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Hydrothermal alteration of magnetic fabrics of rocks in the Xiaoban gold-bearing shear belt, Fujian Province, China

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RESUMEN

La zona de deformación de Xiaoban experimentó alteración hidrotermal a temperaturas moderadas en el Mesozoico (180 Ma). Las muestras estudiadas corresponden a unidades alteradas e inalteradas provenientes de tres niveles en la mina. Después de un estudio sistemático de las fábricas de rocas magnéticas encontramos que: 1) La susceptibilidad se debe principalmente a la presencia de minerales paramagnéticos como la biotita y la pirita. La reducción de la susceptibilidad promedio se debe a la disminución de hierro y al cambio del tamaño del mineral magnético, así como al incremento de minerales diamagnéticos. 2) Decrecimiento de la anisotropía (P) después de la alteración hidrotermal. La tendencia al cambio es la misma que la de la susceptibilidad promedio. 3) El elipsoide de AMS no cambia sustancialmente su forma después de la alteración hidrotermal, y se mantiene una esfera oblada. El eje menor de susceptibilidad axial principal (K3) cae cerca del plano perpendicular al plano de equistosidad de todas las muestras. Sin embargo, el eje mayor de susceptibilidad axial principal está sujeto a grandes cambios. Los resultados indican que los nuevos minerales magnéticos están distribuidos en el plano existente de equistosidad, pero no tienen una orientación preferencial.

PALABRAS CLAVE: Fábrica magnética, susceptibilidad, anisotropía, alteración hidrotermal, China.

ABSTRACT

Magnetic fabrics indicate that the Xiaoban shear zone underwent low-grade hydrothermal alteration in the Mesozoic (~ 180Ma). Samples studied come from altered and unaltered units from three mine levels. (1) Susceptibility is mainly due to paramagnetic minerals such as biotite and pyrite. The reduction of mean susceptibility is due to decrease in Fe content and change of magnetic mineral size, as well as increase of diamagnetic minerals. (2) Anisotropy (P) decreases after hydrothermal alteration. Its tendency to change is the same as that of the mean susceptibility. (3) The AMS ellipsoid does not substantially change its shape after hydrothermal alteration. An oblate sphere is maintained. The minimum principal susceptibility axis (K_3) falls close to the plane which is perpendicular to the schistosity for all samples. However, the maximum principal susceptibility axis is subject to large changes. The results indicate that new magnetic minerals are distributed on the existing schistosity plane, without a preferred orientation.

KEY WORDS: Magnetic fabric, susceptibility, anisotropy, hydrothermal alteration, China.

1. INTRODUCTION

Anisotropy of magnetic susceptibility (AMS) measured in weak magnetic fields can be used to express magnetic fabrics. The AMS second-order tensor is geometrically represented by an ellipsoid described by its eigenvalues K_1 (maximum susceptibility), K_2 (intermediate susceptibility), K_3(minimum susceptibility), and eigenvectors respectively presenting spatial attitude of K_1, K_2, K_3.

Factors producing AMS in rocks may be due to sedimentation, orientation of magnetic minerals according to magmatic flow, orientation recrystallization or orientation of magnetic minerals during ductile or plastic deformation. Thus measurement of AMS is useful in studying strain patterns, effect of hydrothermal alteration, etc. For example, magnetic anisotropy has been utilized in many fabric studies of shear zones (Rathore *et al.,* 1983; Goldstein and Brown, 1986; Ruf *et al.,* 1988).

Deformation re-orients an originally random distribution of magnetic grains (Hrouda, 1982). The maximum susceptibility axis is parallel to the petrographic lineation and the minimum susceptibility axis is perpendicular to foliation (Goldstein and Brown, 1986; Rathore, 1985; Kligfield *et al.,* 1983; Rathore *et al.,* 1983). The relationship between strain and magnetic anisotropy has been established in rock types from different deformed regions (Rathore, 1980; Urrutia-Fucugauchi, 1980 a, b; Kligfield *et al.,* 1983; Hrouda, 1982; Lowrie and Hirt, 1986; Housen *et al.,* 1995, Xu *et al.,* 1998).

Heating can also affect the magnetic fabric of rocks (Xu and Chen, 1998). This has been shown by many experiments and field observations (e.g. Urrutia-Fucugauchi, 1981; Kelso and Banerjee, 1991; Hirt and Gehring, 1991; Walderhaug, 1993; Fujimoto and Kikawa, 1989). Two effects have been reported when rocks (minerals) are heated. First, heated rock samples increase their bulk magnetic susceptibility, commonly due to the growth of iron oxides (Thompson and Oldfield, 1986). This makes it easy to discriminate between sedimentary, magmatic or tectonic flow patterns (Borradaile and Henry, 1997; Rochette *et al.,* 1992; Hrouda, 1982). Second, heated rock samples decrease their bulk magnetic susceptibility. Walderhaug (1993) observed that heat treatment (600°C) led to a general reduction of anisotropy in three dykes from Sunnhordland, western Norway and suggested that the reduction of magnetic grain size on heating offered a possible reason. Borradaile and Lagroix (2000) experimented on tectonites from the high-grade granulite facies in the Kapuskasing Structural Zone of northern Ontario and showed that heating enhanced the AARM (anisotropy of anhysteretic remanence) fabric and refined the AMS orientation-distribution, preserving its directions. Fujimoto and Kikawa (1989) showed that magnetic susceptibility and intensity of magnetization of pyroxene andesite lavas in the Noya geothermal area, Japan, generally had lower values of AMS in more intensely altered rocks. This was due to the decomposition of magnetite in intensely altered rocks. Jelenska and Kadzialko-Hofmokl (1990) observed that the P values and bulk susceptibility for heated felsic porphyry decreased but that those for heated limestones and sandstones increased. Those same properties changed only slightly for gabbro that was heated.

These previous studies indicate that change of AMS is dependent on type of rock, deformation of rocks, hydrothermal fluid, and so on. This paper studies the change in magnetic fabrics of tectonites, which undergo hydrothermal alteration during gold mineralization in the Xiaoban gold-bearing shear zone, Fujian province, China. This area was selected because non-weathering specimens could be obtained within the mine and multi-level sampling was possible.

2. GEOLOGICAL BACKGROUND

Xiaoban is located in the Mesozoic Coastal Volcanic Zone of southeastern China near the Zhenghe-Dapu fault system (Figure 1, Wu *et al.,* 1998; Xu, 1998). A Proterozoic group crops out in the area which consists of biotite-plagioclase leptynite, plagioclase leptynite and leptite, in which migmatization can be seen. Metamorphic schistosity planes are highly developed in these rocks. Strike is NE, dip NW or SE and dip angles are 50°-60º. A low-angle ductile-brittle shear belt is recognized in the area (Figure 2). The belt has a variable strike and a dip angle of 5°-40°. The tectonites in the belt consist of crystalloblastic mylonite, tectonic schist etc.

The shear zone underwent hydrothermal alteration and gold mineralization. There were different alteration processes such as chloritization, silication, sericitization, pyritization and calcitization. The intensity of alteration was higher in the center of mineralization.

3. SAMPLES

Within the mining region, 27 samples were collected along sections on three mining levels (505 m, 525 m, 550 m) (Table 1). Because the shear zone and the altered belt are parallel to each other and have low angles of dip, some sections are vertical. As all types of rocks can not be completely obtained in a section, 12 samples were collected in random locations (Table 2). Samples include non-altered tectonites, such as crystalloblastic mylonite, tectonic schist as well as intensely altered or weakly altered tectonites.

Samples were cut into cylinders 2.5 cm in diameter and 2.2 cm in height, and were measured using a HKB-1 Kappabridge susceptometer, working in low alternate field. Each specimen was characterized by the geographical orientations and the magnitudes of the three principal axes of its AMS ellipsoid. Theoretically, six values measured in six directions for one specimen are necessary in order to calculate eigenvalues and eigenvectors of K_1, K_2, K_3, but 15 values were measured for better accurancy. The 15 values were

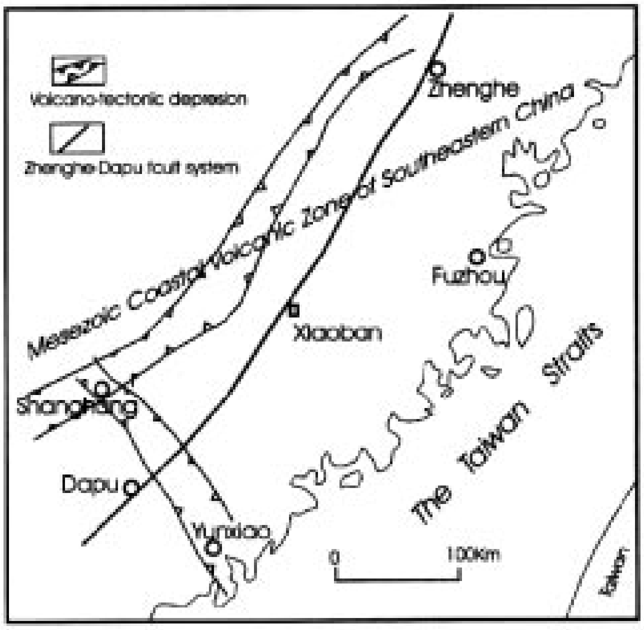

Fig. 1. Sketch map showing the location of regional structure in Xiaoban.

processed by the method of least squares and six mean values were obtained. Subsequently, eigenvalues and eigenvectors were calculated.

4. RESULTS

Mean susceptibility (K_a)

The mean susceptibility data is given in Tables 1 and 2, Figures 3 and 4. Mean susceptibility K_a goes from 30 to 1300 μSI (Tables 1, 2), but is mainly in the range of 100- 500 μSI (Figure 3). Its peak value is 100-200 μSI . This indicates that the susceptibility of rocks in the studied area is due to paramagnetic minerals (Rochette, 1987; Gleizes *et al.,* 1993) (Figure 5). Therefore the magnetic minerals may be biotite and pyrite which exist in both non-altered protolith and altered rocks in the studied region. K_a in rocks of higher intensity of alteration is lower (Figure 4). This effect is also presented by Fujimoto and Kikawa (1989). The reduction of the value of K_a could be due to following factors: (1)The content of TFe_2O_3 in non-altered protolith reaches 10% but that in altered rocks is < 3% (Wu *et al.,* 1998). Reduction of total Fe content in intensely altered rocks can be deduced by change of K_a from Figure 5. (2)It is known that susceptibility is a function of grain size and concentration of magnetic minerals, and thus the observed relation between K_a and alteration intensity could be due to one or both of these factors which can be affected by hydrothermal alteration. The smaller size of pyrite in the intensely altered rocks can be seen in thin section when observed under a microscope (Figure 6). (3) In the intensively altered rocks, altered minerals such as quartz and calcite with negative susceptibilities increase relatively at intensively altered locations. For example, the content of quartz in non-altered protolith is 25%-45%, but in altered rocks it is more than 80%.

Anisotropy degree (P)

Different authors use different parameters for studying degrees of anisotropy. The parameter $P = K_1/K_3$ is used in this paper.

For mineral grains, anisotropy degree is determined by the magnetic anisotropy of the mineral shape and the magnetic

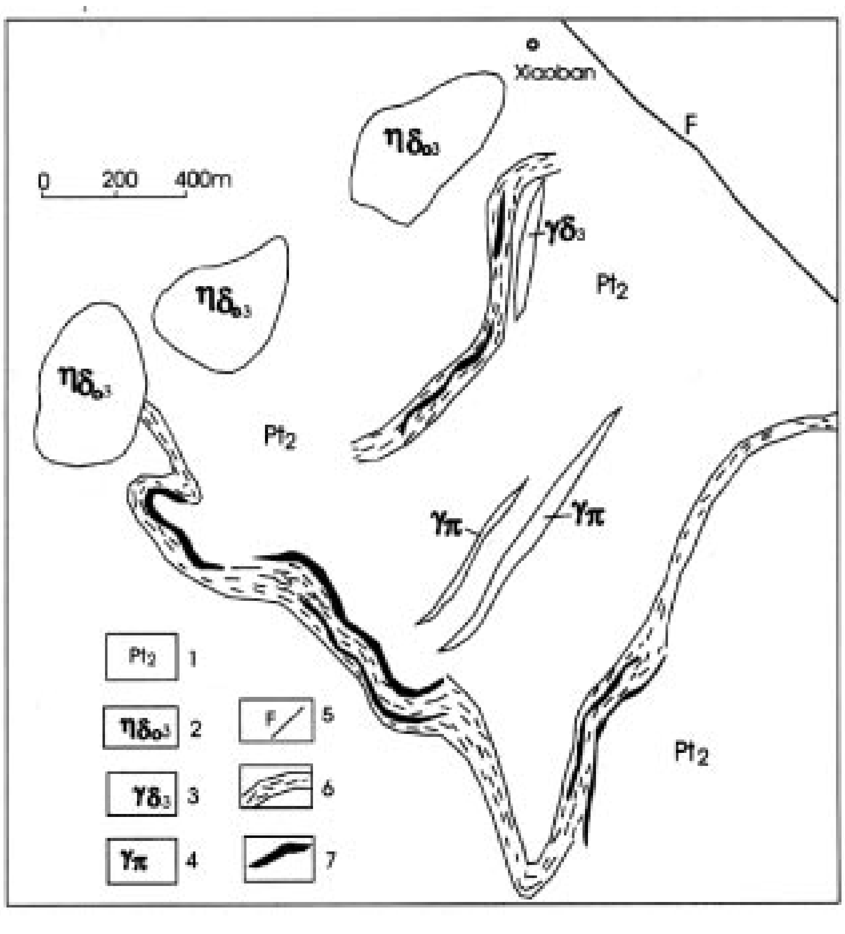

Fig. 2. Geological map of Xiaoban district. 1. proterozoic rocks; 2. monzodiorite; 3. granodiorite; 4. granite-porphyry; 5. fault; 6. shear zone; 7: gold mineralization.

Table 1

Magnetic anisotropy and fabric data from Xiaoban gold deposit

number	K_1	K_2	K_3	P	E	T	F	L	Attitude of K_1 D	Attitude of K_1 I	Attitude of K_2 D	Attitude of K_2 I	Attitude of K_3 D	Attitude of K_3 I	K_a
550 level															
1	383.7	376.8	359.5	1.0674	1.0292	0.4418	1.0481	1.0183	-18	80	245	1	155	9	373.4
2	606.3	557.5	480.3	1.2621	1.0671	0.2792	1.1605	1.0875	29	-37	24	52	117	2	548
3	613.2	576.8	567.5	1.0804	0.9562	-0.5783	1.0164	1.0630	-50	53	30	-7	114	36	585.8
4	129.4	128.7	128.4	1.0081	0.9971	-0.3465	1.0026	1.0055	265	-46	212	29	-39	28	128.8
5	689.1	661.6	584.1	1.1798	1.0875	0.5074	1.1327	1.0415	214	56	233	-32	-41	8	645.0
6	323.1	301.4	278	1.162	1.0115	0.0765	1.0841	1.0718	166	51	243	-10	145	-37	300.8
7	277.7	272.1	265	1.0476	1.0061	0.1316	1.0267	1.0204	104	61	236	20	-26	19	271.6
8	618	588.4	546	1.1318	1.026	0.2075	1.0776	1.0502	2	-30	265	-10	-20	58	584.2
9	183.8	182.0	176	1.0439	1.0245	0.5623	1.0345	1.0094	210	4	-64	-46	-54	43	180.6
10	1455	1312	1225	1.1877	0.9661	-0.2004	1.0711	1.1087	104	45	123	-42	104	9	1331
525 level															
11	660.2	647.5	573.1	1.152	1.108	0.7275	1.1298	1.0196	115	-4	205	6	57	82	627
12	293.6	282.4	262.6	1.1181	1.0343	0.3028	1.0754	1.0396	132	6	221	-12	250	75	279.6
13	396.9	388.7	371.9	1.0671	1.0236	0.3589	1.0451	1.0240	75	-10	166	-6	107	77	385.9
14	351.6	344.9	339.2	1.0365	0.9973	-0.0744	1.0167	1.0194	-25	17	63	-1	147	72	345.3
15	254	252.8	249.8	1.0268	1.007	0.4188	1.0119	1.0048	121	28	223	19	162	-54	252.2
16	216	209.9	205.6	1.0506	0.9924	-0.1529	1.0211	1.0288	65	-15	-19	17	117	66	210.5
17	1097	1035	961	1.1432	1.0167	0.1239	1.0781	1.0604	-59	27	32	3	-51.2	-61	1031
505 level															
18	755.1	742.6	725.8	1.04.3	1.0048	0.1228	1.0224	1.0175	195.1	-54.7	116.5	7.9	211.9	34	741.0
19	317.7	309.4	308.5	1.0104	0.9951	-0.4651	1.0027	1.0076	221.2	50.3	102.0	22	-2.1	31.1	309.9
20	107.1	106.0	100.5	1.0654	1.0449	0.6936	1.0551	1.0097	-51.3	25.1	58.1	35.4	191.6	44	104.5
21	454	469.3	413.1	1.1751	1.0983	0.5812	1.1360	1.0343	25.7	-58.6	65.4	25.1	-33	17.5	455.9
22	101.2	98.75	93.4	1.0845	1.0307	0.3738	1.0573	1.0257	61.4	20.5	177.9	49.9	137.4	-32	97.82
23	201.2	195	185.6	1.0851	1.0176	0.2145	1.0508	1.0326	-89.3	14.3	143	67	5	17	194
24	51	50.79	50.12	1.0174	1.009	0.5218	1.0132	1.0041	140	62	-74	23	22	14	50.64
25	30.36	30.11	29.51	1.0289	1.0117	0.4084	1.0202	1.0084	166	67	82	-2	173	-22	30.0
26	172.1	168.2	164	1.0492	1.0028	0.0580	1.0257	1.0228	55	22	-55	41	-14	-40	168.1
27	161.8	157.9	156.6	1.0328	1.0063	0.1972	1.0159	1.013	40	44	15	-43	117	-12	159.4

* Susceptibility in 1¥10^{-6} unit. $P=K_1/K_3$, $L=K_1/K_2$, $F= K_2/K_3$, $E=K_2^2/K_1\times K_3$, $T=(2\eta_2-\eta_1-\eta_3)(\eta_1-\eta_3)$, $\eta_1=\log K_1$, $\eta_2=\mathrm{Log}\ k_2$, $\eta_3=\mathrm{Log}K_3$.Ka: mean susceptibility

Table 2

Eigenvalues of magnetic susceptibility in different rocks in Xiaoban

Number	**Rocks**	**K_1(×10^{-6})**	**K_2(×10^{-6})**	**K_3(×10^{-6})**	**P**	**F**	**L**
SJ3	Tectonic schist	802.8	758.9	700	1.1468	1.0841	1.0578
SJ4		416	405.3	384.4	1.0812	1.0543	1.0264
SJ17		106.5	104.4	100.2	1.0629	1.0419	1.0201
52511		605.8	577.8	548.9	1.1035	1.0525	1.0484
52512		148.7	142	139.9	1.0628	1.0154	1.0467
YJ8	crystalloblastic mylonite	1006	1002	937.8	1.0725	1.0684	1.0039
YJ18		497.5	488.6	442.4	1.1245	1.1044	1.0182
52513		481.4	433.1	423.9	1.1354	1.0216	1.1113
52513-1		480	431.7	423	1.1348	1.0206	1.1118
52514	Altered rocks	58.1	57.64	56.96	1.0214	1.0118	1.0095
YJ13		379.6	376.2	369.9	1.0262	1.0170	1.0090
YJ20		365.9	361.6	34.47	1.0615	1.0499	1.0111

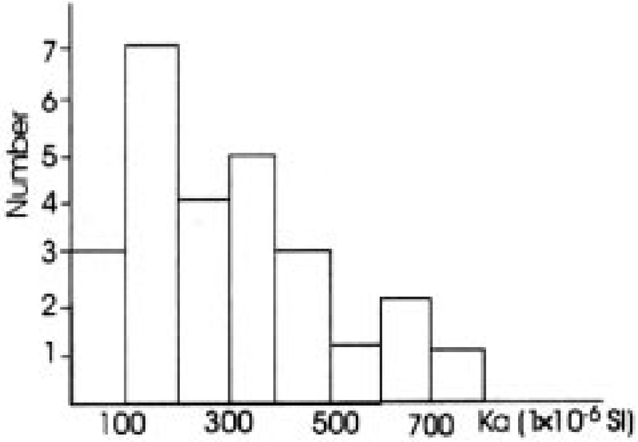

Fig. 3. Histogram of mean susceptibility of rocks in Xiaoban shear belt.

crystal. For mineral aggregate, anisotropy degree is mainly determined by the percentage of magnetic minerals.

The value of P in rocks displaying a higher intensity of alteration is lower in section 1 than section 5 (Figure 4-e). This feature of the variation of P values is the same as K_a as shown above. But there is a different variation between P and K_a in section 6 (Figure 4-f), which is due to the effect of intrusion of granodiorite. Our result is similar to that of Archanjo and Bouchez (1994), who observed that the mean magnitude of P decreases as the bulk susceptibility in the Pombal granite pluton, Brazil. A similar correlation is observed among various deformed magnetite-bearing rocks (Rochette *et al.,* 1992).

Generally, the P value is related to the intensity of deformation. A practical example was shown by Housen *et al.* (1995) (Figure 7). In our case, the P value decreases along with the altered intensity (Figures 4, 8). Park *et al.* (1988) proposed that this effect was due to anisotropy related to the tectonic stress which had been removed by thermal demagnetization. For the sake of better understanding this effect from the microstructure of rocks, we measured the paleostress of non-altered rocks and altered rocks using the method of dislocation intensity in quartz and the formula

$$\sigma = 6.6\times10^{-3}\rho^{0.5}, \qquad (1)$$

where ρ is dislocation density, and σ is paleostress.

Two samples of tectonite and one sample of altered tectonite were selected. Stress values of two tectonites are 152.37 MPa, 133.63MPa. Stress value of the altered tectonite is 113.98 MPa. This indicates that hydrothermal alteration reduced the deformation intensity of deformed rocks.

The ellipsoid shape of AMS and eigenvectors of principal susceptibility

F-L diagram can express ellipsoid shape of AMS (Figure 9-a). This diagram is similar to the Flinn diagram in structural geology. In Figure 9-a, the horizontal coordinate F is magnetic foliation, the vertical coordinate L represents magnetic lineation, and K_m = (F-1)/(L-1). The line K_m = 1 divides the plane into two parts: the part of prolate ellipsoid above the line and the part of oblate ellipsoid beneath the line. There is no evident change in the shape of the AMS ellipsoid in intensely altered rocks (Figure 9-a). Rocks before and after alteration preserve the oblate shape of their AMS ellipsoid. Another diagram for describing the ellipsoid shape of AMS is shown in Figure 10-b, in which the region above the horizontal axis represents an oblate ellipsoid and the

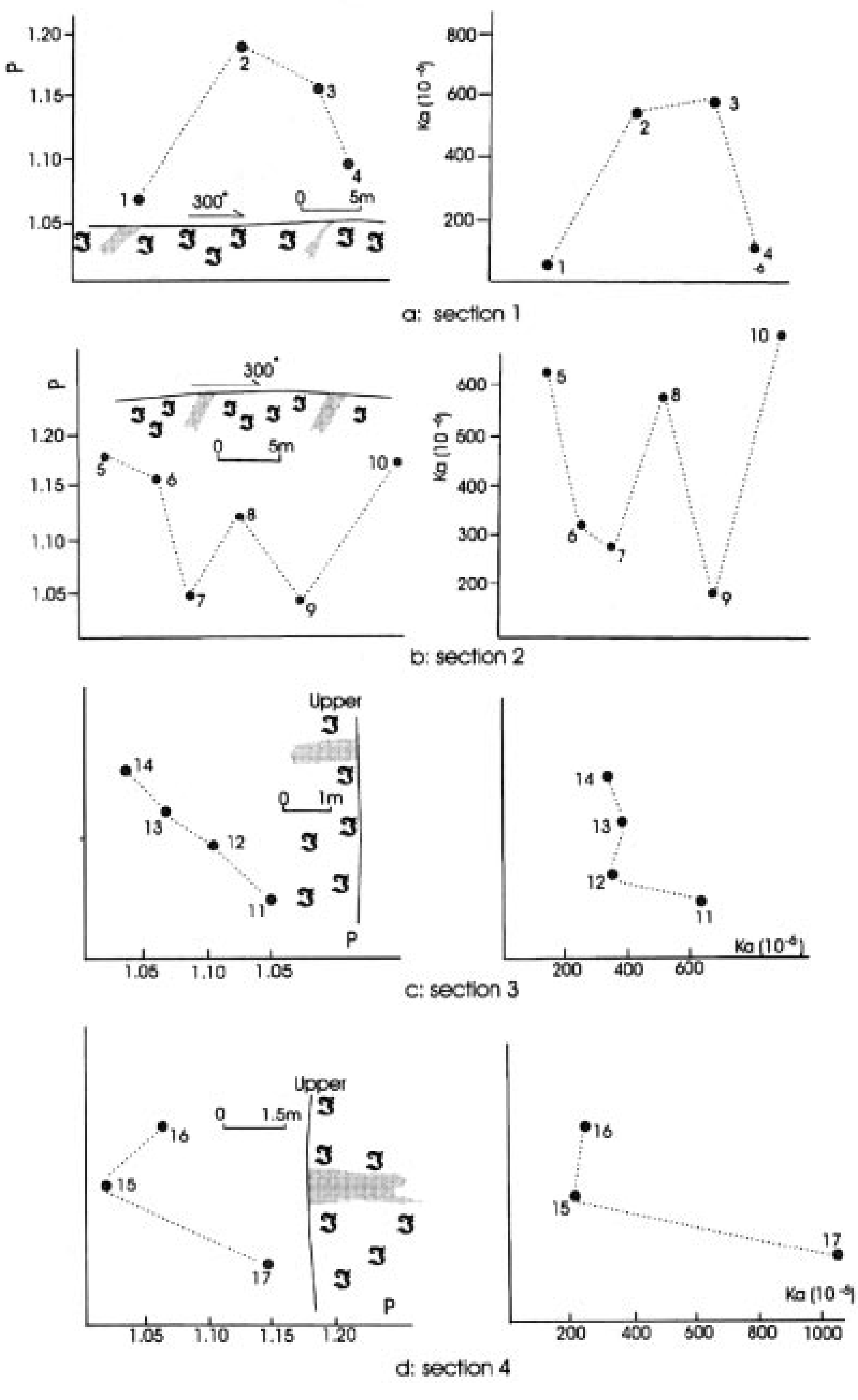

Fig. 4. Maps showing the anisotropy degree (P) and the mean susceptibility of rocks along sections in Xiaoban.

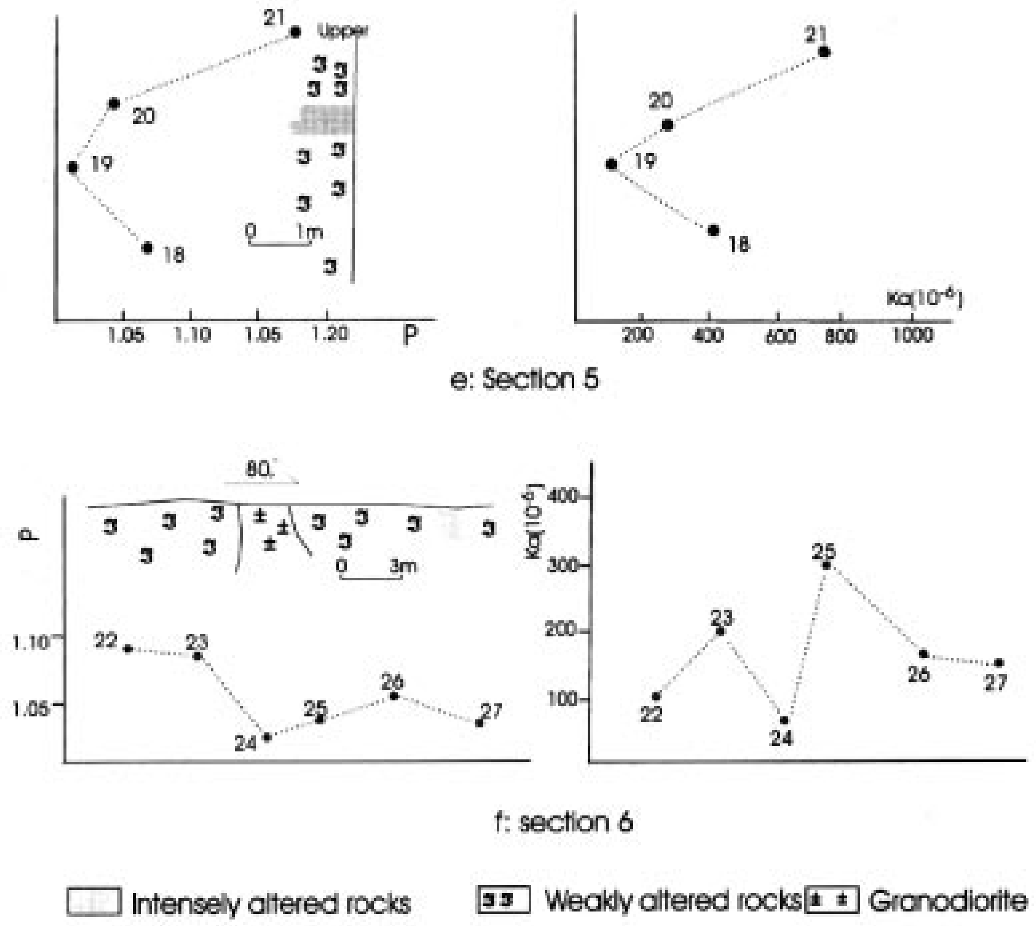

Fig. 4. Continued.

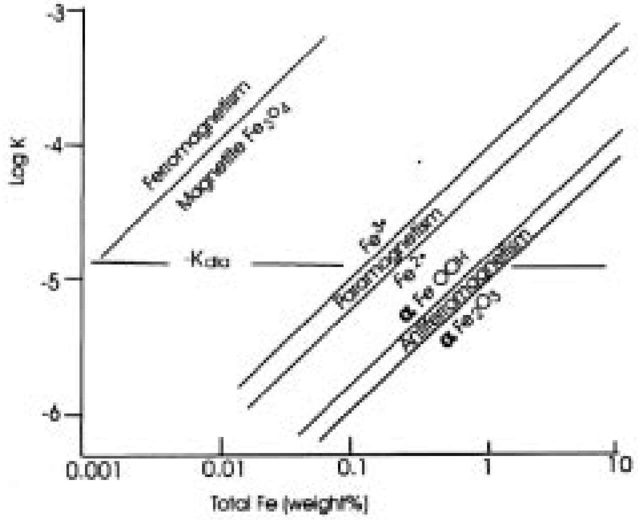

Fig. 5.Magnetic susceptibility in low field as a function of their Fe contents for different mineralogies (from Rochette, 1987).

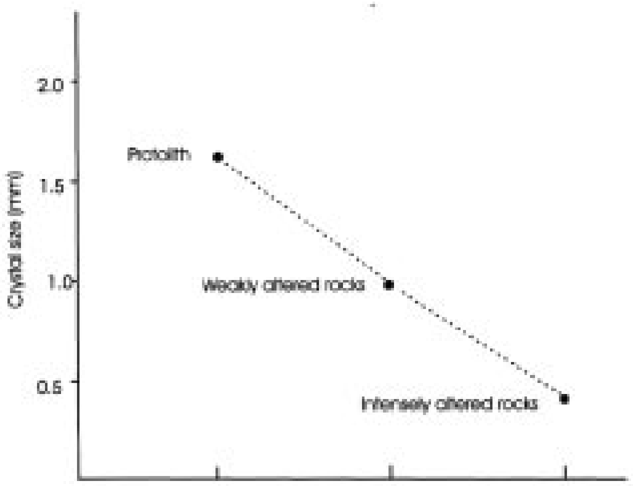

Fig. 6. Curve showing crystal size in different rocks.

region below the horizontal axis represents a prolate ellipsoid. Note that the same conclusion can be obtained from Figure 9-b. These results indicate that the AMS is modified, but not destroyed during hydrothermal alteration.

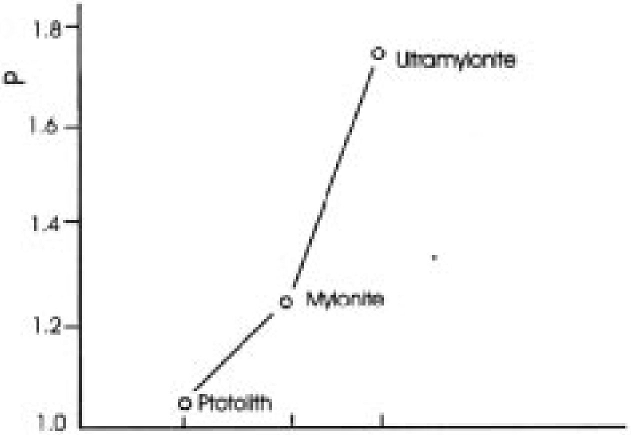

Fig. 7. Curve of P value in different rocks which have different deformation intensity (data from Housen *et al.,* 1995).

The minimum principal susceptibility axis (K_3) falls close to the plane perpendicular to schistosity plane (Figure 10), i.e. altered rocks maintain the main feature of tectonic rocks (Goldstein and Brow, 1986; Rathore, 1985; Kligfield *et al.,* 1983; Rathore *et al.,* 1983). However, the maximum principal susceptibility axis is subject to large changes (Tables 1, 2). This indicates that the new magnetic minerals distribute on the previous schistosity plane, but have no preferred orientation. The same phenomenon was observed in the Pinaleno mountains, Arizona by Ruf *et al.* (1988) and in flume experiment for sands and silts by Rees and Woodall (1975). Our result may indicate that fluid during alteration is under a lower stress state and flows along previous structural planes, which is somewhat similar to flume experiment of Rees and Woodall (1975). Chemical remnant magnetization direction of new minerals should be along the original thermoremnent magnetization direction (Marshall and Cox, 1972).

5. DISCUSSION

(1) According to experiments by previous authors (e.g. Urrutia-Fucugauchi, 1981; Perarnau and Tarling, 1985; Jelenska and Kodzialko-Hofmokl, 1990), magnetic susceptibility Ka generally increases after heating and hence the anisotropy of magnetic susceptibility may also be increased. But our results lead to an opposite conclusion. The probable reasons are: (a) Laboratory heating is performed under dry conditions without fluidization whereas large quantities of fluids are present during hydrothermal alteration; (b) The physicochemical conditions during laboratory heating and hydrothermal alteration are different. LogfO_2 during hydrothermal alteration in the Xiaoban gold deposit is –40, which indicates a reducing environment. However, laboratory heating is performed in an oxidising environment; (c) The temperature in the laboratory is usually above 600°C (e.g. Urrutia-Fucugauchi, 1981; Perarnau and Tarling, 1985), which is much higher than that of hydrothermal alteration in Xiaoban gold deposit.

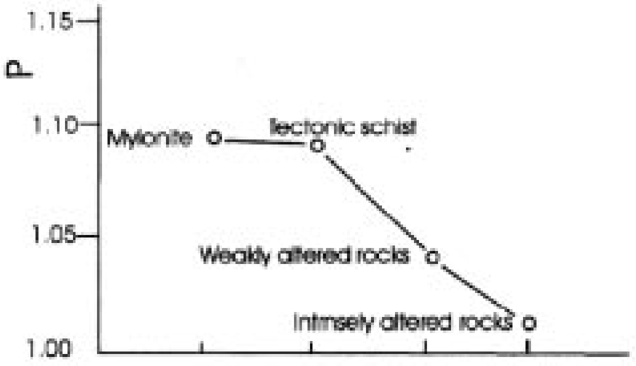

Fig. 8. The change of P values of rocks in Xiaoban shear zone.

(2) Walderhaug (1994) reported that the heated specimens close to dyke margins retain their original axis directions. He explained that when heating to a temperature below 400°C, this may be due to the removal of secondary anisotropy related to tectonic stress. Above 400°C, alteration of magnetic minerals and formulation of new magnetic phases in low-stress environment further contributes to a lowering of anisotropy. Urrutia-Fucugauchi (1981) showed that the direction of eigenvectors of AMS slightly changes up to 300°C, but largely changes stronger at 400°C and 500°C. Similar results were obtained by Jelensk and Kadzialko-Hofmokl (1990). Urrutia-Fucugauchi (1981) observed that, although the heated fabric contained a greater component of the "sedimentary" fabric than the unheated fabrics, both the initial and heated fabric shapes had similar axis directions. Fujimoto and Kikawa (1989) considered that altered titanomagnetites at low temperature (<150°C) have nearly the same characteristics as low temperature oxidized titanomagnetite.

In the Xiaoban ore deposit, the temperature of alteration is not high and peaks at 210°C- 230°C. Considering the geothermal gradient, ambient temperature is about 45°C - 55°C at a depth of 1.48-1.81km. The temperature during alteration is therefore increased by 150°C-190°C. The low temperatures at which this alteration occurred may explain why the shape of the AMS ellipsoid changed little.

In brief, AMS is dependent on many factors such as temperature, deformation, chemistry of rocks etc. Alteration is a chemical and mineralogical response of rocks to hydrothermal fluid and a complex process controlled by many factors such as temperature, chemistry of fluid, hydrodynamic condition, properities of original rocks, the fluid/rock ratio and so on.

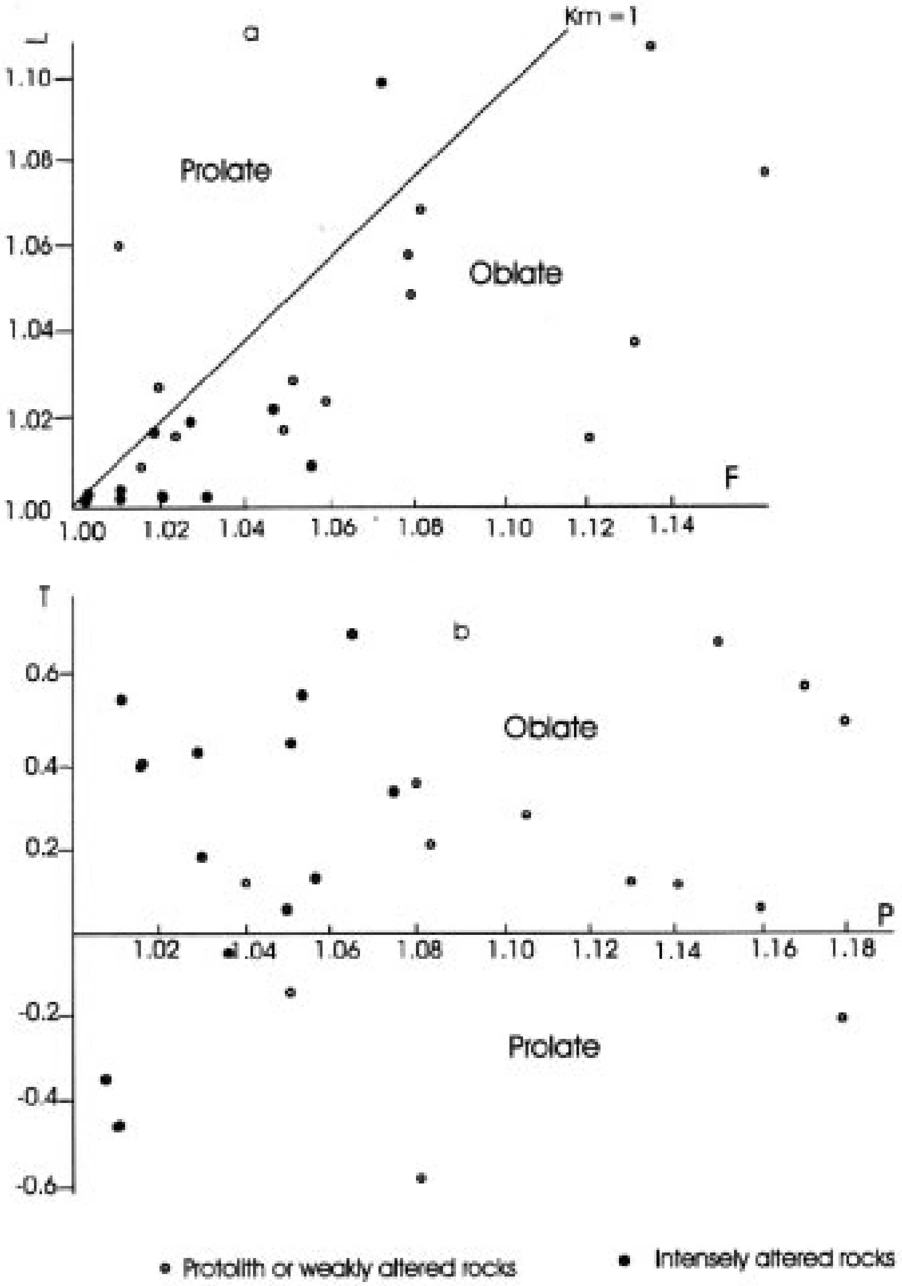

Fig. 9. Diagram of T-P and F-L.Explanation see text.

6. CONCLUSIONS

The Xiaoban shear zone was developed in Proterozoic metamophic rocks. The zone consists of crystalloblastic mylonite, tectonic schist etc, which underwent hydrothermal alteration (mineralization). After systematically studying the magnetic fabrics of rocks before and after hydrothermal alteration, we draw the following conclusions.

(1) The susceptibility is mainly due to paramagnetic minerals such as biotite and pyrite. The reduction of mean susceptibility is because of a decrease in Fe content and changes in magnetic mineral size, as well as increases in the quantity of diamagnetic minerals.

(2) Anisotropy (P) decreases due to hydrothermal alteration. Anisotropy related to tectonic stress was removed by thermal demagnetization. Practical stress measurement indicates that paleostress values decreased in altered rocks.

(3) The shape of the AMS ellipsoid changes little after hydrothermal alteration. That is to say, the ellipsoid in most of the altered rocks maintained an oblate ellipsoid shape, although the maximum principal susceptibility axis

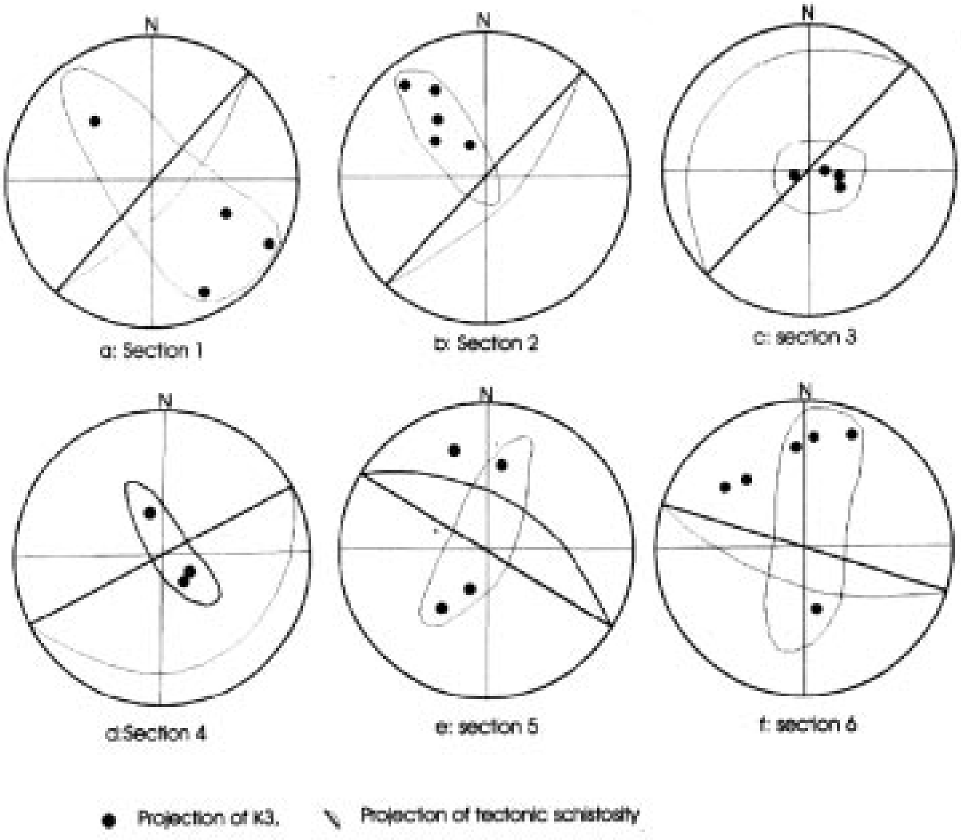

Fig. 10. Diagram of projection showing minimum susceptibility axis (K_3) and tectonic plane. Low hemisphere projection is used.

is subject to large changes. The reason for this may be that the temperature was low during alteration.

(4) The direction of the minimum principal susceptibility axis (K_3) falls close to the plane perpendicular to the schistosity plane. The direction of the maximum principal susceptibility axis changes dramatically however. This indicates that new magnetic minerals distribute on the existing schistosity plane, but have no preferred orientation.

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