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ROCK MAGNETISM OF THE KOHISTAN ISLAND ARC, PAKISTAN

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ABSTRACT

In Northern Pakistan a section of island arc crust is exposed in Kohistan, northwest Himalaya. To better understand how magnetism and magnetic mineralogy depend on metamorphism, we have sutdied, by means of field and laboratory investigations, crystalline rocks of the Kohistan island arc. Our results are based on susceptibility and sampling traverses over 500 km in length, and rock magnetic and petrograhic study of collected samples. Measurements and sampling concentrated on two profiles through Kohistan, one following the Swat River, the other following the Karakorm Highway. Of the lithologies sampled along these two profiles, the main sequence of interest consists of rocks of the Kohistan island arc. With the exception of volumetrically-minor serpentinized ultramafic rocks, the magnetic lithologies are pyroxene granulite, and gabbro-norite of the Chilas complex. Amphibolites, garnet granulites, metasupra-crustals and Kohistan arc diorites and granites are only weakly magnetized. The same is true of Karakoram batholith granitoids. As far as prograde metamorhism of moderate to high-grade mafic rocks in the section is concerned, magnetic pyroxene granulites are strongly magnetized, relative to amphibolite facies equivalents and garnet granulites. Considering all lithologies, the calculated Koenigsberger's ratios are generally less than 2 (110 of 127 samples), commonly less than 1 (89 samples), and rarely in excess of 10 (3 samples), which indicates that the magnetization of these rocks is rarely dominated by remanence. The directions of natural remanent magnetization (NRM) are scattered, with a mean declination not far from zero, and a positive mean inclination. Petrographic and electron microprobe study of mineral assemblages and textures related to retrogressive metamorphism of pyroxene and garnet granulites shows that amphibolite facies overprinting along planar zones was an Fe-Ti oxide-consuming event. Lamellae of magnetite in magnetite-ilmenite intergrowths were replaced by silicates during retrogressive metamorphism of the pyroxene granulites. Regional-scale magnetic structure in this part of the crust is defined by magnetic contrasts between the Chilas complex and the surrounding Kamila amphibolites and Kohistan granites and diorites.

INTRODUCTION

A component of current research on the continental crust and lithosphere of the earth includes efforts to determine the magnetic properties and magnetic mineralogy of rocks at depth. Studies of high-grade rocks exposed at the surface form a cornerstone of this endeavour and at the present time our interest lies in a section of the earth's continental crust that is exposed in Kohistan, NW Himalaya of Pakistan. While other sections do exist and have been, or are currently being studied, the Kohistan section is of interest because the cross-section appears to be nearly complete, the high-grade lithology is mafic garnet granulite, and the age of formation and metamorhism is relatively recent, c. ~40-100 m.y. ago (versus the Proterozoic and Archean terrains that have been at the focus of most similar types of studies). Additionally, there is a fair amount of published work on the geology, geochronology, petrology and mineralogy on rocks from this section. Ultimately, the focus of our research is to obtain results that can be used to constrain geological/geophysical models of the crust at depth in the continents, and offer a better geological interpretation of regional magnetic anomalies associated with structure in the deep crust, and, local magnetic anomalies in basement terrain. From this study of young mafic-intermediate composition island arc crust we can add to our knowledge about the magnetic signature(s) of crustal composition, plate tectonic evolution, and perhaps crustal age. Indeed, there is much to be learned about the earth's crust through study of its magnetization and its manifestation in magnetic anomalies.

A recent model for crustal evolution in Kohistan (Coward et al., 1987) proposes the following sequence of events.

Collision of the Kohistan arc with the Asian plate along a northern suture, c. 90-100 m.y. ago (obduction).

Development of the calc-alkaline Kohistan batholith related to Andean-type subduction, c. 80 m.y. ago.

Collision of the Indian continent with rocks of the Kohistan arc.

Geologically, Kohistan is a relatively young province. Within Kohistan a great thickness of layered mafic intrusives is found, metamorphosed in places to garnet granulites — the Chilas and Jijal complexes (Jan and Howie, 1981; Bard, 1983) (Fig. 1). The structure is more complicated than originally thought, due in part of multiple folding of the section, as pointed out by Coward et al., 1982. Furthermore, metamorphism and plutonism related to obduction, Andean-type subduction and continent-continent collison (Khan et al., 1989) complicate the interpretation. In part, it is because of the structural complexity and metamorphism that there is much to be learned from rocks in Kohistan.

There are a number of issues that we seek to investigate by means of this study. The results presented below are cast in the light of the following questions.

1) **How do magnetic properties and magnetic mineralogy vary with position in the crustal section exposed in Kohistan and do these variations reflect the evolution of the terrain?**

Metamporphism is known to have an effect on magnetic mineralogy and magnetic properties of high-grade rocks (e.g., Larson, 1981; Schlinger et al., 1985). Consequently, vari-

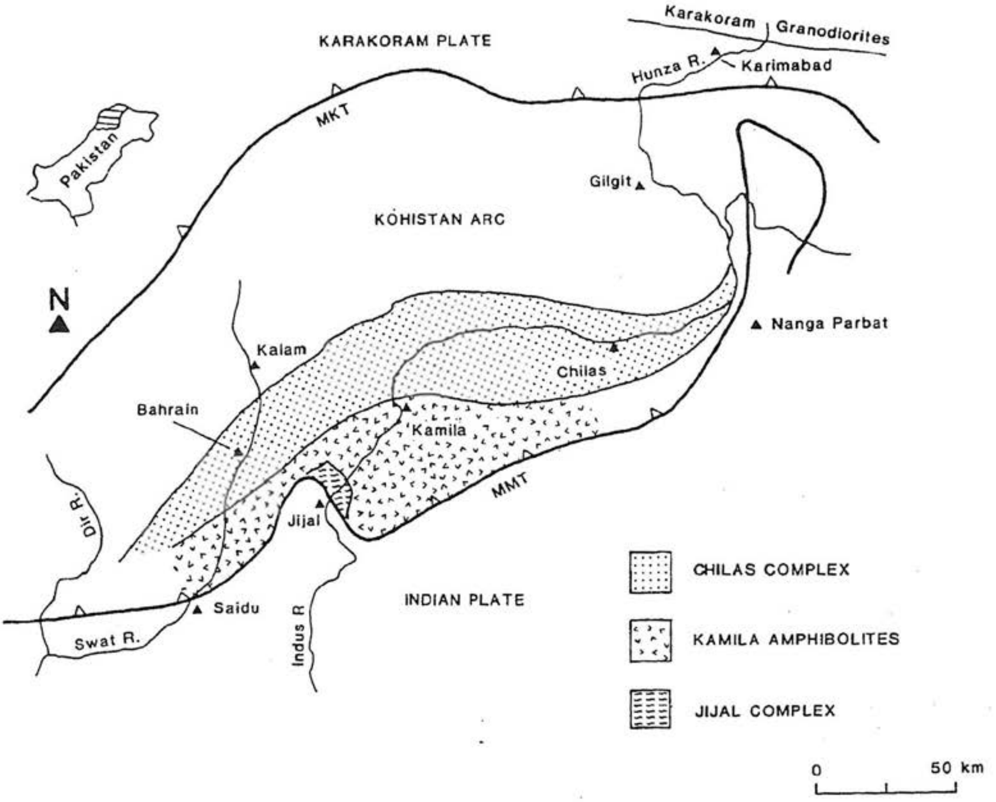

Fig. 1. Geological map of Kohistan. Modified from Khan et al. (1989). Rocks of the Kohistan complex lie between the MMT (main mantle thrust) and MKT (main Karakoram thrust).

ations in magnetization can be related to the metamorphic evolution of a particular portion of the crust. Measurement of the magnetic properties and magnetic mineralogy in the Kohistan section provide an indication of variations that might be expected in continental crust of petrologically similar but tectonically undisturbed areas. Furthermore, the tectonic environment in which a volume of the crust forms and equilibrates presumably has a magnetic signature; through systematic study of regions with different tectonic histories an answer to this question may be arrived at. This is an especially important problem in Kohistan, where the present magnetic mineralogy may to a large degree reflect metamorphic recrystallization during obduction and continent-continent collision subsequent to the formation of the Kohistan arc. Additionally, because magmatic and metamorphic conditions in the deep crust depend on fluids, in part, and since conditions at depth in the earth may have evolved from relatively oxidizing to relatively reducing during the 4.5 billion years of earth history, the age of a particular portion of the crust may be reflected in its magnetization. Finally, the mean composition of rock has an effect on the magnetic mineralogy and magnetization; this should be manifested on a variety of scales, from outcrop to crustal. The intermediate-mafic-composition crust of the Kohistan arc is an appropriate laboratory for exploring these and a variety of other issues. Of primary interest are the variations of magnetic mineralogy and magnetic properties in mafic compositions, ranging in metamorphic grade from greenshist to garnet granulite.

2) What are the petrologic sources of magnetic anomalies in Kohistan and elsewhere?

A consensus of various studies (e.g., Wasilewski and Fountain, 1982; Wasilewski and Mayhew, 1982; Schlinger, 1985; Williams et al., 1986; Wasilewski and Warner, 1988) is that the sources of regional magnetic anomalies often lie in the deep or middle-lower crust. Rock magnetic data on mafic garnet granulites and amphibolites in the Kohistan section provide additional constraints for geological and geophysical models of these sources. By means of petrological and magnetic studies, we can refine our ideas about where in the crust these sources are apt to lie, e.g., lower versus middle crust, and in what sorts of rocks such sources may be anticipated, e.g., amphibolite versus granulite sources for mafic compositions. Additionally, the interpretation of small-scale local magnetic anomalies requires rock magnetic constraints that can be gained from such studies.

Results of ongoing work on the magnetism and magnetic mineralogy, or magnetic petrology, of rocks from Kohistan can be interpreted with the above question and issues in mind. Beforehand, a few comments about the prior work on magnetic properties of Kohistan rocks are in order. The only published study that we are aware of is that of Malinconico (1982). In his study of the Himalayan suture zone in Pakistan using gravity and magnetic data, Malinconico reports susceptibilities based on an unstated number of measurements. The data for different petrologic groups were often combined together in determining averages and it is impossible to determine petrologic variations with, for example, metamorphic grade, or composition (mafic pyroxene granulite versus granites and diorites) from the published data. Finally, the NRM intensity, Koenigsberger ratio, or magnetic mineralogy were not established for the samples.

FIELD AND LABORATORY STUDIES

Regional Geology

For the purposes of this paper, a concise review of the regional geology and main petrologic units witll be of use. In this section we draw upon published work on Kohistan, including work by: Bard, 1983; Coward et al., 1987, 1982; Hamidullah and Jan, 1986; Ivanac et al., 1956; Jan, 1988, 1983, 1979 a,b,c; Jan and Howie, 1981, 1980; Khan et al., 1989; Petterson and Windley, 1986; Tahirkheli, 1979a,b.

Magnetic measurements, sampling and laboratory study focussed on two profiles, discussed in detail below, running approximately north-south and perpendicular to the strike of the Kohistan arc, which is approximately east-west (Fig. 1). There is a not a simple increase or decrease in metamorphic grade moving from the south to the north. Beginning in the south, just above the Main Mantle Thrust (MMT), which separates Kohistan arc rocks from the Indian Plate to the south, one encounters rocks of the Jijal-Patan complex, a ~150 km^2 wedge of ultramafic rocks and garnet granulites. Moving north, there is an extensive zone known as the Kamila amphibolite belt, extending E-W for several hundred km and N-S for 20-40 km. Continuing on, one crosses a thick lopolithic body of pyroxene granulite of noritic composition, known as the Chilas complex, which is up to 40 km wide and over 300km long. Progressing further north, there is the Kohistan-Ladakh belt of calc-alkaline plutons. Finally, before crossing the Main Karakoram Thrust (MKT) fault, one passes through the Yasin sediments and

Chalt volcanics, which have been metamorphosed at low to moderate grades. Crossing the MKT, one leaves the Kohistan complex, and encounters (meta) sediments of the Karakoram plate, with Karakoram granitic belt in the south and Khunjerab-Wakhan-Tirichmir granites in the north.

The pyroxene granulites of the Chilas complex are thought to represent the base of the Kohistan (-Ladakh) island arc. The granulites of the Jijal-Patan complex may be related to the Chilas complex. The calc-alkaline plutons consist of rocks thought to represent the upper part of the island arc, together with rocks thought to be indicative of later Andean-type subduction at the margin of the Asian plate (formed after obduction of the Kohistan arc). The Yasin Sediments and Chalt Volcanics are thought to be representative of uppermost crustal ligholo-gies of the Kohistan arc.

Methods and Procedures

Fieldwork for this project was conducted during the spring of 1988 and consisted of magnetic susceptibility measurements and collection of oriented cores along two profiles crossing the Kohistan arc. The majority of emphasis was placed on a profile following the Karakoram Highway, which took us along the Indus, Gilgit and Hunza rivers, from Jijal to about 50 miles east of Karimabad, in Hunza (Fig. 1). A shorter profile followed the main road that parallels the Swat river in Swat Kohistan, from Mingora (Saidu) to just below Kalam (Fig. 1). Magnetic susceptibilities were measured in the field, primarily with a Bartington MS2 susceptibility meter and on a few occasions with an EDA K2 susceptibility meter. Over 700 measurements were made. Locations along the profiles were obtained by means of odometer mileages, which have been converted into distances along the Karakoram Highway, relative to Jijal, in Indus Kohistan, and distances relative to Bahrain, along a road that parallels the Swat River, in Swat Kohistan. Standard-size oriented cores were taken using portable core drills; orientations were obtained using both solar and magnetic compasses.

Thus far, we have measured the magnetic properties of 127 samples, the majority of which (116) are in the form of oriented cores. Unoriented block samples constitute the remainder. Magnetic susceptibility, NRM intensity and direction, and the Koenigsberger ratio (Q) were determined for each sample. A Molspin spinner magnetometer was used for measurements of NRM intensity and directions. This magnetometer has been calibrated using a synthetic calibration specimen supplied by the manufacturer and by means of interlaboratory comparison of magnetic moments of this specimen and other natural specimens. The orientations obtained by means of sun compass differ little from orientations obtained with the magnetic compass. Consequently, absolute NRM directions were obtained by correcting for variable drilling orientations using the magnetic compass orientation information alone. Magnetic susceptibilities were measured in the laboratory with a Sapphire Instruments SI-2 susceptibility meter, calibrated with MnO_2.

Polished thin sections of the above-described samples were made and the silicate and oxide mineralogy were examined in transmitted and reflected light. Fe-Ti oxides and mafic sillicates of selected samples have been analyzed with a Cameca SX-50 electron microprobe.

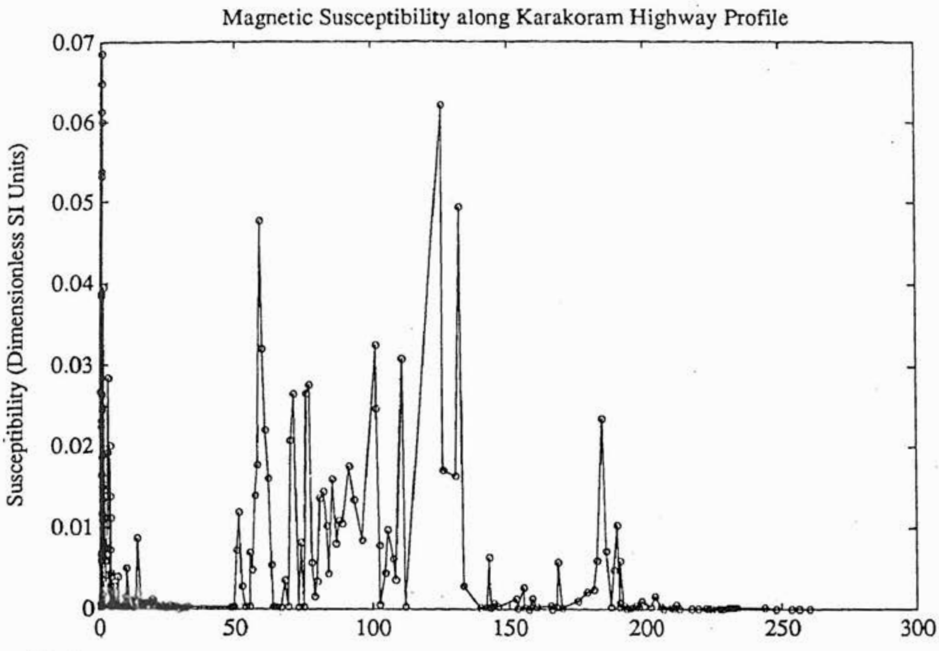

Fig. 2a.

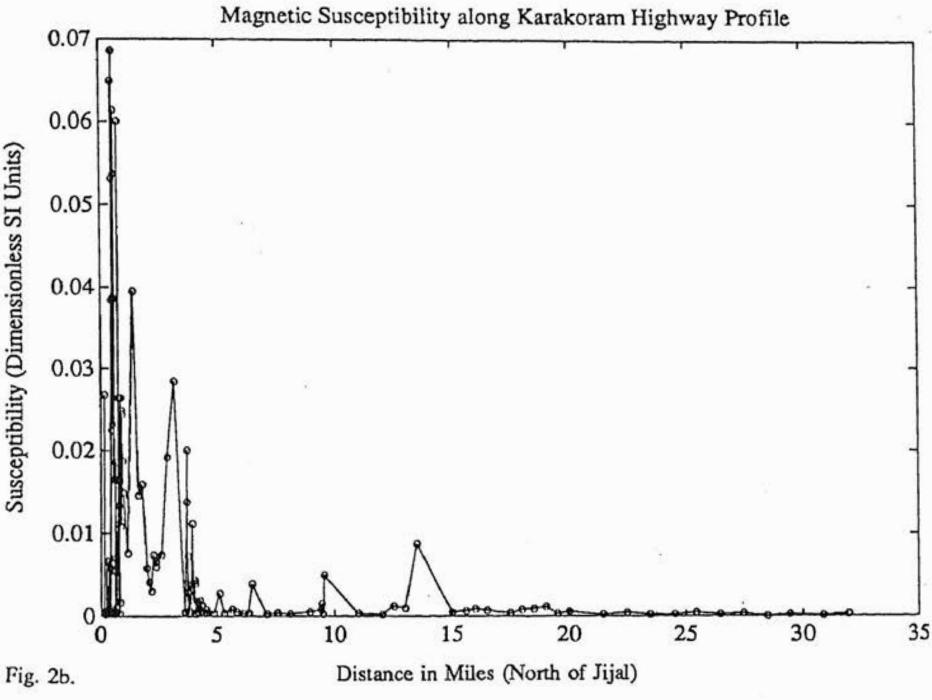

Fig. 2b.

Fig. 2. a) Magnetic susceptibility as a function of distance along the Karakoram Highway (0 is Jijal) profile. b) and c) are magnifications of profile a).

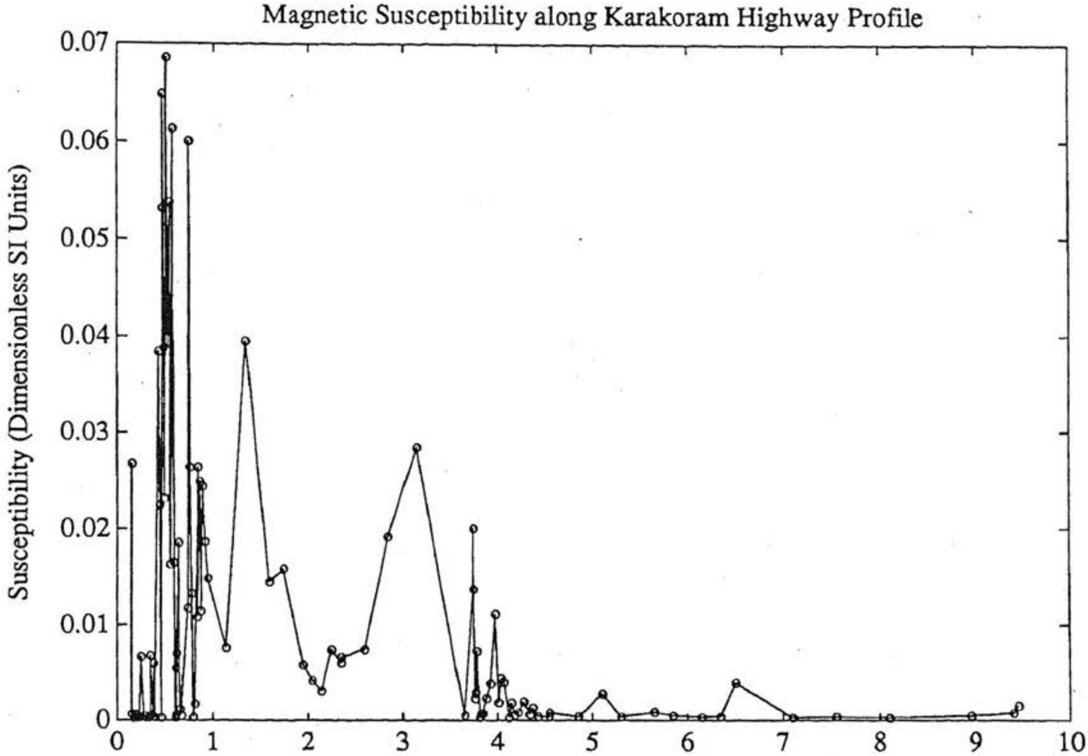

Fig. 2c. Distance in Miles (North of Jijal)

RESULTS

The observed susceptibility variations along the traverses through Indus Kohistan and Swat Kohistan are shown in Figures 2 and 3. The high-frequency high-amplitude variations observed near Jijal (0 km in Fig. 2) are from ultramafic rocks, with susceptibility generally an indicator of the amount of fine-grained magnetite produced during serpentinization. The ultramafic rock group has the highest susceptibility of all lithologies in Kohistan, however, this rock type is volumetrically minor. Moving north from Jijal, the garnet granulites (mileage 4 to 8 in Fig. 2) have low susceptibilities. The Kamila amphibolites (mileage 8 to 33 in Fig. 2; mileage -31 to -10 in Fig. 3) have uniformly low susceptibilities, generally less than 10^{-3} (SI dimensionless units). This is true both in an absolute sense, and more importantly, it is true reltive to their granulite-facies equivalents, pyroxene granulites of the Chilas complex (mileage 50 to 130 in Fig. 2; mileage -9 to +10 Fig. 3). Finally, diorites, granites supracrustal and metasupracrustal rocks of the Kohisan arc (mileages 130 to 220 in Fig. 2) generally have small magnetic susceptibilities relative to the pyroxene granulites of the Chilas complex, although high susceptibility is found in an amphibole-poor quartz-rich magnetite-bearing rock(s) of the Chalt Volcanic group. Low susceptibilities are found in Chalt metabasalts with high amphibole content. Rocks northward of the Kohistan arc (north of the MKT in Fig. 1), including Karakoram batholith granites, have uniformly low susceptibilities (mileages greater than about 220 in Fig. 2).

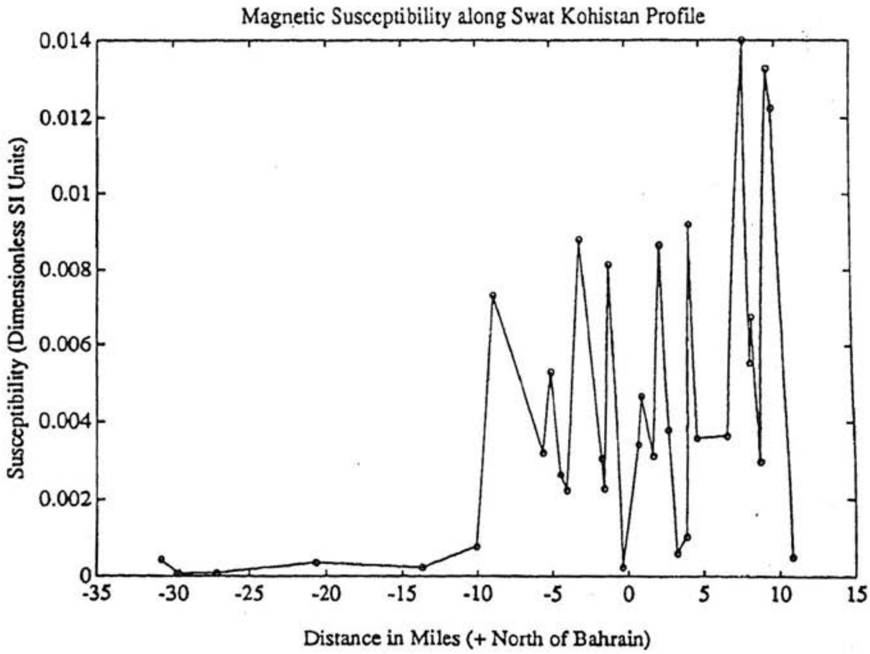

Fig. 3. Magnetic susceptibility as a function of distance along highway paralleling the Swat River, in Swat Kohistan.

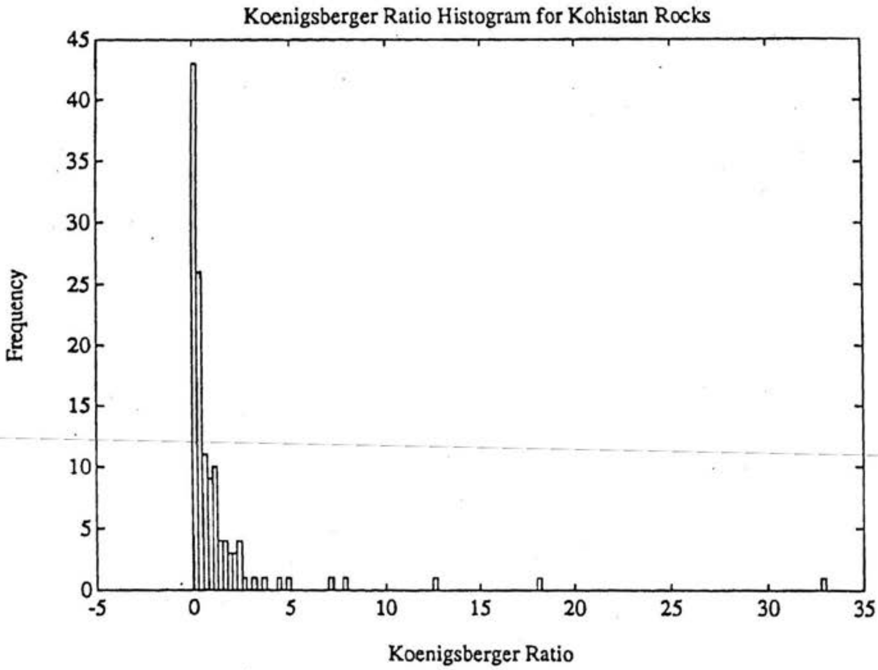

Fig. 4. Histogram of Koenigsberger ratios for Kohistan rocks. Total number of samples: 127. Inducing field: 50.6 μTesla.

A parameter used to assess the importance of remanent magnetization in total rock magnetization is the Koenigsberger ratio, or Q, defined as the ratio of NRM intensity to the induced magnetization, using an inducing field appropriate for Kohistan (40.27 A/m or 50.6 μTesla). A histogram of the Koenigsberger ratios for the 127 collected samples is given in Fig. 4. Data for two unoriented Jijal complex serpentinite samples with Q of 18 and 33 are included in this plot. The mean value is 1.3 and the median is 0.4. Q is generally less than 2 (110 samples of 127), commonly less than 1 (89 of 127), and rarely greater than 10 (3 of 127). Therefore, NRM does not dominate the magnetization of these rocks. High Q (>3) is found for rocks of the Jijal complex and for some of the Chalt volcanics. Both Kohistan arc and Karakoram intrusives (granites and diorites) generally have Q less than 1 (16 of 17 samples); serpentinized ultramafics of the Jijal Complex typically have Q much greater than 1; Kamila amphibolites have Q less than 1; pyroxene granulites (norites) generally have Q less than 2 and high susceptibility norite generally has Q less than 1.

The NRM intensities and directions obtained for the 116 oriented samples are initial values, corrected only for field orientation, with no thermal or alternating field demagnetization applied; neither was demagnetization applied to the 11 unoriented samples. Fig. 5 is a histo-

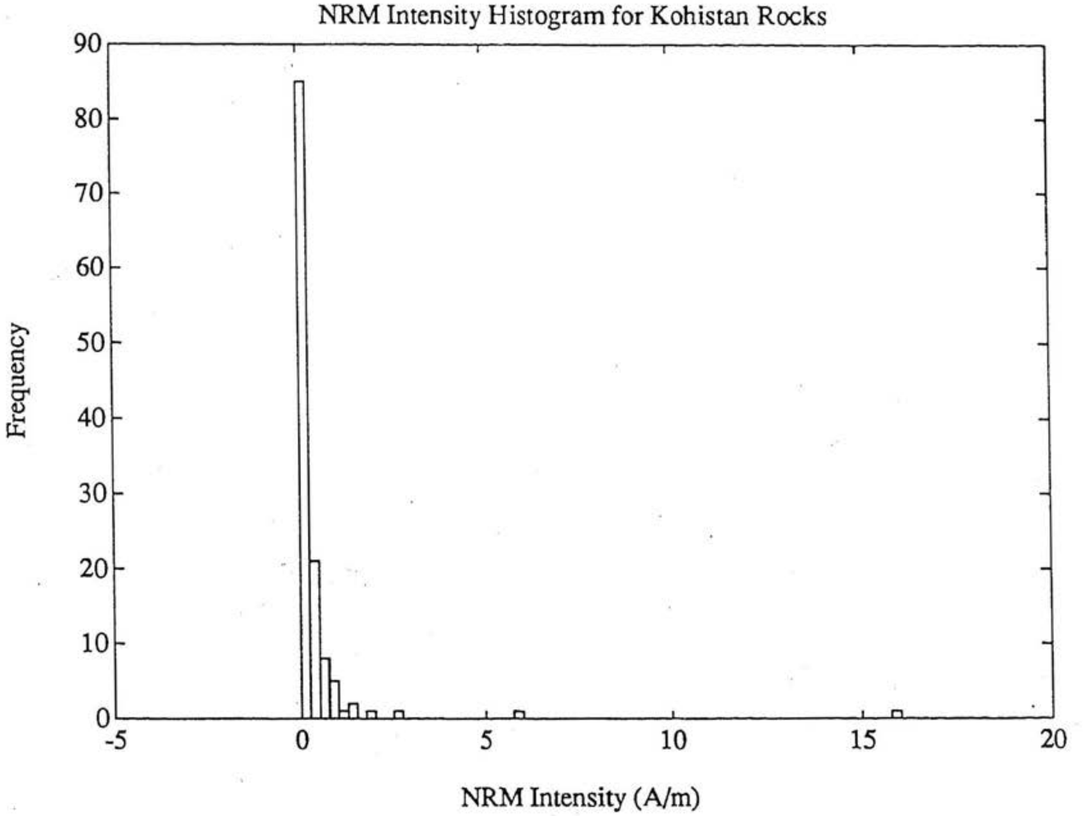

Fig. 5. Histogram of NRM intensities for Kohistan rocks. Total number of samples: 126. One data point for Jijal Complex serpentinite sample 3-1 (NRM of 148 A/m) has not been included.

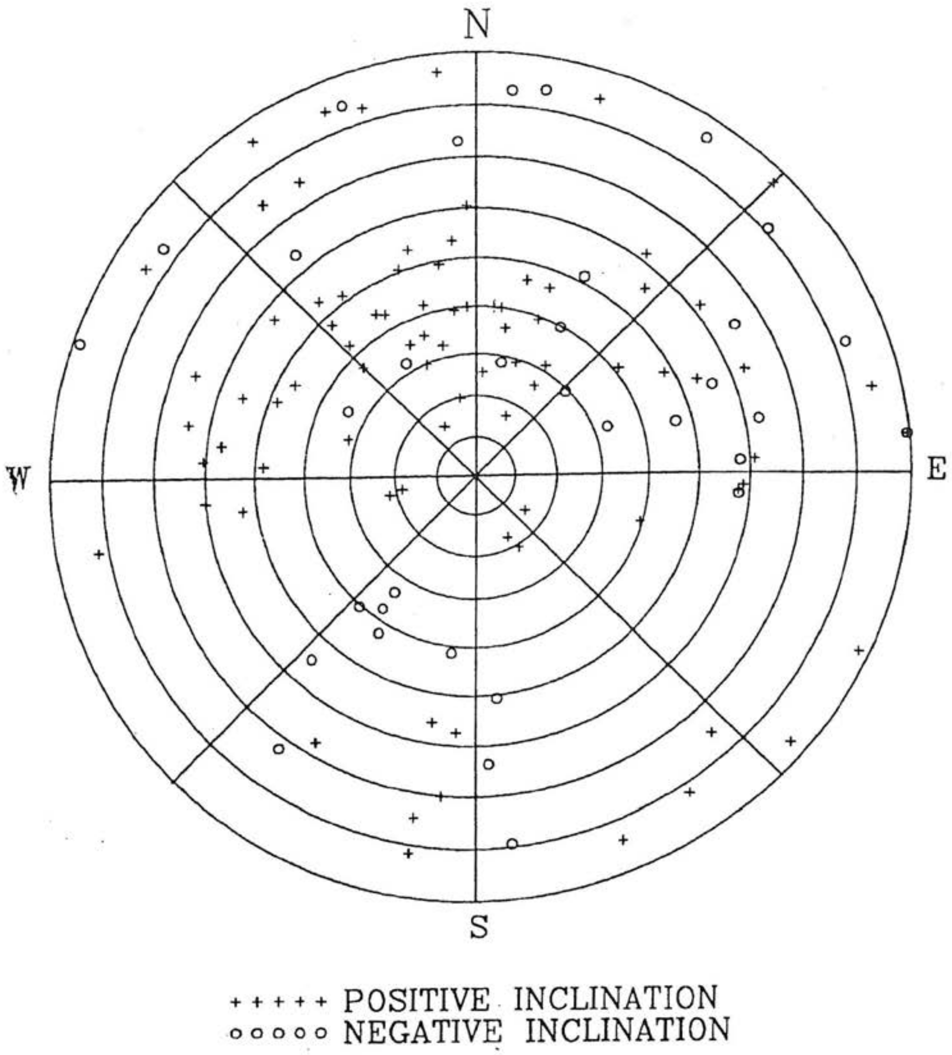

Fig. 6. Equal area polar projection stereoplot of NRM directions for Kohistan rocks. Total number of samples is 116.

gram of NRM intensities for 126 of 127 samples. NRM intensities are generally less than 1 A/m (114 of 127 samples), with extremely high intensity (greater than 10 A/m) found only in serpentinized ultramafics of the Jijal Complex. Norites and Chalt volcanics have intermediate NRM, between 0.1 and 1 A/m. Kohistan arc and Karakoram intrusives, Kamila amphibolites, and garnet granulites of the Jijal Complex have the lowest NRM intensities (less than 0.1 A/m). Fig. 6 is a stereoplot of the initial NRM directions for the oriented samples. Generally these directions have positive inclination with a mean declination of 4.5° west of north and a mean inclination of about 17°.

Thin sections of all 127 samples were examined in transmitted and reflected light. The following generalities can be made. Kamila amphibolites typically contain a yellowish-brown rutile, ilmenite (often intergrown with hematite), occasional titanite (sphene), sulfides, and traces of magnetite. Abundant coarse-grained magnetite is found only in the pyroxene granulites (norites), which may contain ilmenite with fine-grained exsolution blebs of ilmenite or more complex intergrowths of the two rhombohedral oxides. The ubiquitous magnetite in the pyroxene granulites is commonly intergrown with ilmenite (Fig. 7a). Abundant fine-grained Fe-oxide related to the serpentinization process is found in the serpentinized ultramafic rocks of the Jijal Complex (Fig. 7b). Much of the orthopyroxene in the norites contains lamellae of what appears to be hematite, which itself exhibits exsolution of a second phase. A high-susceptibility sample from the Chalt volcanics contains mostly magnetite; the low susceptibility Chalt metabasalts contain intergrowths of rhombohedral Fe-Ti oxides.

DISCUSSION

On behalf of the available magnetic property data there are a number of critical interpretations that can be made without assumption. These have to do with the present state of magnetism in Kohistan, and the magnetic property and magnetic mineralogy contrasts amongst the various grades of metamorphism preserved in the rocks there. Other interpretations, such as predictions of lower crustal magnetization based on Kohistan data are not at all straightforward.

Magnetic Anomaly Interpretation

The susceptibility traverses through Kohistan and laboratory measurement of NRM intensities of collected samples show that the most intensely magnetized rock group is serpentinized ultramafic rock, whose precursor was in all likelihood olivine-rich dunite. Magnetic anomalies related to this lithology will be local in scale because the occurrence of serpentinites is arealy restricted (recognized by Pudsey and Maguire, 1986), large in magnitude (due to the intense magnetization), dominated by remanent magnetization (high Koenigsberger ratios), and consequently have the possibility for either negative or positive polarity. As far as the issue of polarity is concerned, the intensity of the anomaly is more diagnostic since intense negative anomalies can only be associated with a large magnetization contrast. Locally intense anomalies may also be anticipated over magnetic lithologies within the Chalt volcanics. It is not unlikely that contact zones between intrusive granitic rocks and sedimentary country rock will exhibit local magnetic anomalies (as observed by Pudsey and Maguire, 1986).

Regional magnetic anomalies in Kohistan will arise due to magnetization contrasts between large masses of nonmagnetic amphibolite, — the Kamila amphibolite, and nonmagnetic Kohistan arc intrusives (granites and diorites) that border the magnetic Chilas Complex pyroxene granulites (norite). The amphibolites and granites have large areal extents and volumes, low susceptibilities, less than 10^{-3} SI, low intensity of NRM (generally less than 0.1 A/m), and have Koenigsberger ratios much less than 1, meaning that a small component of induced magnetization dominates. The Chilas complex pyroxene granulites also have large areal extent and volume, and generally have susceptibilities in excess of 10^{-2} SI, but rarely in excess of $5X10^{-2}$ SI. Their NRM intensities are generally on the order of 0.5 A/m, and the total magnetization, based on Koenigsberger ratios, generally will be parallel or subparallel to the inducing geomagnetic field. While not the primary objective of this investigation, rocks of the Karakoram Batholith have low susceptibilities and NRM, with Koenigsberger ratios that indicate magnetization dominated by the induced component.

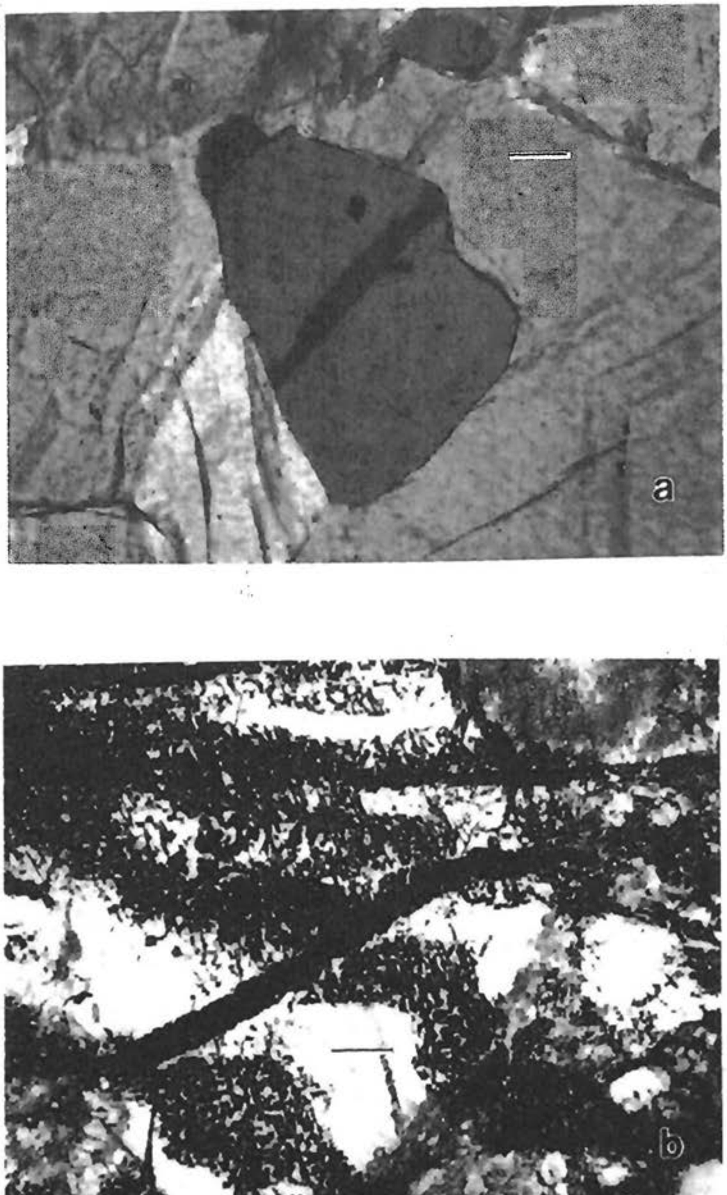

Fig. 7. Micrographs of Kohistan rocks. a) Reflected light (crossed-polars) image of a crystal of magnetite with a dark grey lamella of ilmenite (sample 58). Scale bar is 50μm. b) Transmitted light (uncrossed polars) image of fine-grained magnetite in a serpentinite (sample 3-1). Scale bar is 100 μm.

Effects of Metamorphism

Metamorphic effects on magnetic mineralogy and magnetic properties of Kohistan arc lithologies are manifested on a range of scales. Regional scale effects can be seen by simply comparing amphibolite facies mafic rocks, — Kamila amphibolites, with granulite facies rocks, — the Chilas Complex pyroxene granulites. Some of these Kamila amphibolites are thought to be amphibolite facies equivalents of Chilas Complex pyroxene granulites, metamorphosed in the prograde sense. Others may be derived from volcanic parent rocks (Jan, 1988).

On an outcrop scale it is also possible to document the effects of retrograde metamorphism of pyroxene granulites (norite) to lower grade assemblages. An example from within the Chilas Complex will be illustrative. Sample site 51 is a road cut near the center of the Chilas Complex, approximately 47 miles west of Chilas (53 miles north from Jijal). Present within norite at this locality are numerous planar zones exhibiting retrograde metamorphism from the granulite facies, presumably related to fluid migration. Four samples were taken from a profile across one of these zones: one sample is from the center of it and three more were taken going out into fresher norite. The 4 samples span a distance of .33m and their magnetic properties are given in Table 1. Sample 51-1 is from the freshest norite and 51-4 is from the centre of the zone. With the petrographic microscope one can see a clear progression in alteration of magnetite-ilmenite intergrowths, going from relatively fresh norite (sample 51-1) toward the center of the alteration zone. Figs. 8a and 8b are reflected light micrographs of magnetite-ilmenite intergrowths in sample 51-1. Fig. 8c illustrates the development of an amphibole and biotite corona about one of these intergrowths in sample 51-3. Figs. 8d and 8e illustrate the wholesale replacement of magnetite in such intergrowths by silicate (sample 5-4). Based on microprobe analysis, the silicate includes biotite, and the Fe-Ti oxide remaining is ilmenite. In addition, in Fig. 8e one can see the extreme development of an amphibole corona about one of these remnants. The progressive destruction of Fe-Ti oxide minerals with increasing degree of retrogressive metamorphism is paralleled by systematic changes in magnetic susceptibility, NRM intensity and Koenigsberger ratio (Table1).

TABLE 1 RETROGRADE METAMORPHIC EFFECTS ON MAGNETIC PROPERTIES OF A PYROXENE GRANULITE

Sample	NRM (A/m)	Susceptibility*	Koenigsberger Ratio**
51-1	0.452	8.75×10^{-3}	1.28
51-2	0.357	9.05×10^{-3}	0.98
51-3	0.049	8.35×10^{-3}	0.15
51-4	0.003	0.65×10^{-3}	0.11

*Dimensionless SI units

**Inducing field of 40.27 A/m (50.6 microTeslas)

Another example of retrogressive metamorphic effects comes from investigation of a similar alteration zone in amphibole-rich garnet granulite of the Jijal Complex. In this case, amphibolite facies alteration along a planar zone can be studied with a petrographic microscope. The alteration consists of a 2-5 mm-thick zone of secondary amphibole with the surrounding alteration envelope extending out a few cm into the granulite. About 4 cm distant

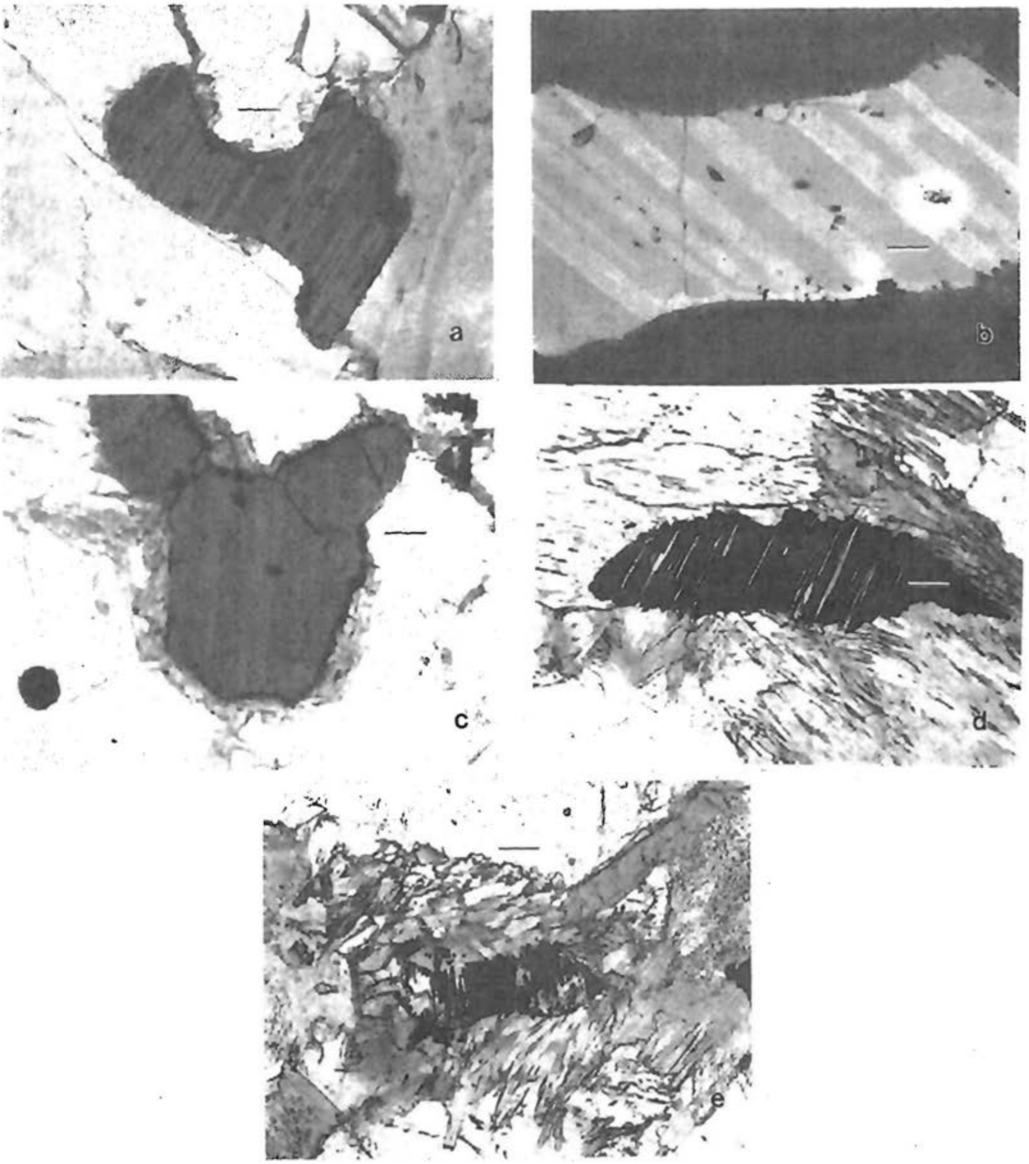

Fig. 8. Micrographs of samples from site 51, which show effects of retrogressive metamorphism of pyroxene granulite (norite) that contains intergrowths of magnetite and ilmenite. a) Reflected light (crossed polars) image of coarse-grained magnetite-ilmentite intergrowth in sample 51-1. Scale bar is 50 μm. b) Reflected light (crossed polars) image of coarse-grained magnetite-ilmenite intergrowth in sample 51-1. Scale bar is 20 μm. c) Combined reflected and transmitted light (uncrossed polars) of coarse-grained magnetite–ilmenite intergrowth in sample 51-3 with a thin incipient corona of amphibole and lesser amounts of biotite surrounding it. d) Transmitted light (uncrossed polars) of a remanent of coarse-grained magnetite-ilmenite intergrwoth in which the magnetite has been replaced by biotite (sample 51-4). Scale bar is 50 μm. e) Transmitted light (uncrossed polars) of a remanent of coarse-grained magnetite-ilmenite intergrowth in which the magnetite has been replaced by silicate (sample 51-4). There is a well-developed corona of amphibole surrounding the remaining ilmenite. Scale bar is 50 μm.

from the zone, intergrowths of hematite and ilmenite (Fig. 9a) are relatively fresh and titanite (sphene) is absent. Within a few mm of the zone, there are abundant isolated crystals of titanite, and coronas of titanite (Fig. 9b) about remants of hematite-ilmenite intergrowth are present.

Magnetization at Depth in the Crust

The magnetization contrasts that we can thus far outline for Kohistan rocks presently at the earth's surface are unequivocal. However, applying these results to rocks at depth in the crust presents some challenges. One issue is whether the magnetic mineralogy of moderate-to high-grade metamorphic rocks in Kohistan is in fact indicative of the mineralogy that exists at high pressure and temperature in the deep crust. Bearing on this, Frost and Shive (1986) have argued for the stability of magnetite in the deep, or lower, crust. A second issue is to what degree the metamorphism of the Kohistan island arc reflects the tectonism and metamorphism experienced by the island arc lithologies subsequent to their formation c. 95-110 m.y. ago. Finally, there is the question of the relationship between pressure(s) and temperature(s) of equilibration gleaned from the mineral chemistry of granulites now at the surface of the earth to in-situ pressures and temperatures of rocks at depth in the lower crust (Bohlen et al., 1983). These are key issues for any inference of lower crustal magnetization based on the magnetization of surficial exposures of moderate- to high-grade rocks thought to populate the deep crust.

Geothermometry and geobarometry of granulites in regionally metamorphosed terrains commonly do not yield pressures in excess of about 8 or 9 kb or temperatures in excess of 800 to 900°C (Newton and Perkins, 1981; Bohlen et al., 1983). Consequently, the suggestion has been made (Bohlen et al., 1983) that regionally-metamorphosed granulites may not represent the lower crust. Frost and Chacko (in press), on the other hand, advocate that mineral chemistry, upon which geothermometry and geobarometry rely, may be reset duirng slow uplift of regionally metamorphosed terrains. Indeed, O'Hara (1977) found that closure of mineral systems to chemical change at different stages of the pressure-temperature evolution of Scourie gneisses permits a determination of thermal history during the ascent to the surface of the regionally metamorphosed terrain of Scourie. It seems then that peak pressure-temperature conditions may not always be recorded by mineral geobarometers and geothermometers.

While the above conundrum is problematic for regionally metamorphosed terrains it does not seem appropriate to generalize to Kohistan, where relatively rapid uplift and exposure have been achieved by means of obduction and continent-continent collision. Even so, the maximum metamorphic pressures and temperatures recorded by Kohistan arc garnet granulites of the Jijal complex are only about 9-10 kb and 700-850°C (Jan, pers. commun., 1988). Therefore, the garnet and pyroxene granulites exposed at the surface in Kohistan, while of likely lower crustal origin, may not in fact contain a mineralogical record of temperatures and pressures related to their ultimate formation in the lower crust. Instead, relatively rapid tectonic uplift of low-level Kohsitan arc rocks appears to have been accompanied by metamorphic recrystallization and re-equilibration at lower pressure(s) and temperature(s).

Clearly, there are some fundamental questions that must be addressed before we can generalize from magnetic properties of moderate- to high-grade rocks presently exposed at the earth's surface to magnetic properties of rocks at depth in the lower crust. In spite of this, we can make a statement about the variations of magnetization and magnetic mineralogy at intermediate pressure and temperature in amphibolite and granulite facies mafic rocks at depth,

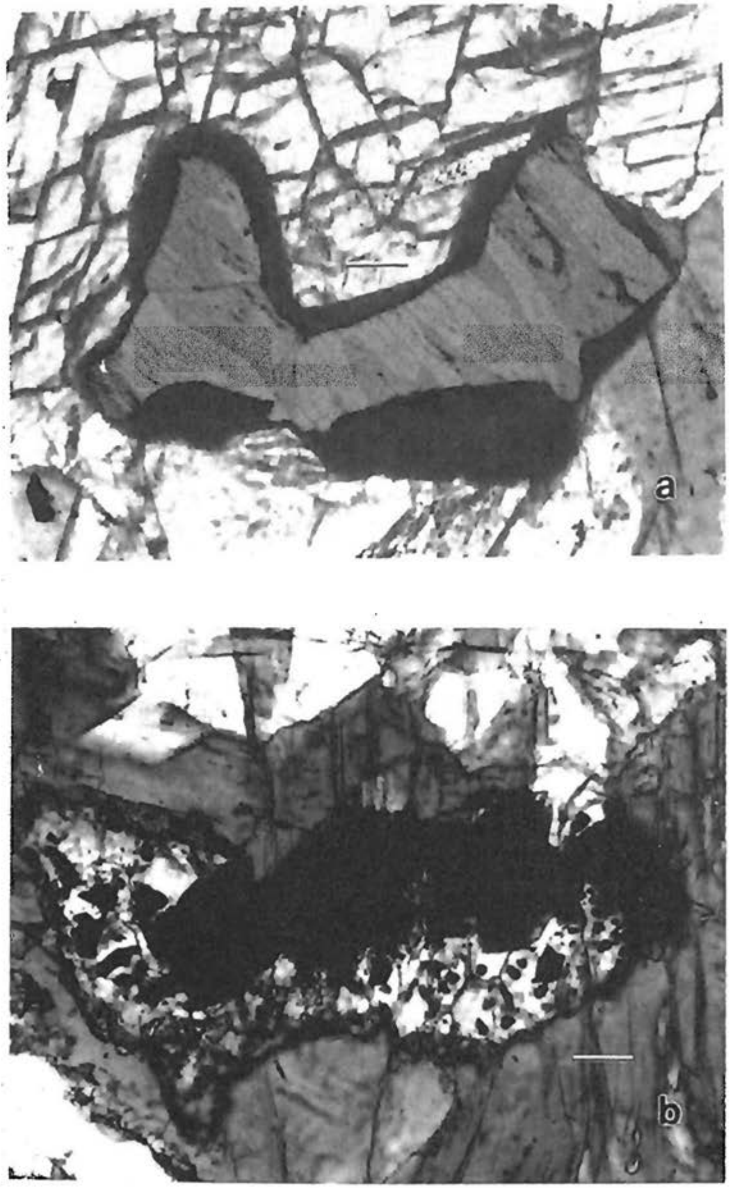

Fig. 9. Petrographic microscope micrographs of sample 14-7, which contains hematite–ilmenite intergrowths. a) Combined transmitted and refelected light (uncrossed polars) image of an unaltered intergrowth of hematite and ilmenite. The Fe-Ti oxide sits in a matrix of amphibole and pyroxene about 4 cm from the plane of alteration. The dark grey envelope surrounding the reflective Fe-Ti oxide is a shadow due to combined use of transmitted and reflected light. Scale bar is 50 µm. b) Transmitted light (uncrossed polars) image of an altered intergrowth of hematite and ilmenite, which has a well-developed corona of titanite. The Fe-Ti oxide remanent resides in a matrix that is mostly what appears to be secondary amphibole. The image is from an area within a few mm of the alteration zone. Scale bar is 50 µm.

based on results from Kohistan. In particular, the information gleaned from this study may be used to constrain the magnetic mineralogy and magnetic properties of geologically young (versus Proterozoic and Archean) mafic rocks at depth in crust that equilibrated under conditions of pressure, temperature and vapor phase fugacities similar to those at which Kohistan arc rocks equilibrated. This encompasses depths where pressures are presently less than about 8-9 kb and temperatures are less than about 700°C, the maximum expected Curie temperature of magnetic phases common in moderate- to high-grade metamorphic rocks (Schlinger, 1983; Schlinger and Veblen, in press). It is essential that we gain a better idea of equilibrium mineral assemblages and chemistry at higher temperature(s) and pressure(s) before attempting to speculate on magnetization at greater depth.

CONCLUSIONS

— Based on magnetic susceptibility and NRM measurements in the Himalaya and Karakoram ranges of NW Pakistan, the magnetic lithology on a local scale (0.1 to 10 km) is serpentinized ultramafic rock. On a regional scale (10 to 100 km), the magnetic lithology is pyroxene granulite (norite), with magnetization of 1 to 2 A/m.

— Weakly magnetized rocks are represented by the Kamila amphibolites, garnet-granulites, Kohistan arc and Karakoram granitic intrusives, and Yasin metasediments.

— The prograde metamorphic transition in mafic rocks from amphibolite to pyroxene granulite yields a relatively magnetic lithology; retrograde metamorphism of pyroxene granulite to the amphibolite facies yields a nonmagnetic equivalent (which is also true for weakly magnetic garnet granulites).

— Mafic pyroxene granulites and amphibolites at depth in geologically young crust with a metamorphic history similar to that of Kohistan can be expected to possess similar magnetizations.

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