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Deformation of Stibnites and Pyrites in the Madsan Antimony Deposit (Niğde, Turkey): Implications for Pressure-Temperature Conditions of Local Deformation

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Abstract: The Madsan antimony deposit at the southeastern part of the Niğde province (south-central Turkey) includes a series of epithermal veins hosted by marbles and gneisses. The veins have a simple mineralogy of quartz, calcite, stibnite and pyrite as major constituents, and cinnabar occurs in trace amounts. The deposit experienced a progressive deformation evidenced by a set of textures developed especially in stibnite and pyrite. These are pressure lamellae and annealing as the main textures, and curvature, off-set of pressure lamellae and fracture filling as the textures of minor importance. These were developed in three successive deformation phases. Pressure lamellae represent the first stage of deformation in the region, while the second stage of deformation is represented by curved pressure lamellae and annealing texture, and the third stage of deformation is characterised by truncation and offset of pressure lamellae. The deformations probably occurred at temperatures reaching 180°C and at pressures about 0.2 MPa. Geological evidence supports that the first phase of deformation is explained by the southward thrusting of the Niğde Massif over the Ulukışla Basin. The second phase of deformation is due to an increase in internal compression within the stibnites after the first deformation ended. The third phase of deformation is the direct result of younger normal faulting close to the deposit.

Madsan Antimuan Yatağında (Niğde, Türkiye) Stibnitlerin ve Piritlerin Deformasyonu: Yerel Deformasyonda Basınç-Sıcaklık Koşulları Göstergeleri

Özet: Mermerler ve gnayslar içerisindeki epitermal damarlardan oluşan Madsan antimuan yatağı Niğde ilinin (orta-güney Türkiye) güneydoğusunda yer alır. Damarlar ana bileşenler olarak kuvars, kalsit, stibnit ve pirit içeren basit bir mineralojiye sahiptir; zinober iz miktarlarda bulunur. Özellikle stibnit ve piritte gelişen bir dizi dokunun işaret ettiği ilerleyen bir deformasyon yatağı etkilemiştir. Ana dokular basınç lamelleri ve kaynaklanma olup, eğilme, basınç lamellerinin ötelenmesi ve çatlak dolguları ikinci derecede önemli dokulardır. Bu dokular birbirini izleyen üç deformasyon evresinde gelişmişlerdir. Basınç lamelleri bölgedeki deformasyonun ilk evresini temsil ederler; ikinci deformasyon evresinin temsilcileri eğilmiş basınç lamelleri ve kaynaklanma dokularıdır; üçüncü deformasyon evresi basınç lamellerinin kesilmesi ve ötelenmesi ile belirginleşir. Deformasyonlar olasılıkla 180 °C ye kadar ulaşan sıcaklıklarda ve 0.2 MPa dolayında basınç altında gelişmiştir. Jeolojik veriler, Niğde Masifinin güneye doğru Ulukışla Havzasına bindirmesi ile deformasyonun birinci evresinin açıklanmasını desteklemektedir. Deformasyonun ikinci evresinin nedeni ilk deformasyonun bitiminden sonra stibnitlerdeki iç sıkışma kuvvetlerinin artmasıdır. Deformasyonun üçüncü evresi, yatağa yakın genç normal faylanmaların sonucudur.

Introduction

Studies dealing with the experimental deformation of sulfide minerals (Gill, 1969; McDonald, 1970; Clark and Kelly, 1973; McClay and Atkinson, 1977; Atkinson, 1975; McClay and Ellis, 1983) have provided a detailed insight into the behaviour of these under different pressure and temperature conditions. A variety of deformational textures and fabrics in naturally and experimentally deformed sulfides are studied by reflected light and electron microscopy. Correlations and comparisons of the deformation textures observed in naturally and experimentally deformed minerals resulted in quantitative relationships between textures temperatures and pressures affecting a mineral deposit (McClay and Ellis, 1983; Cox et al. 1981). Such relations are based on minerals with extreme differences in strength and ductility. The differences suggest that the sulfides might serve as sensitive guides to conditions of deformations taking place at low to medium P-T conditions. This study presents the deformation textures and fabrics of stibnites and pyrites in the Madsan antimony deposit, in order to estimate the local P-T conditions that caused these textures.

Geology of the Madsan Antimony Deposit

The Madsan antimony deposit is located 1 km north-northeast of Çamardı and 68 km southeast of Niğde. It lies at the southeastern part of the Niğde Massif, close to its boundary with the Ecemiş Fault. The Madsan antimony deposit is hosted by white marbles, calc-silicate marbles and sericitized gneisses of the Gümüşler Metamorphics of the Central Anatolian Metamorphics (Göncüoğlu et al., 1992). The Üçkapılı Granodiorite that intruded the Gümüşler Metamorphics crops out as small patches around the Madsan antimony deposit.

The mineralizations are restricted to a zone of structural disturbance, where faults, folds, foliation planes, fractures and rarely joints act as structural controls. The wall rocks are silicified, sericitized, chloritized and recrystallized. Silicification, sericitic alteration and chloritization are observed in the gneisses while recrystallization and silicification are dominant in the marbles. The principal mineralizations are (1) quartz-stibnite veins along the marble-gneiss contacts and at the crests of folded calc-silicate marbles, (2) quartz-pyrite-stibnite veins along the foliation planes of the gneisses, (3) quartz-pyrite veins along the foliation and fracture planes of the gneisses, and (4) quartz veins along the marble-gneiss contacts. Stibnite is the dominant ore mineral with rare cinnabar. The gangue minerals are pyrite, fine and coarse grained quartz, calcite, sericite and calcite. The main ore bodies are lensoidal quartz-stibnite and quartz-pyrite-stibnite veins (Figure 1). The deposit can be classified as epithermal using Lindgren's (1933) definition, in terms of mineral paragenesis.

The mineralization post-dates the metamorphism and is related to the emplacement of the Üçkapılı Granodiorite (Göncüoğlu, 1977) into the metamorphics. Remobilization from source beds appear to explain the mode of formation of veins in the area (Kuşcu and Erler, 1992). According to this model, antimony and other metals were remobilized from syngenetically deposited sulfides within the lower parts of the Gümüşler

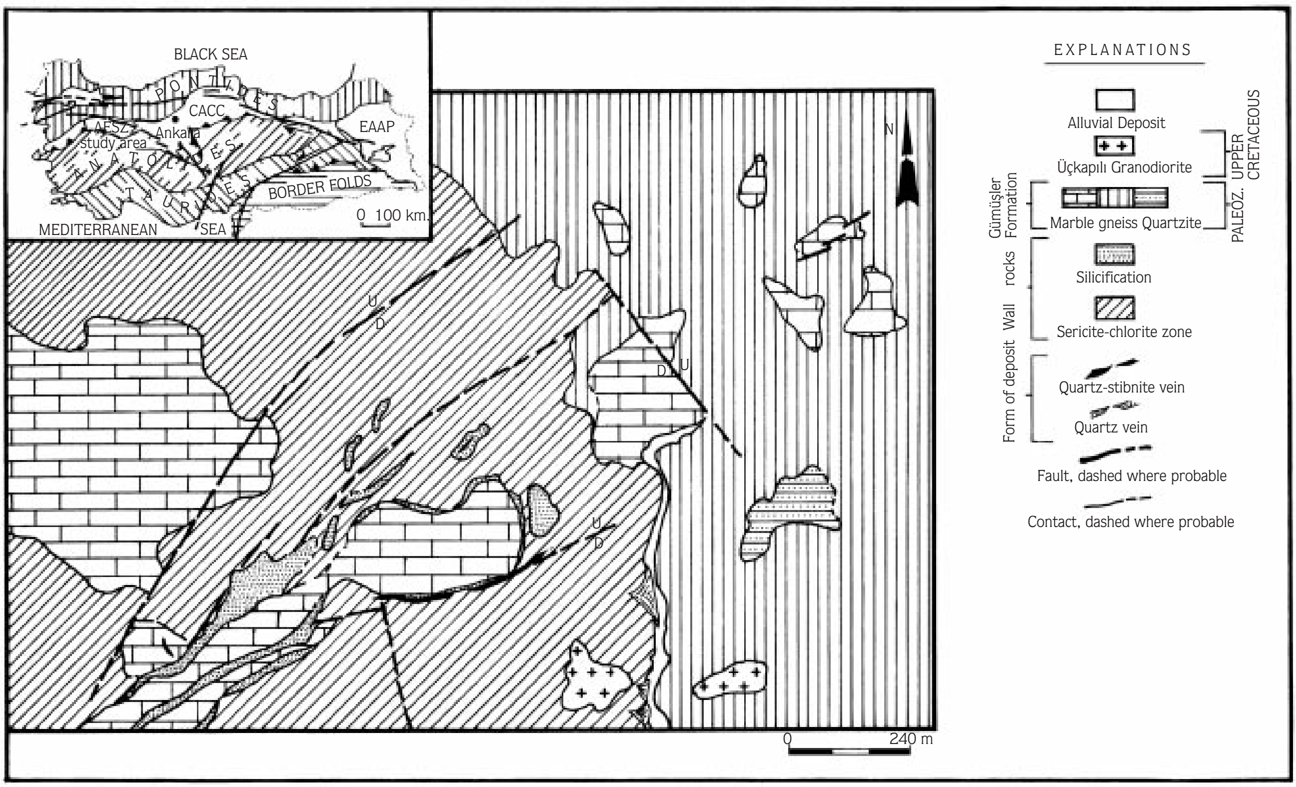

Figure 1. Geological map of the Madsan Antimony deposit (After Kuşcu and Erler, 1992).

Metamorphics into the structurally controlled places during and after the intrusion of the Üçkapılı Granodiorite. The role of the Üçkapılı Granodiorite was to provide heat for circulation of the fluids to leach metals from source beds.

The Madsan antimony deposit is located in an area that undergoes a continuous N-S compression since at least Middle Eocene. Most of the structures within the area are related to neotectonic fault systems, such as NW-SE trending dextral Tuzgölü strike-slip fault system, and NNE-SSW trending sinistral Ecemiş strike-slip fault system. The Central Anatolian Metamorphics including the Gümüşler Metamorphics, the Üçkapılı Granodiorite and overlying Upper Maastrichtian-Middle Eocene sedimentary rock units are thrusted over the Late Cretaceous-Upper Paleocene volcano-sedimentary rock units along the Celaller Thrust (Kuşcu et al., 1993). The Üçkapılı Fault is a younger normal fault that displaces the Celaller Thrust and it is one of the en echelon faults of the Tuzgölü strike-slip fault system. The effects of these two faults are well observed both on the rock units that host the Madsan antimony deposit and on the stibnites and pyrites in the veins.

Mineral Textures

The textures described in this paper are observed on pyrite and stibnite with the reflected light microscope studies. Typical textures in the veins are related to deformational and post-deformational events (Table 1). The traces and products of deformational events are clear on pyrites with well developed cataclastic texture, and on stibnites with pressure lamellae, off-set and curved pressure lamellae, while post-deformational events are represented only by stibnites with well developed annealing and fracture filling textures.

Table 1. Typical Textures in the Madsan Antimony Deposit

TYPE OF VEINS	DEFORMATION TEXTURES	POST-DEFORMATION TEXTURES
Quartz-stibnite	Pressure lamellae Off-set pressure lamellae Curvature	Annealing
Quartz-pyrite-stibnite	Cataclastic	Fracture filling

Pyrite Textures

Textures of Deformation Events. Three main processes are the major agents of rock/mineral deformation. These are (1) cataclastic processes, (2) dislocation processes and (3) diffusive mass transfer processes (Stanton, 1972; McClay, 1977; Lianxing and McClay, 1992). The effects of these are reflected very well as deformation textures on ore minerals and can be distinguished easily under the microscope.

Pyrites in the Madsan antimony deposit are characteristically found within the pyrite-quartz veins mostly parallel to the schistosity planes of the gneisses. Pyrite textures in the Madsan antimony deposit are restricted to those produced by the brittle deformation. Pyrites display cataclastic textures in places where coarse grained pyrite cubes are dominant (Figure 2a). Random and oriented fractures were observed in polycrystalline and individual pyrite grains of quartz-pyrite-stibnite veins (Figure 2b).

Experimental studies confirmed that pyrite undergoes permanent deformation by cataclasis due to its highly brittle nature under low temperature and pressure conditions typical of upper crust (Graff and Skinner, 1970; Atkinson, 1975; Cox et al., 1981). Cataclastic deformation is accompanied by grain boundary sliding (Barker, 1990). The pressure, temperature and strain rate conditions for cataclastic texture to develop on a pyrite grain are estimated as (1) 200°- 400°C, 0.1 MPa to 100 MPa and 10^{-4} to 10^{-7} sec^{-1} (Atkinson, 1975), (2) about 400°C, 100 MPa (McClay and Ellis, 1983), (3) <200°C or <300°C (McClay and Ellis, 1984), and (4) about 450°C, 300 MPa (Cox et al., 1981).

Stibnite Textures

Sulfide minerals with moderate hardness such as galena, sphalerite, chalcopyrite, pyrrhotite and stibnite were deformed experimentally and results were reported by Graff and Skinner (1970), Schull (1971), Wangs (1973) and İleri (1973). These studies indicated that the deformation twinning is the most striking property of the deformed minerals. However, İleri (1973), in his studies on stibnites, proposed that the twin-like bandings which were originally named as deformation twinning should be called pressure lamellae or twin lamellae.

The typical textures of stibnites in the Madsan antimony deposit (Table 1) are the products of deformational and post-deformational events. These two events are characterised by a series of textures, such as pressure lamellae, off-set features, annealing and fracture filling (Stanton, 1972; Craig and Vaughan, 1981; Kuşcu and Erler, 1992).

Textures of Deformation Events. Stibnite is very susceptible to any changes in pressure and temperature of the environment and tends to respond by re-orienting its internal structure to eliminate the effects of changes, as most minerals do. The first response results in the

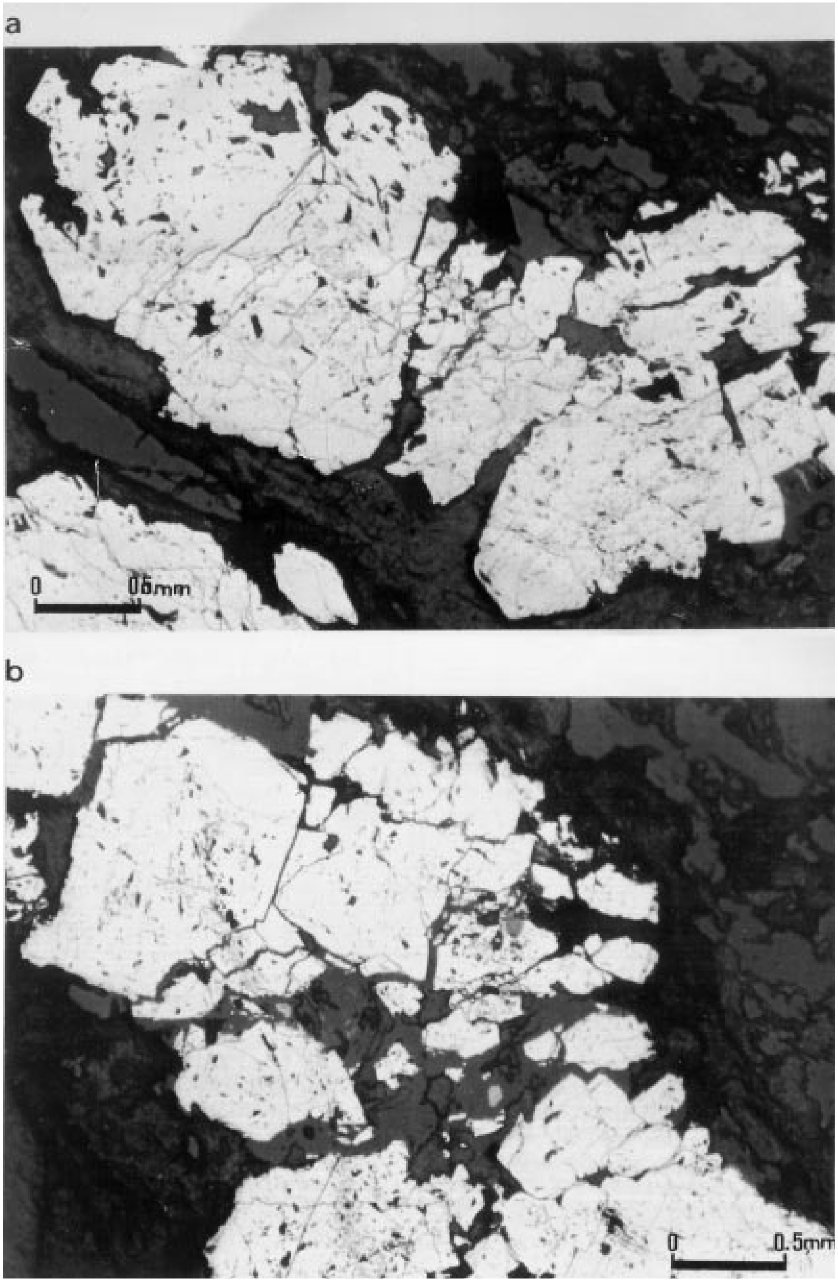

Figure 2. Deformation textures in pyrite. a. Cataclastic texture in coarse pyrite grains. b. Random and oriented fractures in polycrystalline pyrites.

appearance of pressure lamellae. When a specimen is compressed, well defined bands which are usually nearly parallel to each other and nearly perpendicular to the axis of compression (Stanton, 1972) develop. This is very common in some sulfides like galena, stibnite and molybdenite. In case of a further increase in the deformation, parallel bands are curved, and off-set along micro-fractures called curvature and off-set textures.

Pressure Lamellae. These features, especially for stibnite, occur in ores subjected to any kind of deformation and can even be formed by rough treatment of specimens during polishing. Pressure lamellae occur with uniform thickness, associated with incipient recrystallization and cataclasis. Studies concerning the P-T conditions necessary for pressure lamellae to develop is rare and involve mainly pyrrhotites. However, some moderately hard minerals, galena, sphalerite and stibnite exhibit pressure lamellae at less than 0.2 MPa and below 300°C (Craig and Vaughan, 1981).

The stibnites of the quartz-stibnite veins in the deposit display well developed and preserved pressure lamellae of more or less uniform thickness but sometimes they pinch and swell (Figure 3a). The trends of lamellae are not similar. One of the sets may contain lamellae in a single trend (Figure 3a), whereas another may contain lamellae in two trends obliquely superimposed on each other (Figure 3b). Both are likely to be formed due to temporal changes in principal stress directions. The widths of the lamellae range between 0.05 mm to 0.2 mm. They also seem to be tapered (Figure 3a).

Curved Pressure Lamellae. Deformation induced pressure lamellae in pyrrhotite, chalcopyrite, and many other sulfides frequently exhibit significant curvature (Craig and Vaughan, 1981). The pressure lamellae on stibnites observed in this study also exhibit curved structures (Figure 4a and 4b). They are characterized by development of curvature or micro-scale open folds. Along the fold axes, uncurved linear second order pressure lamellae may predominate.

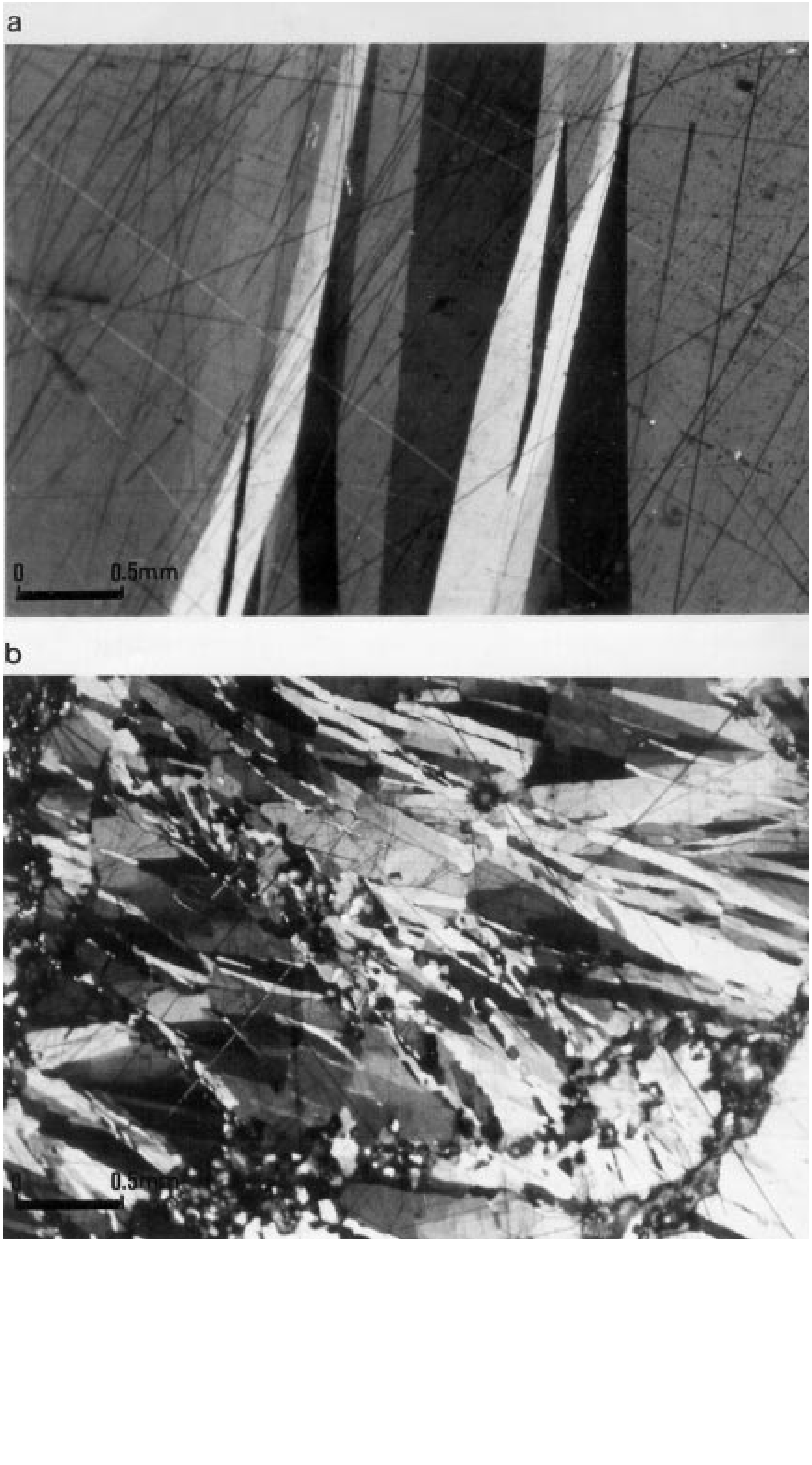

Figure 3. Deformation textures in stibnite, a. pressure lamellae in a single trend. b. pressure lamellae in two trends.

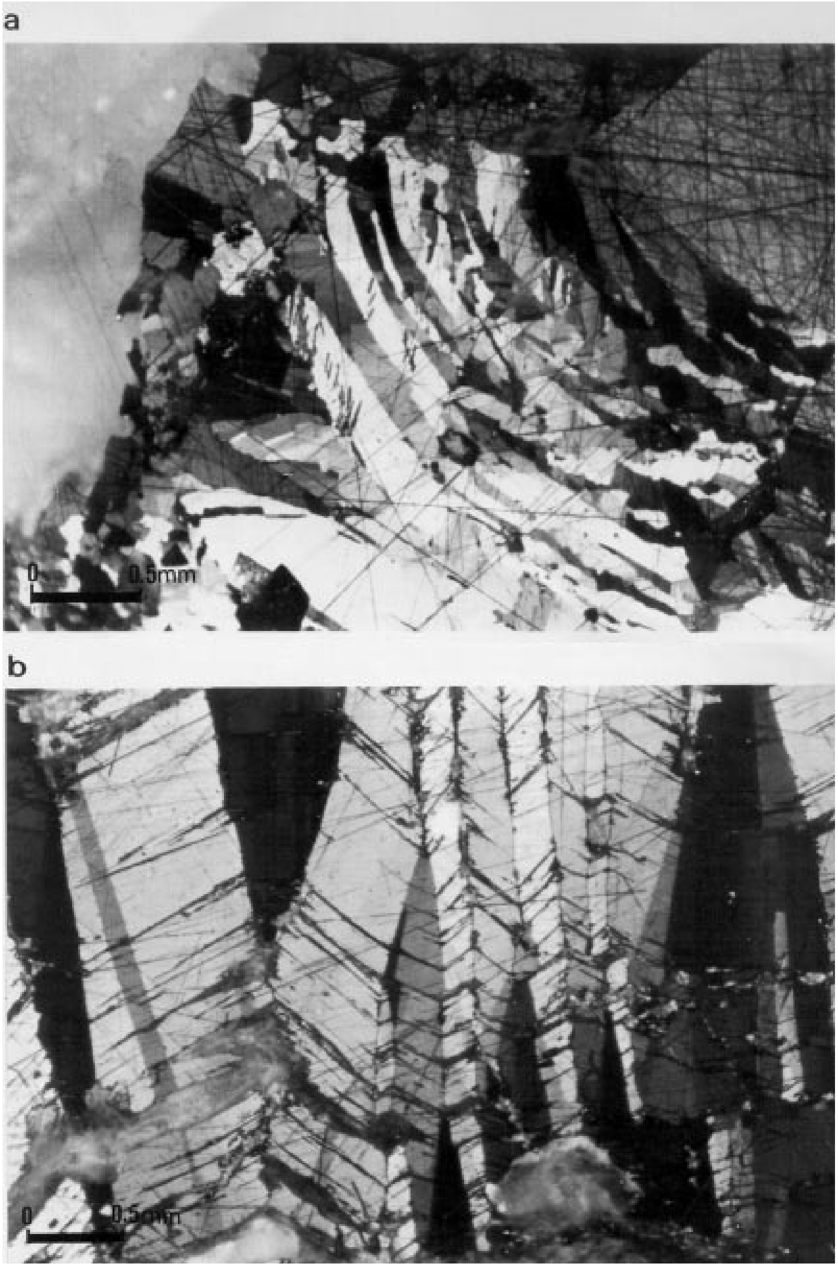

Figure 4. Curved pressure lamellae, a. open fold-like curvatures of pressure lamellae. b. folding and kinking in pressure lamellae.

Offset Pressure Lamellae. A secondary phase of deformation is often evident by the off-set of normally linear features such as cleavages, fractures, twins and pressure lamellae. In the studied samples the pressure lamellae are off-set by oblique micro-fractures (Figure 5). The off-set structures are noteworthy as diagnostic features along the micro-fracture planes. It is clear within the encircled area on Figure 5 that two sides of the lamellae on both sides do not match . It also appears that there is some recrystallization within the fracture zones indicating pressure solution and recrystallization (Figure 5).

Textures of Post-deformation Events. Post-deformation textures discussed here are produced by heating and increasing dislocations within the internal structure of stibnite without any additional stress application. Annealing, or secondary grain growth, is the most striking example for the post-deformational textures on the stibnite as well as fracture fillings.

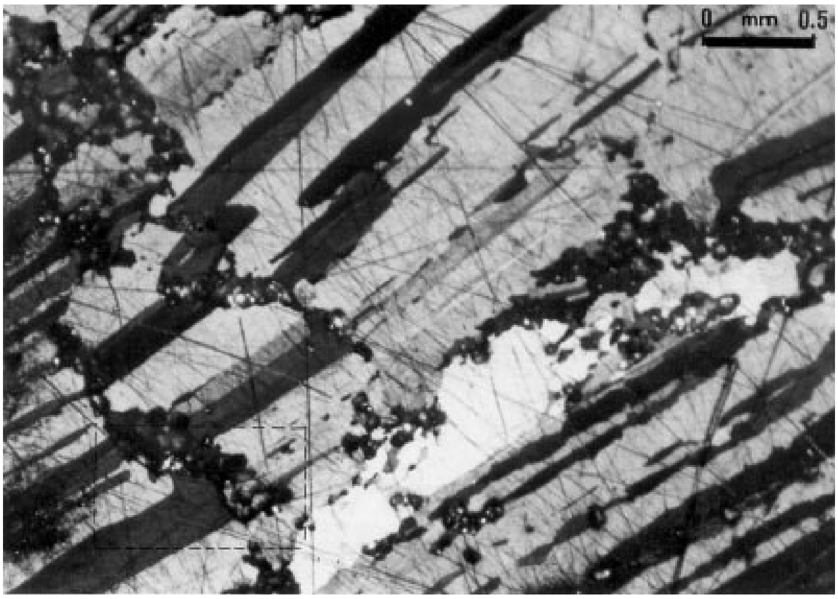

Figure 5. Off-set pressure lamellae and oblique micro-fractures.

Annealing. Following the deformation event, some sulfides like stibnite continue to be deformed plastically. The stress generated by these processes remain within the material by grain boundary migration leading to grain growth (Stanton, 1972; Lianxing and McClay, 1992; Kuşcu and Erler, 1992). Annealing is one of the processes by which the residual stresses and accumulated strain can be reduced and eliminated during high T and low P conditions. It occurs when deformed ores are heated to a temperature that permits lattice diffusion and boundary migration, leading to grain growth. The most characteristic property of annealing is recrystallization to minimize the areas of grain surfaces and to decrease interfacial tension by the development of roughly equant grains with 120° interfacial angles (triple junctions) (Stanton, 1972; Craig and Vaughan, 1981). The major results of annealing is subgrain development and the polygonization (Craig and Vaughan, 1981).

Two major types of annealing are differentiated in the stibnite-bearing veins of the deposit (Kuşcu and Erler, 1992). The first type is characterized by its transitional nature intermediate between pressure lamellae and annealing (incipient recrystallization) (Figure 6a). The second type is characterized by its well developed polygonal interfacial grains (Figure 6b). The first group represents a progressive transition from pressure lamellae, subgrain development and polygonization, whereas the second group is the final stages of polygonization and annealing that produce polygonal equant grains with 120° triple junctions. These two types are the direct products of a progressive internal deformation. The only criterion to distinguish them is the coexistence of pressure lamellae with recovery and subgrain development (Figure 6a).

Fracture Filling Texture. Post deformation textures are related to filling of the cataclastically formed fractures in pyrites by stibnites of quartz-stibnite-pyrite veins. Fractures of pyrites formed during cataclasis are occasionally infilled during post-deformational phases by stibnites (Figure 7). Stibnites behave plastically and, under conditions during which pyrite undergoes cataclasis, they are enhanced to flow and are remobilized into fractures of pyrites.

Discussions and Conclusions

The textures discussed above are the key to understanding the behaviour of stibnites and pyrites under various pressure and temperature conditions. The temperature necessary for pressure lamellae to develop in stibnite is suggested to be 180°C (İleri, 1973). No data are available for pressure conditions. It is proposed that above this temperature all the textures on the stibnites tend to disappear, and a single large grain forms (İleri, 1973). However, Craig and Vaughan (1981) suggested that the pyrrhotites and many other sulfides like stibnite also deform to yield pressure lamellae at pressures less than 0.2 MPa and below 300°C. Clark and Kelly (1973) also obtained similar results from their studies on pyrrhotite and sphalerite. Cataclastic textures and diagnostic features of pyrites associated with annealed stibnite in quartz-pyrite-stibnite veins of the deposit may

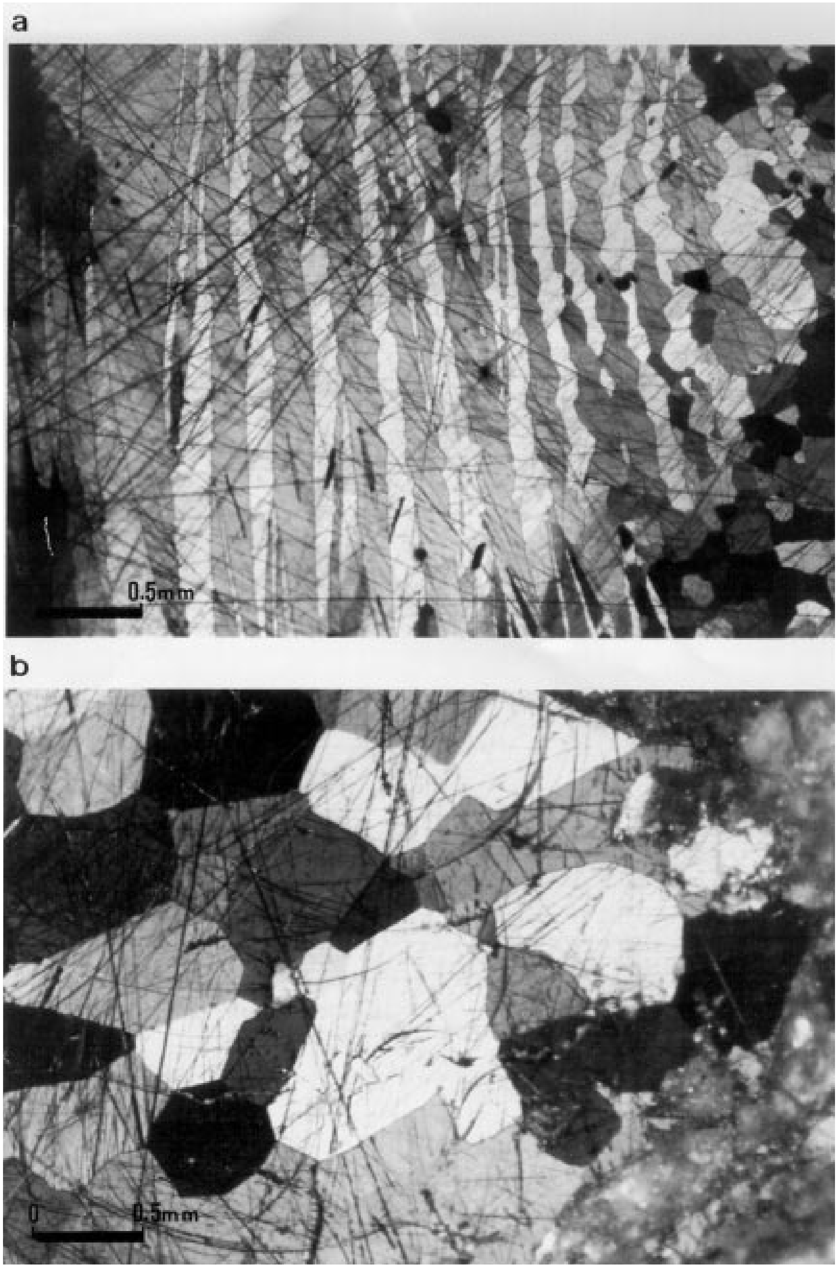

Figure 6. Post deformation textures in stibnites. a. Transitional stage from pressure lamellae to annealing. b. 120° triple junctions in annealed stibnites.

serve as guides to estimate the relative temperature of formation of pressure lamellae and cataclastic textures. In these veins, both recrystallized and annealed stibnites coexist with cataclastic pyrites. Many studies on pyrite deformations and deformation mechanisms (Gill, 1969; Vokes, 1969; Atkinson, 1975; Cox et al., 1981; Craig, 1983; McClay and Ellis, 1983; McClay and Ellis, 1984; Lianxing and McClay, 1992) verified that at least 100 MPa to 300 MPa confining pressure and temperature of about 300°C to 400°C is necessary for such kinds of textures to be formed. On the other hand, the coexistence of annealed stibnites with cataclastically deformed pyrites in the same vein may show that the temperature conditions discussed by these authors should be decreased down to <200°C for Madsan antimony deposit (accepting 180°C as the upper limit of the last appearance of stibnite textures) in cases where brittle minerals coexist with ductile minerals. In such cases, temperature and strain rate seem to be the dominant mechanisms for deformation and pressure is of second

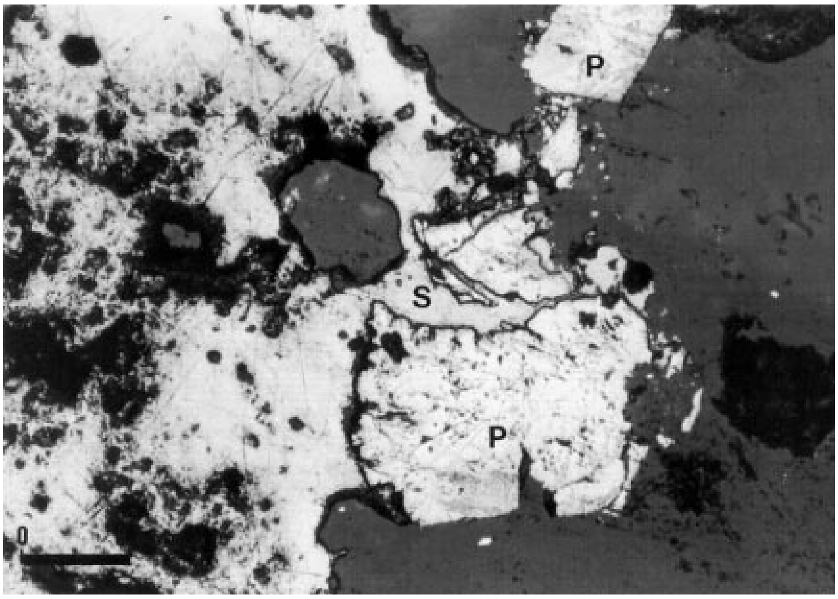

Figure 7. Pyrite euhedra infilled with stibnite, p: pyrite euhedra, s: stibnite

and/or minor importance. All the pressures discussed by various authors are confining pressures. However, the dominant effect of increasing confining pressure is to inhibit brittle failure and increase the compressive failure strength (Cox et al, 1981). Therefore, the deformation of pyrite with stibnite in this circumstances may be achieved in a system of which temperature is the major mechanism. McClay and Ellis (1984) showed this clearly stating that pyrite may undergo cataclastic deformation under temperatures less than 300°C even less than 200°C. Under these conditions, stibnite is likely to be annealed while pyrite starts to deform by brittle failure and form cataclastic textures.

A second noteworthy point is the mechanism that cause obliquely superimposed pressure lamellae, curvature and off-set . All these features indicate a progressive deformation in the regional context. Coexistence of two pressure lamellae obliquely superimposed on each other is the sign of a new principal stress in a direction different and oblique to the former one. The second lamellae are observed as pressure lamellae aligned differently to previously formed lamellae in a direction perpendicular to maximum stress directions or parallel to least stress directions. This may point out that a second order deformation affected the region after first order deformation was completed, or it may indicate that the direction of maximum stress was changed. Folding and curvature of the lamellae on some specimens support the idea that a second order deformation was applied to already formed first order pressure lamellae. The curvature and off-set of linear features are explained only by the dominance of a new stress more or less normal to the first order longitudinal directions. A series of newly generated pressure lamellae are seen more or less parallel to the axes of these folds. This may indicate an additional/progressive increase in the deformation within the same phase. Truncation and off-set of pressure lamellae by micro-fractures are interpreted to be results of a third order deformation that affect the deposit. These features support the idea that the deposit was subjected to a new deformation different than the others evidenced by micro-fractures by which pressure lamellae were off-set about 0.05mm. This deformation seems to be active in P-T conditions that do not exceed the brittle nature of the mineral.

The stibnite and pyrite textures discussed in this paper provide evidences that quasi-plastic and cataclastic processes are important deformation mechanisms on these minerals. Mineral deposits subjected to deformation at low grade metamorphism conditions yield cataclastic textures if the mineral is strong and brittle, and quasi-plastic textures like pressure lamellae if the mineral is moderately strong and ductile. These textures dominate at pressures at least 0.2 MPa up to 100 MPa and at about 200°C. Coexistence of cataclastically deformed pyrites with annealed stibnites shows that the deformation is principally a thermal deformation during which the temperature is a significant agent, and the pressure is a minor agent, and occurred at about 0.2 MPa and less than 200°C within the Madsan antimony deposit and its surroundings.

The curvature and off-set of first order deformation induced pressure lamellae provide evidences that the ore body was subjected to second and third order deformation phases as well. The textures are explained in terms of (1) southward thrusting of the block containing Central Anatolian Metamorphics (Gümüşler Metamorphics) and the Madsan antimony deposit hosted by the Gümüşler Metamorphics over the sedimentary rock units (Kuşcu and Erler, 1992), (2) resulting internal compressive forces, and (3) local increases in the temperature of the environment (Kuşcu and Erler, 1992), and (4) increasing dislocations in crystal lattices of the minerals. The Madsan antimony deposit lies within the leading edge of the Celaller Thrust. The second and third phase deformations are explained by later activities of younger normal faulting close to deposit, such as the Üçkapılı Fault.

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