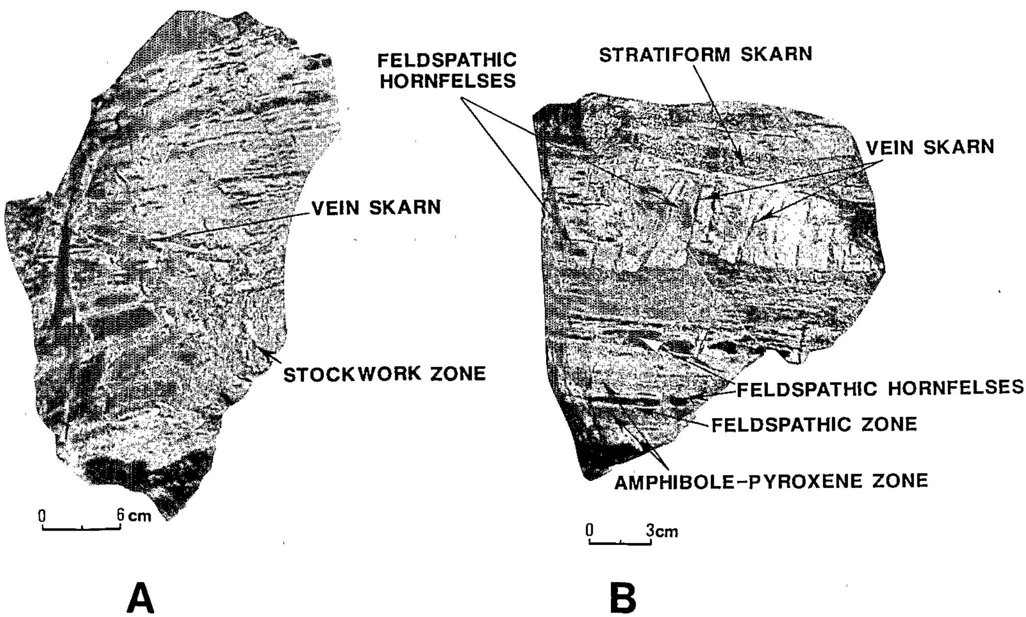

Fig. 4. A. Hand-samples of zoned calc-silicate skarn 1 crosscut by vein type skarn 2 with stockwork zone. B. Zoned calc-silicate skarn 1 with stratiform mineralized skarn 2 replacing the amphibole-pyroxene zone.

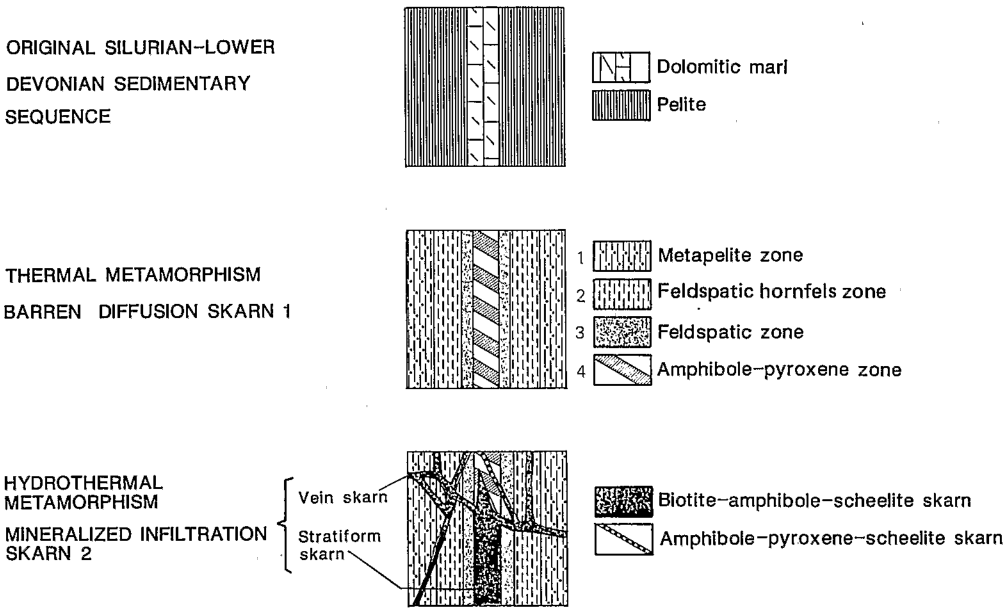

Fig. 5. Schematic sections illustrating the development of 'skarn 1' and stratiform and vein-type mineralized 'skarn 2' by means of a two-stage metasomatic model.

The first three zones are developed in original pelitic sediments; the amphibole pyroxene zone (Z4) is developed in calcareous layers as shown by the existence of pseudomorphosed fossil fragments; therefore the Z3–Z4 limit constitutes the initial lithologic boundary. Massive stratiform phlogopite bands are found in underground mine workings close to the calc-silicate bands. They are probably derived from magnesian-chlorite schist layers outcropping with the calcareous nodules in the Silurian – Lower Devonian series. The chemical composition of the initial sedimentary rocks and the different metasomatic zones have been analysed.

The evolution of the metasomatic process can be described using an ACF diagram where selected samples from unmetamorphosed sediments and the different skarn 1 zones have been plotted (Fig. 6). The representative points of zones Z1–Z4 are situated inside the individual triangles fixing the assemblages described earlier. Moreover, it is clear that the evolution of the composition of the different zones does not correspond to a gradual mixing model between pelitic and calcareous initial rocks. To explain such a broken evolution line, it is necessary to refer to a metasomatic model by diffusion of cations with differential mobility as in other calc-silicate occurrences (Korzhinski 1968, Vidale 1969, Thompson 1975, Kerrick 1977). The petrographic characteristics of the Djebel Aouam skarn 1 and particularly the lack of wollastonite-idocrase-garnet assemblages in Z4 zone are well explained by the relatively low CaO concentration of calcareous layers, i.e., CaO component appears diluted by the large quantities of MgO and FeO. This induces the chemical potential of CaO in interstitial fluids to be insufficient to reach the stability field of garnet and the Ca-rich silicates. The development of the Z3 monomineralic anorthitic zone may be due to the double cation diffusion mechanism as related earlier and to the initial richness in alumina of the Silurian – Lower Devonian pelitic series (Fig. 6).

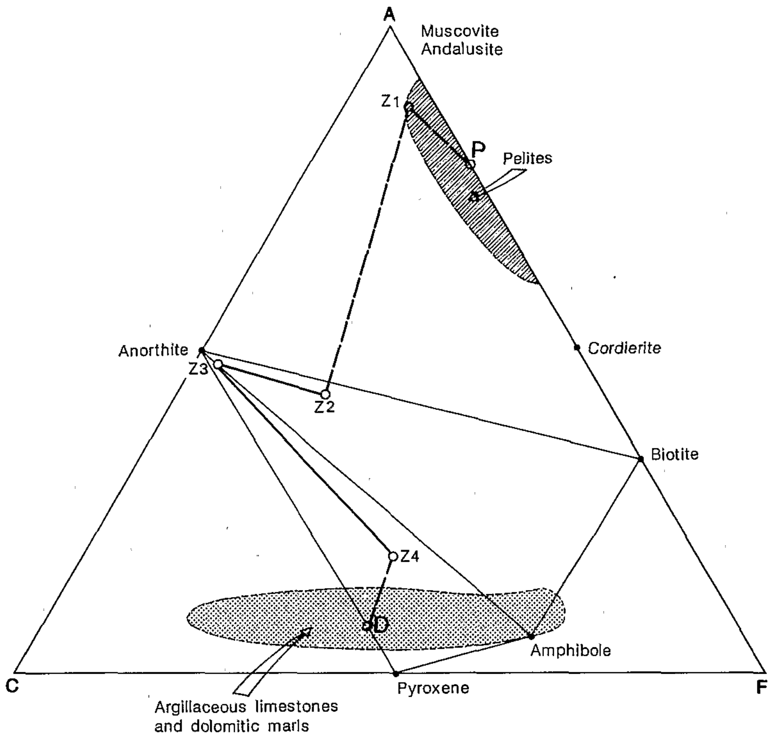

Fig. 6. Illustration of a standard metasomatic zonation of 'skarn 1' in an A (Al_2O_3+Na_2O+K_2O) – C (CaO) – F (MgO+FeO+MnO) triangle based on the chemical analyses of the different zone types. Z1, Z2, Z3, Z4 metasomatic zones are indicated. P (pelite) and D (dolomitic marl) are two original sedimentary rocks of the Silurian – Lower Devonian unmetamorphosed series. Shaded areas represent the variation in composition of the unmetamorphosed interlayered pelitic and calcareous levels, respectively, that give rise to the calc-silicate 'skarn 1'.

Skarn 2 petrogenesis

The important factor during the fluid flow and infiltrational process giving rise to skarn 2 development appears to be the specific replacement of amphibole-pyroxene Z4 zone of skarn 1 (Fig. 5). This selective fluid percolation produces stratiform mineralized skarn 2 and gives rise to the banded structure of the scheelite ore (Fig. 4B). The mineralized layers are composed of granoblastic assemblages of phlogopite, quartz, actinolite, scheelite, plagioclase $An_{20\text{-}50}$, K-feldspar, minor pyrrhotite, chalcopyrite, sphene, ilmenite and sphalerite. The infiltration and replacement of phlogopite layers produce highly mineralized stratiform ore bodies (more than 1% WO_3 grade) consisting mainly of fine-grained phlogopite intergrown with scheelite, pyrrhotite, minor actinolite, plagioclase An_{25} and fluorite. Vein skarns and stockwork zones (Fig. 4A) cross-cut the metamorphic zonation of skarn 1 and join together the successive stratiform skarn layers. Amphibole-pyroxene-scheelite assemblages may develop at the intersection of narrow vein skarns and Z4 zone (Fig. 5C). The reduced nature of the Djebel Aouam stratiform skarns (Einaudi et al. 1981) is reflected by the pure scheelite composition (typically molybdenum-free) and the ferric-iron poor gangue minerals with major pyrrhotite, biotite and ilmenite assemblages.

Retrograde alteration, developed mainly along the border of metasomatic skarn 1 and skarn 2 zones or along veinlets, caused the development of a microcrystalline jumble of muscovite, K-feldspar, albite, quartz, epidote, prehnite, calcite, chlorite, sphene, fluorite and scheelite.

Conclusions

The composition and the banded structure of the Djebel Aouam stratiform tungsten skarns are the consequence of the superposition of three main factors:

(1) The inhomogeneity of the initial sedimentary layers which are composed of irregular alternating pelitic and impure calcareous dolomitic marl strata.

(2) The effect of thermal contact metamorphism producing a metasomatic zonation by reaction and cation diffusion between contiguous layers in skarn 1.

(3) The vertical infiltration of mineralized hydrothermal solutions along straightened bedding planes and the replacement of the previously formed amphibole-pyroxene metasomatic zones (=stratiform skarn 2). Crosscutting structures (=vein skarn 2) result from the percolation of the hydrothermal fluids between the stratiform skarns bands.

The resulting scheelite-biotite stratiform skarns, first described from Morocco, appear less common than the massive skarn bodies developed at the contact of granitic bodies (e.g. the Azegour W-Mo skarn in High Atlas, Permingeat 1957). However, there appears to be some similarities with barren calc-silicate formations or "skarnoids" from Costabonne, Pyrénées (Guitard & Laffitte 1958, Marcke de Lummen 1983) and with tungsten-mineralized skarns of Mac Tung, Canadian Cordillera (Dick & Hodgson 1982) and Sangdong, Korea (Klepper 1947). In the Djebel Aouam district, the formation of the tungsten stratiform skarns occurred at the beginning of the development of a huge palaeogeothermal system producing polymetallic W-Pb-Zn-Ag mineralization.

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