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Pyrite Deformation Textures in the Deposits of the Küre Mining District (Kastamonu-Turkey)

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Abstract: The Küre volcanogenic massive sulfide deposits lie within the Kastamonu province in the western part of the Pontide tectonic belt of Turkey, and are hosted by ophiolite-related pre-Liassic basaltic sequences. Mineralogical studies of the pyritic massive sulfide deposits of the Küre mining district have shown that the sulfide assemblages, particularly pyrite, have undergone a history of deformation and metamorphism. The Küre volcanogenic massive sulfide deposits show a range of macroscopic and microscopic textures, which are also observed in metamorphosed VMS deposits elsewhere. These textures are cataclastic, annealing and fracture-filling textures which developed in two successive stages; cataclastic texture predominated during main deformational stages, whereas annealing and fracture filling textures predominate during late-deformational stages.

Cataclastic texture predominantes in polycrystalline and coarser-grained pyrite. Little or no cataclastic texture is observed in single, fine-grained pyrite crystals. Annealing is characterized by recrystallization of pyrite, while fracture filling is characterized by replacement and infilling of cataclastic fractures in pyrite grains by chalcopyrite. Cataclastic deformation texture is likely to have formed at about 400°C to 500°C and at 1 kb to 3 kb pressures, typical of low-grade and/or greenschist-facies metamorphic conditions, whereas annealing textures dominate at temperatures over 500°C–550°C and at 0.69 kb to 1.7 kb pressures, typical of upper greenschist-/amphibolite-facies metamorphism. Fracture-filling textures, however, should have formed at less than 600°C and less than 500 bars. These temperatures indicate the maximum temperatures that could be reached in such deformation processes. The actual temperatures should be less than these values.

The coexistence of at least two or all of the textures in at least one sample from the Küre massive sulfide deposits may indicate that the ore bodies were subjected to a progressive deformation/metamorphic event, ranging from greenschist- to upper greenschist- or even to amphibolite-facies conditions.

The imbricate thrust fault and plunging anticlinal/synclinal structures between the Akgöl Formation and the Küre Ophiolite, which postdate the formation of the massive sulfide deposits, may have been the driving mechanism for the development of deformational- and late-deformational textures in the district. Also, it is proposed that many of the copper-bearing minerals may have been remobilized from their original settings to nearby fractures during late deformational stages; this is a possible explanation of why the massive ore tends to be confined to fault planes rather than within altered basalt sequences.

Key Words: Küre (Kastamonu), volcanogenic massive sulfide deposits, pyrite deformation textures

Küre Maden Sahası Yataklarında Pirit Deformasyon Dokuları (Kastamonu-Türkiye)

Özet: Küre volkanojenik masif sülfid yatakları Pontid Kuşağı'nın batısındaki Kastamonu bölgesinde yer alır. Yataklar, ofiyolitlerle ilişkili Liyas öncesi yaşlı bazaltik seriler içinde bulunur. Bu yataklarda yapılan cevher mikroskopisi çalışmaları piritlerin deformasyon etkileri altında kaldığını ve dolayısıyla bir seri deformasyon ve geç-deformasyon dokusunun oluştuğunu göstermektedir. Bu dokular ardışık iki aşamanın ürünleri olan kataklastik, ikincil tane gelişimi ve çatlak dolgu dokularıdır. Kataklastik doku deformasyon evresinde oluşurken ikincil tane gelişimi ve çatlak dolgu dokusu ise geç-deformasyon aşamalarında oluşmuştur.

Kataklastik doku daha çok iri taneli pirit kümelerinde daha baskın bir dokudur. Tek tük taneler üzerinde kataklastik doku ya hiç gelişmemiş ya da çok azdır. İkincil tane gelişim dokusu piritin rekristalizasyonuyla oluşurken çatlak dolgu dokusu piritlerdeki çatlakların kalkopirit ile doldurulmasıyla oluşmuştur. Kataklastik dokunun, düşük dereceli metamorfik koşullarda ve/veya yeşilşist fasiyesi koşullarına benzer olarak yaklaşık 400°C–500°C sıcaklık ve 1 kb–3 kb basınç koşullarında oluştuğu düşünülmektedir. İkincil tane gelişim dokusu ise üst yeşilşist/amfibolit fasiyesleri için tipik olan 500°C–550°C sıcaklık ve 0.69 kb–1.7 kb basınç koşullarında baskın hale gelmektedir. Çatlak dolgu dokuları ise 600°C'den daha yüksek sıcaklık ve 500 bar'dan daha düşük basınç koşullarında oluşmuş

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* Prof. Dr. Ayhan Erler passed away on October 13, 1998

olmalıdır. Bu sıcaklık değerleri bu tür bir deformasyonda ulaşılabilecek en yüksek sıcaklıklara karşılık gelmekte olup gerçek değerler daha düşük olmalıdır.

Küre masif sülfid yatağında bu dokulardan en az ikisinin veya tümümün aynı örnekte gözleniyor olması bu yatakların oluştuktan sonra ilerleyen bir deformasyon etkisiyle yeşilşist-amfibolit fasiyeslerinde deforme olduklarının bir göstergesi olarak değerlendirilebilir.

Anahtar Sözcükler: Küre (Kastamonu), volkanojenik masif sülfid yatakları, pirit deformasyon dokuları

Introduction

The Küre volcanogenic massive sulfide (KVMS) deposits constitutes one of the most productive copper districts of Turkey, and are located near Küre (Kastamonu Province, northern Turkey) about 250 km north of Ankara. Mining has been active in the Küre district since ancient times, but only since the late 1950's and 1960's have limited geologic studies been carried out. Ancient mining activities, 400 to 1000 years ago, were carried out by the Geneose and Byzantines and/or the Ottoman Empire. The old slag dumps produced by ancient smelting are located to the north of Küre.

Mineralogical studies of the pyritic massive sulfide deposits of the Küre district have shown that the sulfide minerals, particularly pyrite, have undergone a history of deformation and metamorphism similar to that of the host rocks that enclose them. The Küre volcanogenic massive sulfide (KVMS) deposits are regarded as Cyprus-type VMS deposits contained within a regionally deformed allochthon of Liassic ophiolitic rocks. The KVMS deposits show a range of macroscopic and microscopic textures which are also observed in metamorphosed VMS deposits elsewhere. Although, many of these textures were partly described in earlier works of Erler *et al.* (1994) and Kuşcu & Erler (1994), the effects of deformation on the relative settings and the positions of the ore bodies have not been studied. Also, the relationships between major deformational phases and deformational textures have not been outlined. Therefore, this study aims (1) to examine the naturally deformed pyrites and their textures, and (2) to show how these textures can be incorporated into the deformational/metamorphic history of the KVMS deposits and their host rocks.

Geologic Setting of the Deposits

The area of interest comprises a part of the western Pontides tectonic belt of Turkey in which Palaeozoic metamorphic rocks, such as marble, gneiss, schist and quartzite, and Pre-Liassic ophiolitic rocks, such as serpentinite, diabase and basalts (Pehlivanoğlu 1985) occur as the most widespread rocks. In this belt, the Palaeozoic is represented by coal-bearing Carboniferous sequences which are thrusted over the Cretaceous flysch sequences. The Permian is represented by clastic rocks such as conglomerate, sandstone and sandy shales. Triassic rocks are present only as massive limestones to the east of Küre. Liassic sequences, which contain black shale, siltstone, sandstone and graywacke, unconformably overlie the pillow lavas of the ophiolitic sequence (Bailey *et al.* 1966; Güner 1980; Pehlivanoğlu 1985).

The rock units in the Kastamonu district can be regarded as basement rocks and cover rocks (Figure 1). Basement rocks that host the KVMS deposits include (1) the pre-Liassic Küre ophiolite, characterized by dismembered ophiolitic rocks (serpentinites, peridotites, diabases and basalt), (2) the Liassic epi-ophiolitic Akgöl Formation, comprising black shale and subgraywacke (Ketin & Gümüş 1963), and (3) Dogger plutonic and volcanic rocks (granodioritic intrusions and dacitic dikes) (Yılmaz 1980). The cover rocks include (1) the Bürnük Formation (Ergün 1980), late Dogger–Malm in age, dominated mainly by intramontane alluvial fan-type deposits – mainly conglomerates, and (2) the İnaltı Formation (Aydın *et al.* 1986), Malm–Early Cretaceous in age, characterized by massive reefal limestone.

A series of thrust faults and plunging anticlines/synclines between the Küre ophiolite and the Akgöl Formation are the major structures of the area. The area is dominated by southward- and northward-plunging anticlines and synclines, around which the basalts and subgraywacke sequence wrap in concentric arcs (Figure 1), indicating post-thrust warping. These, however, do not extend to depth as they are underlain by a thrust fault, the Küre fault (Bailey *et al.* 1966), a major thrust fault between the black shales and basalts. The Küre fault is a low-angle thrust fault that brings the basaltic rocks on top of the black shale and subgraywacke. In addition, two intersecting faults – along with three other N-trending major faults (at right angles to the others) – are observed (Bailey *et al.* 1966; Güner 1980) (Figure 1). These trend N63°E and N15°W, and are the major structures in which some of the chalcopyrite-rich ore is concentrated. Of these structures, thrust faults and folds have also affected the ore body. The host rocks were isoclinally folded, and were thrust over the black shale and subgraywacke together with the ore body (Figure 1). Therefore, the ore body has a prograde metamorphic history involving burial and heating, and associated deformation. All these structures have been intruded by late dacitic and granodioritic rocks during Dogger time (Çakır 1995).

The KVMS deposits are Cyprus-type volcanogenic massive sulfide deposits (Koç *et al.* 1995). Three major deposits have been mined, namely as the Aşıköy, Bakibaba and Kızılsu mines (Figure 1). Of these, the Aşıköy and Bakibaba mines are still operating. The deposits are associated with basement rocks, are hosted by extensively altered basaltic rocks with typical pillow structures (Bailey *et al.* 1966; Güner 1980; Pehlivanoğlu 1985). In general, the ore is of two types (disseminated

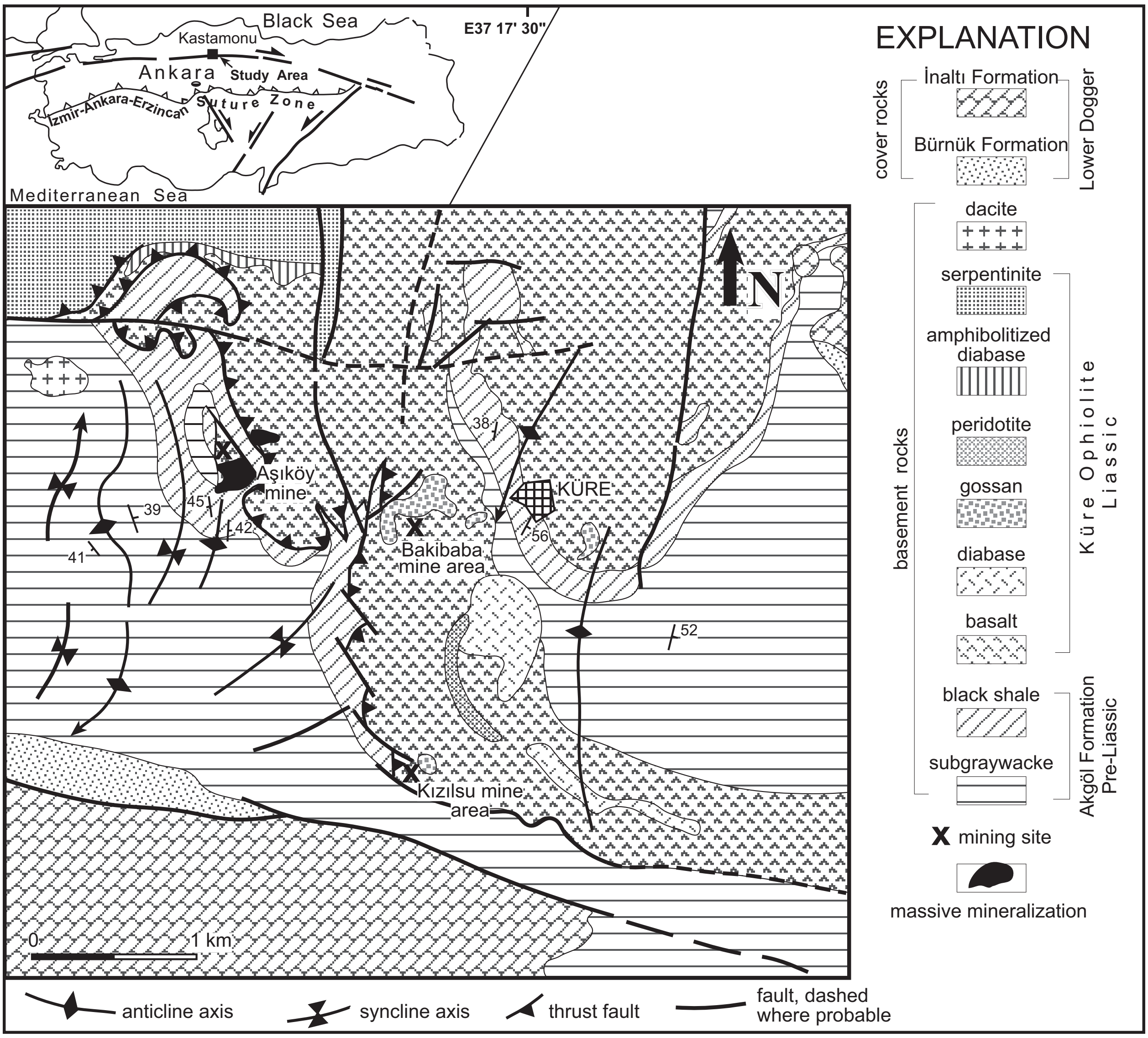

Figure 1. Simplified geological map of the Küre mining district (Modified from Bailey *et al.* 1966; Güner 1980).

and massive ore), which are locally gradational into each other. The lower grade ore is referred to as disseminated sulfide ore and consists of disseminated pyrite in brecciated pillow lava. The richer ore consists of massive lenses of pyrite and copper within the upper levels of the basaltic volcanics that are underlain by stockworks and veinlets of pyrite and locally chalcopyrite in altered rocks. A variety of minor tetrahedrite, covellite, bornite, chalcocite, hematite and magnetite mineralization are also reported (Erler *et al.* 1994).

The ore is localized by a combination of structural (mostly) and lithologic controls. The fractures and small-scale faults were presumably the feeder channels through which the KVMS deposits were formed. However, the ore body rich in chalcopyrite is sharply bounded by the intersection of two faults, trending respectively N63°E and N15°W (Bailey *et al.* 1966). Bailey *et al.* (1966) suggested that these were pre-existing fractures (prior to chalcopyrite mineralization) and controlled the initial localization of ore rather than displacing it. There is no apparent brecciation or dragging of ore along the faults. Veins and veinlets of chalcopyrite and pyrite occur along the axial planes of isoclinal folds around Toykunduk Hill (Çakır 1995).

Ore-mineral Textures

Many large base-metal sulfide deposits around the world were deposited in areas that were tectonically active and, thus, have been subjected to various degrees of late-depositional deformation/and or metamorphism. Studies of sulfides (Cox *et al.* 1981; McClay & Ellis 1983, 1984; Lianxing & McClay 1992; Craig & Vokes 1993) in these areas have revealed a variety of deformational textures. Since the sulfides are quite susceptible to any kind of deformation due to their extreme differences in strength and ductility a series of deformational textures can develop. These textures are regarded as direct responses to the effects of deformation. Studies of these textures might serve as guides to determine conditions of deformation that have affected not only the ore minerals but also the host rocks that enclose them.

Deformation textures related to pyrite in VMS and other sulfide-bearing deposits around the world have been the subject of many studies (Gill 1969; Vokes 1969; Graff & Skinner 1970; Stanton 1972; Atkinson 1975; McClay 1977; Cox *et al.* 1981; Craig & Vaughan 1981; McClay & Ellis 1983, 1984; Cox 1987; Lianxing & McClay 1992; Vokes & Craig 1993; Cook *et al.* 1994; Boyle *et al.* 1998; Kuşcu & Erler 1994, 1999). These studies have been concerned with: (a) experimental deformation of polycrystalline and single crystals of pyrite (Cox *et al.* 1981; McClay & Ellis 1983, 1984), and (b) naturally deformed pyrites and their textures in ore bodies which have experienced varying degrees of deformation (Vokes 1969; McDonald 1970; Craig 1983; Cook *et al.* 1993, 1994; Lianxing & McClay 1992). The results of these researches clearly show correlation between deformation textures and the tectonic development/history of the pyrites and corresponding temperature-pressure data. The correlations and comparison of the textures observed in deformed minerals resulted in establishment of quantitative relationships between textures and pressures affecting a mineral deposit (McClay & Ellis 1983). Although early studies suggested that the pyrite does not deform plastically, new evidence obtained from electron-microscope studies shows that pyrite may indeed undergo plastic deformation as well as cataclastic deformation (Boyle *et al.* 1998).

The pyrite textures described in this study were examined microscopically in samples from the Aşıköy, Bakibaba and Kızılsu mines (Figure 1). Following the microscope work, textures were categorized into (1) deformational and (2) late-deformational classes. The relationships and relative time of formation of these textures suggest a sequential development from deformational to late-deformational stages in the Küre district.

Deformational Textures

Cataclastic and other deformational processes are the main mechanisms that affect ore minerals and their host rocks; these can be regarded as the direct consequences of dynamic metamorphic/deformational effects on mineral deposits and sulfide minerals. These processes were coeval with the main deformation phases, and produce deformation textures distinguishable under the microscope (Stanton 1972; McClay 1977; Craig 1983; Cox *et al.* 1981, 1994; Lianxing & McClay 1992; Barker 1990). Cataclastic processes were the dominant mechanisms affecting the sulfide deposits of the Küre district.

Cataclastic Texture– Cataclastic texture is due to the mechanical effects of pressure. In the Küre district, cataclastic textures are typically observed in disseminated coarser-grained pyrite grains (Figures 2 & 3). Aggregates of grains do not show cataclastic textures; instead, they are characterized by oriented microfractures in certain directions. A series of oriented and random fractures have been observed in cataclastically deformed pyrite grains. This fracturing is related to the brittle nature of pyrite, and is the most characteristic texture developed under low-grade metamorphic conditions (McClay & Ellis 1983; Lianxing & McClay 1992). Experimental deformation of pyrite has consistently been in the brittle deformation field for temperatures up to 400°C and confining pressures up to 1000 Mpa (McClay & Ellis 1983).

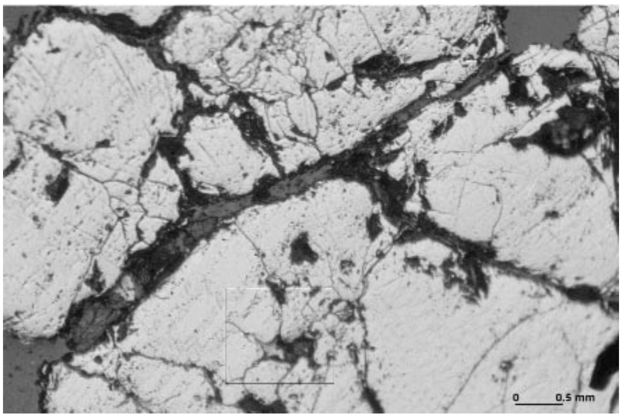

Figure 2. Cataclastically deformed pyrite with oriented fractures (Bakibaba mine) (rectangle shows an annealed grain).

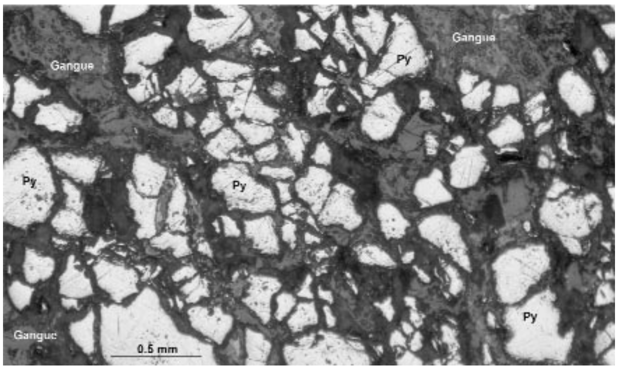

Figure 3. Cataclastic textures in polycrystalline pyrite aggregates (Aşıköy Mine) (py- pyrite, gangue: gangue mineral)

The most diagnostic feature of this texture in the Küre district is the intersection of two fracture sets; a major fracture intersects a subparallel oblique microfracture (Figure 2). Experimental results (Atkinson 1975; McClay & Ellis 1983; Cox 1987) indicate that the major fractures always make an angle of 30° to the principal stress direction, while subparallel microfractures tend to develop parallel to the principal stress direction. However, since no oriented samples were collected, and no oriented thin sections were prepared, the direction of principal stress could not be determined in this study, but will be the subject of another study.

Cataclastic fractures mainly dominate at the margins and along the fracture planes of the pyrites (Figures 2, 4 & 5). The fractures and discontinuities are joined and combined at certain angles to each other toward the inner parts of the grains (Figures 3 & 4) to form a larger grain in the advanced stages of deformation. This property is diagnostic with the first appearance of annealed pyrites within the inner parts of the pyrites (Figures 2 & 4) indicating a transitional stage from cataclastic deformation to thermal annealing.

Late-deformation Textures

In this study, late-deformation textures are represented by thermal annealing and fracture-filling textures. These textures are also termed equilibrium textures (Cook *et al.* 1993). Late-deformation textures form by decreases in pressure effects and a simultaneous increase in temperature in the sulfide minerals, and may develop by accumulated strain within the internal structure of pyrite, or by heat generated by post-tectonic granodiorite bodies and dacitic dikes intruding the ore-hosting sequence. In addition, late-deformation textures may also be accompanied by heating that resulted from accumulated dislocations within the internal structure of pyrite (Gill 1969; Cook *et al.* 1993).

Thermal Annealing Textures– During the advanced stages of regional deformation, the stress exerted on pyrites may remain and accumulate within pyrites. Annealing, thus, is the process by which the accumulated strain can be reduced by grain-boundary migration leading to grain growth (Stanton 1972; Lianxing & McClay 1992; Kuşcu & Erler 1994, 1999). Pyrites that accumulated dislocations during deformational events may lose these dislocations during the subsequent annealing processes involving essentially no external deformation while the temperature remains high enough to drive the process. This process may be the continuation of the initial deformation event, or may be aided by heat generated by dacitic intrusions during the late stages of deformation during which the effect of stress is minimized – although the effects of intrusive rocks vary locally with distance to intrusive contacts. The granodioritic and dacitic intrusions are some distance away from the ore bodies, and this would suggest that the effects of post-ore intrusions may not have played a major role in annealing. The appearance of annealing is typified by 120° triple junctions (Figures 4 & 5). The most striking property of annealing is recrystallization with development of roughly equant grains (Stanton 1972; Craig & Vaughan 1981) (Figures 4 & 5). In the Küre district annealing is always associated with cataclastic texture in the inner parts of cataclastically deformed pyrites.

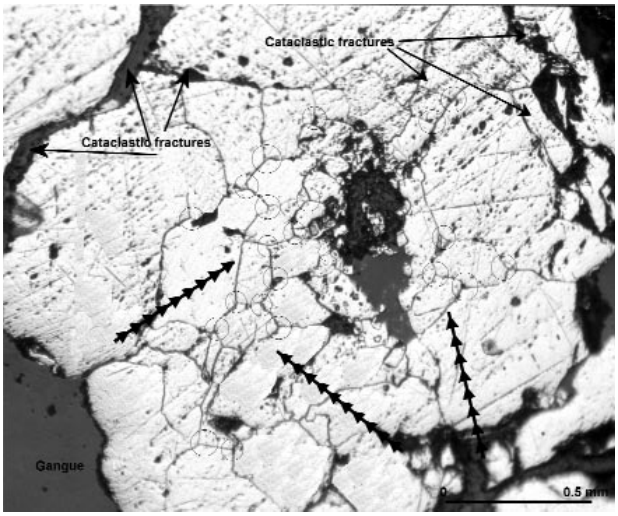

Figure 4. Cataclastically deformed pyrite with a transition from cataclastic texture to annealing texture. Arrows show propagation directions of deformation (circles outline triple-junction points).

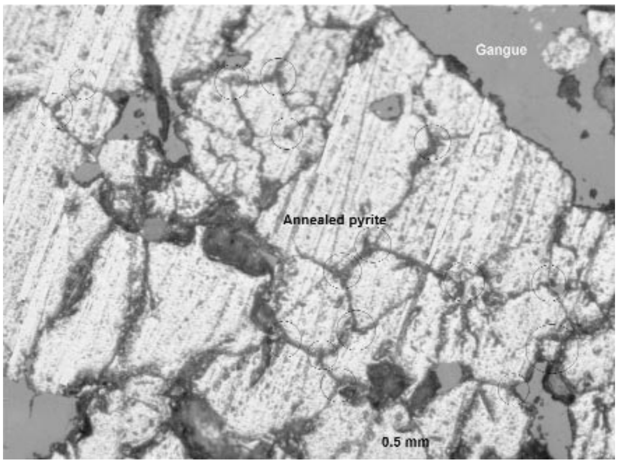

Figure 5. Annealed pyrite with 120° triple junctions (circles outline triple junction points) (gangue: gangue mineral).

Fracture-filling Textures– Fracture-filling textures are related to the infilling of cataclastically formed fractures by other phases. Fractures within pyrite grains were often filled during late-deformational stages by remobilized chalcopyrite (Figure 6). This texture is typically observed in the Bakibaba and Aşıköy mines. World wide examples of these textures have been reported by Lianxing & McClay (1992). Gill (1969) considered that this texture develops at 0.7 to 1.7 kb pressure and 600°C. Disseminated grains of chalcopyrite occur either as inclusions within pyrite grains or filling fractures in cataclastically deformed pyrites suggesting a late remobilization of chalcopyrite. Generally the disseminated chalcopyrite occurs between undeformed pyrite grains.

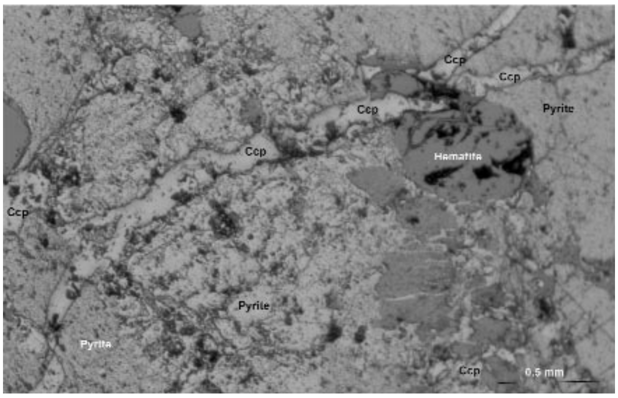

Figure 6. Fracture filling texture showing remobilization of chalcopyrite (Ccp- chalcopyrite) into fractures in pyrite

Discussion

Experimental Data as Deduced from Previous Research

Table 1 is a correlation table showing the temperature and pressure data necessary for the textures described above. In this table, the upper half (first 5 rows) lists studies dealing only with the experimental deformation of pyrite under known temperature and pressure conditions. The lower half lists studies dealing with microscopic examinations of sulfide deposits that have undergone metamorphism and/or deformation.

Table 1. Temperature and pressure data related to pyrite and other sulfide mineral textures ("s" represents a single crystal of pyrite; "p" represents polycrystalline aggregates).

	DATA	TEXTURES					
		DEFORMATION				LATE DEFORMATION	
		CATACLASTIC		ANNEALING (secondary grain development)		FACTURE FILLING	
		T (°C)	P (kb)	T (°C)	P (kb)	T (°C)	P (kb)
EXPERIMENTAL STUDIES	Gill (1969)	300–400	1.3 (p)	500-562	1.7-0.69	max. 600	0.7–1.7
	Graff & Skinner (1970)	650	6 (s)				
	Atkinson (1975)	400	3				
	Cox *et al.* (1981)	500	3 (s)	650	3		
	McClay & Ellis (1983)	500		upper greenschist amphibolite			
	Cook *et al.* (1994)	510–540	6-6.5 (p)			>200	<0.5
NATURAL OCCURENCES	McClay & Ellis (1984)	low-grade metamorphism (300)					
	Craig (1983)			amphibolite			
	Lianxing & McClay (1992)	greenschist		upper-greenschist			
	Cook *et al.* (1993)	Greenschist (retrograde) 450–500					
	Kuşcu & Erler (1994)	Greenschist		upper greenschist– amphibolite			
	Kuşcu & Erler (1995)	Greenschist upper greenschist		<600	<600		

The data in the upper half of Table 1 indicate that cataclastic texture dominates if pyrite is subjected to deformation under 400–500°C temperature and 1.3 to 3 kb pressures. Thermal annealing dominates if the temperature exceeds 500–550°C and if the pressure is between 0.69 to 1.7 kb.

The data in the lower half of the table show that cataclastic texture is the dominant texture of pyrite in deposits which have experienced greenschist-facies metamorphism. Thermal annealing texture in pyrite tends to appear in areas subjected to upper greenschist- and even amphibolite-facies metamorphism.

In this study, no experimental deformation studies have been carried out on pyrite grains. Furthermore, there is a little information about the metamorphic history of the area. The only indications of the P-T conditions of deformation are the deformational- and late-deformational textures in the district. Using the results of the two groups given above, at least two major deformation phases are suggested for the formation of the textures seen in the KVMS deposits. The first phase is one of progressive cataclastic deformation during lower greenschist-facies metamorphic conditions (under 400–500°C and 1.3 to 3 kb pressure). The second phase is one of a late-progressive deformation type at higher temperatures but lower pressures. Using the data above, deformation at a temperature >550°C, and 0.69 to 1.7 kb pressure is suggested for the district during the advanced stages of deformation. These conditions are also regarded as the deformation conditions that affected the host rocks.

Metamorphic History of the Ores

Using the pressure and temperature data summarized above, an attempt can be made to relate the metamorphic and structural features observed in the KVMS deposits to the P-T deformation history of the Küre fault and isoclinal folds. The data are consistent with the results defining the brittle-ductile transition boundaries for the main sulfide minerals by experimental data from Clark & Kelly (1973), Atkinson (1975), Kelly & Clark (1975), and Cox *et al.* (1981), together with the stability fields of greenschist- and amphibolite-facies metamorphism. However, it should be noted that the boundaries for the sulfides are the maximum observed values due to differences between experimental strain rates and geologically realistic strain rates. It should also be noted that the experiments were carried out under dry conditions, which are not the case for most natural deformation processes (Marshall & Gilligan 1987). Natural deformation usually takes place in the presence of hydrous fluids that have permitted deformation to continue under lower-grade conditions than would be required to produce the same effects in dry rocks (Atkinson 1975; Marshall & Gilligan 1987). Therefore, the T-P conditions regarding the deformation history of the KVMS deposits could be lower than the values given above.

The conditions under which the two main stages of deformation took place in the KVMS deposits should be brittle. Since no ductile deformation is observed in the KVMS deposits, all deformation phases should lie below the brittle-ductile transition boundary for pyrite. For example, for cataclastic textures to develop, deformation at/below 400–500°C temperatures and at 1.3 to 3kb pressures is necessary. This suggests that most of the brittle deformation, which produced the cataclastic textures, as well as the recrystallization, occurred under prograde conditions following the decollement and initial thrusting of the Küre ophiolite (D1) (Lias to Dogger) (Figure 7). Based on the P-T data, however, it should be noted that the cataclastic textures should have formed under upper greenschist-facies conditions as a consequence of initial thrusting and folding (D2) (Figure 7). This is consistent with the observations by Aydın *et al.*

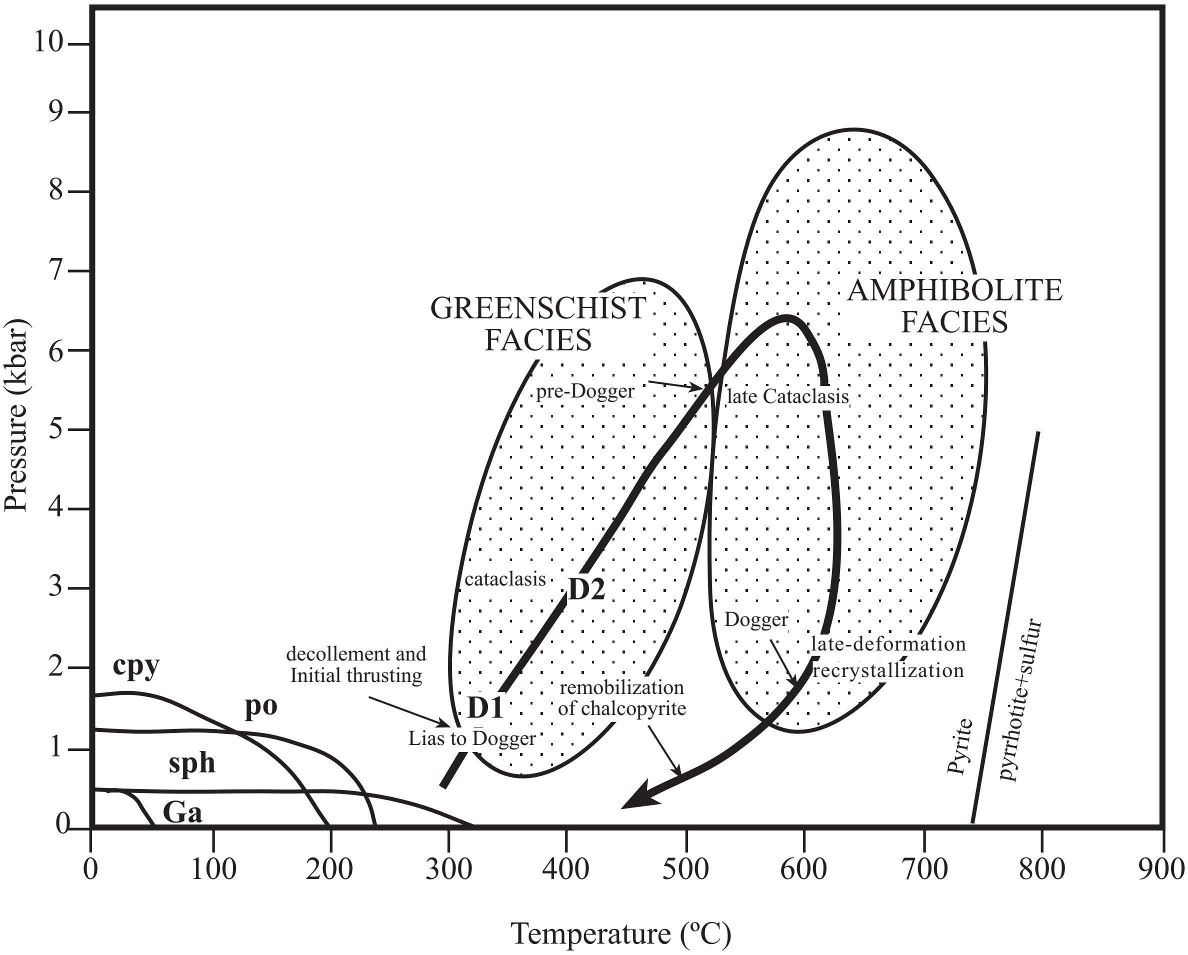

Figure 7. Diagram showing the metamorphic history of sulfides in the KVMS deposits (the P-T boundaries for phases were adapted from Marshall & Gilligan 1987; Cook *et al.* 1993).

(1986) who reported that the Akgöl Formation was metamorphosed at greenschist facies, and the fine- to medium-grained sedimentary rocks were converted into “meta-flysch sequences”. Therefore, the Akgöl Formation was re-named the “Metamorphic Akgöl Formation”. This may also imply that the ore body was also metamorphosed at greenschist facies. However, the presence of at least two sets of oblique fractures would imply that the conditions should reach 550–600°C with pressures about 6 kbars, quite higher than greenschist facies conditions. This were probably related to late cataclasis of sulfides during advanced stages of thrusting and folding (D_2), and the oriented fractures were likely caused by principal stresses acting obliquely to the sulfide (bearing) ore body. The annealing or recrystallization caused by increase in temperature gradient of the environment is probably caused by the internal accumulation of strain within the structure of pyrite at the advanced stages of thrusting and folding. However, this may also have been accompanied by the intrusion of granitic and dacitic rocks into the wall rocks of the KVMS deposits. The same event also caused some metasomatic reactions and baked zones along the contacts between dacitic rocks and basalts (Bailey *et al.* 1966). Under these conditions, some sulfides may well have been remobilized into pre-existing fractures and cavities. The remobilization of chalcopyrite into cataclastic fractures in pyrite and into micro faults and axial planes of isoclinal folds within the shaley units occurred during this stage. The brittle-ductile transition of chalcopyrite takes place below 500 bars and 200°C; this implies that for a chalcopyrite to behave plastically, the conditions of deformation should be higher than these values. In other words, the remobilization of chalcopyrite should occur just after the cessation of cataclastic deformation during which the pressure is decreased. The remobilization of chalcopyrite corresponds to the late cataclasis of other sulfides such as sphalerite and pyrrhotite.

Conclusions and Recommendations

Well-preserved deformation textures (cataclastic texture), and late-deformation textures (thermal annealing and fracture filling textures) have been recognised in the Küre district. The pressure-temperature conditions of deformation cited in this study clearly indicate that there must have been a phase of prograde metamorphism subsequent to a regional thrusting and folding of the Küre ophiolite. This deformation/metamorphism most likely occurred at lower greenschist-facies conditions. Imbricate structures (thrust faults and folds) between the Küre ophiolite and the Akgöl Formation are the most probable mechanisms in the deformation. Post-ore granitic intrusions are also present and may be considered as possible heat sources for producing annealing. However, since the distances to the intrusive contacts are not well known, annealing cannot be simply related to these intrusions. Detailed temperature and pressure determinations as well as metamorphic petrogenetic studies should be conducted on rocks from the area in order to gain a complete picture of temperature and pressure data. The remobilization of chalcopyrite into microfractures in pyrite, and chalcopyrite enrichment along the intersections of fault planes in the district, may suggest that the chalcopyrite was remobilized from its original host rocks into structurally controlled settings during late-stage deformation of the KVMS deposits. Although the fractures could not remain open under the conditions of deformation that affected the KVMS, the presence of chalcopyrite veins in pyrite, and the localization of chalcopyrite mainly at the intersections of faults would suggest that they remained open and some of the ore minerals were remobilized into these open spaces.

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