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Magnetomineralogical changes along the Kohistan-Karakoram collision zone in North Pakistan: implications for variable thermochemical activities

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Abstract: To identify remanence-carrying magnetic minerals and document their thermochemical behavior, detailed rock magnetic investigations were conducted on Cretaceous-Tertiary rocks collected from northwestern and northeastern Kohistan, northern Pakistan. Rock magnetic results from each area are clearly differentiated on the basis of site location. Detrital hematite is identified as a main magnetic carrier in red beds of northwestern Kohistan located at some distance from the Northern Suture Zone with subsidiary pigmentary hematite and altered magnetite. In contrast, the magnetic mineralogy of purple-colored rocks adjacent to the Northern Suture Zone is shared by unstable secondary pyrrhotite, magnetite, and hematite. The magnetic mineralogy of northeastern Kohistan is dominated by recently formed pyrrhotite with contributions from secondary hematite and magnetite. The widespread presence of pyrrhotite in the eastern sector indicates contrasting thermochemical regimes. Two geological implications are inferred from magnetization contrasts in the eastern and western sectors of the Kohistan Range. First, rocks at a distance from the Northern Suture Zone are less intensely remagnetized than those closer to it and provide a signature of the thermochemical gradient. Second, rocks in northeastern Kohistan are more intensely remagnetized compared to their counterparts in the northwest, implying an increase in the thermochemical gradient from west to east. The reported occurrences of numerous sulfide mineral zones in the study areas support our interpretation of intense remagnetization as a result of increased thermochemical activity near the Northern Suture Zone.

Key words: Kohistan, Northern Suture Zone, magnetic mineralogy, red beds, detrital hematite, pyrrhotite, remagnetization

1. Introduction

During the past few decades rock magnetic and paleomagnetic techniques have been increasingly used to study magnetic behavior of sedimentary rocks, particularly red beds of various ages. Widespread secondary magnetization in sedimentary rocks has been reported from many parts of the world with migration of hot exotic fluids assumed to be the cause of remagnetization (Turner, 1980; McCabe and Elmore, 1989; Katz et al., 1998; Meijers et al., 2011; Appel et al., 2012; Elmore et al., 2012; Van Der Voo and Torsvik, 2012) and is likely to explain contrasts between collision zones and mid-continent regions.

Rocks in the Himalaya-Kohistan-Karakoram collision zone are also severely remagnetized as a result of ongoing tectonometamorphic activity. Because the grade of metamorphism and related thermochemical processes varied from place to place, different degrees of remagnetization are anticipated along the Kohistan Island Arc. Here we present a detailed rock magnetic study to link secondary magnetic minerals and their remanent magnetizations with metamorphic/thermochemical activity in the Kohistan Arc of the Pakistani Himalaya. The rock magnetic investigations of remanence-carrying minerals in Cretaceous-Tertiary rocks presented here complement paleomagnetic results from the same Kohistan rock suites reported elsewhere (Zaman et al., 1999; Zaman et al., 2013). The results from NW and NE Kohistan reveal significant indications of postfolding remagnetization in these rocks following their deposition at equatorial to low southern paleolatitudes, suggesting thousands of kilometers of northward displacement along with blocks/thrust sheets rotations.

2. Tectonic setting of the study area

The crustal lineament separating the Indian Plate from Gondwanic-origin microcontinental blocks of Asia divides into two branches at the northwestern Himalayan Syntaxis. The northern branch of the suture, named the Shyok Suture in Ladakh and the Northern Suture Zone (NSZ) in Kohistan, separates Paleozoic Tethyan shelf sediments of the Karakoram block to the north from the Jurassic to Cretaceous Kohistan Island Arc to the south (Figure 1). The southern branch of this fault, named as the Main Mantle Thrust by Tahirkheli et al. (1979), juxtaposes

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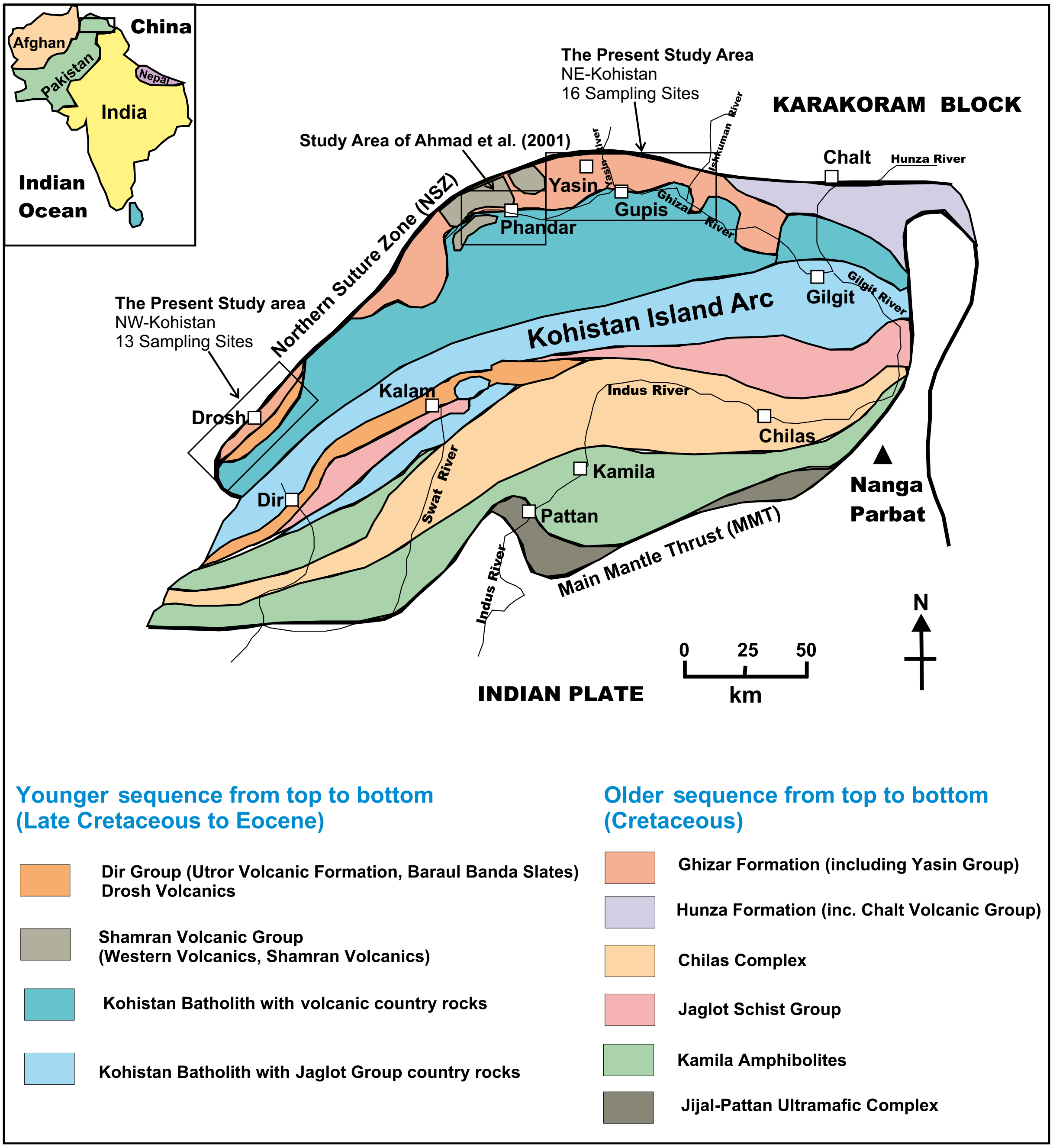

Figure 1. Geological map of the Cretaceous Kohistan Island Arc. The areas within rectangles, located around the towns of Drosh and Gupis, are investigated in this study. The study area of Ahmad et al. (2001) is also marked by a small rectangle. Detailed geological maps of the Yasin-Gupis and Drosh areas are shown in Figures 2 and 3.

the Kohistan Arc with Precambrian to Mesozoic gneisses, sedimentary rocks, and volcanics of the Indian Plate to the south (Figure 1). The Kohistan Arc is thought to have accreted onto the Karakoram microplate during the Cretaceous by closure of a back-arc basin between these two terranes between 102 Ma and 85 Ma as dated by Rb-Sr, K-Ar, and Ar-Ar evidence (Treloar et al., 1989). Immediately after arc-continent collision, the red beds of northern Kohistan used in this study were deposited in a nonmarine environment at equatorial to low southern paleolatitudes.

Several researchers have recently published papers on the India-Kohistan-Asia collision in western Himalaya (Burg, 2011; Bouilhol et al., 2013) and reported an ongoing tectonic instability in the area as a result of continuous Indian Plate indentation into Asia. Prior to these studies, Searle et al. (1999) reported multiple episodes of metamorphism from the latest Cretaceous and throughout the Tertiary as a result of postcollisional crustal thickening along the collision belt. These tectonometamorphic events have significantly altered the magnetic mineralogy in the area; this is evident from a widespread postfolding secondary magnetization found in the Cretaceous-Tertiary rocks of Kohistan (Zaman and Torii, 1999; Zaman et al., 2013).

3. Geology of the study area and sampling

The study area forms part of northern Kohistan located just south of the NSZ and covers an area between the Ishkuman Valley in the east and the Drosh-Shishi area in the west (Figure 1). Geological descriptions of the northwestern and northeastern parts of Kohistan follow below.

3.1. NW Kohistan

According to reconstructed stratigraphical sequences and structural determination (Pudsey et al., 1985; Pudsey, 1986), the NW part of the Kohistan Island Arc, named the southeastern unit, comprises Cretaceous volcanic and sedimentary rocks incorporating the Shamran Volcanic Group and the Drosh, Purit, and Gawuch formations intruded by diorites, tonalities, and granites.

The Cretaceous rocks of NW Kohistan in the Drosh-Shishi area are divided into three units (Figure 2). The basal unit of green to dark green phyllite, the Gawuch Formation, incorporates limestone linked to the last marine sedimentation before deposition of continental red beds. The overlying Purit Formation is about 1 km thick in the southwest and wedges out half-way along the Shishi Valley. Red calcareous shale with abundant calcite veins, interpreted as fluvial by Pudsey et al. (1985), is the dominant rock type. About 45 samples of red sandstone and shale were collected from this formation at 6 sites. The Purit Formation is overlain in the study area by the Drosh Formation, comprising a sequence of thickly bedded but strongly epidotized andesites, where chalcopyrite is an accessory mineral in some flows. Some thin red calcareous shale is interbedded with these andesitic lava flows, from which 32 samples were collected at 5 sites. According to Calkins et al. (1981), a belt of limestone and phyllite overlies the rocks of the Drosh Formation. *Orbitolina* fossils in limestone beds of the Drosh area indicate deposition during the Cretaceous. Pudsey et al. (1985) considered this unit to lie within the NSZ, a zone of mélange (150 m to 4 km wide) containing blocks of volcanic rocks, limestone, red dark-colored shale, conglomerates, quartzite, and

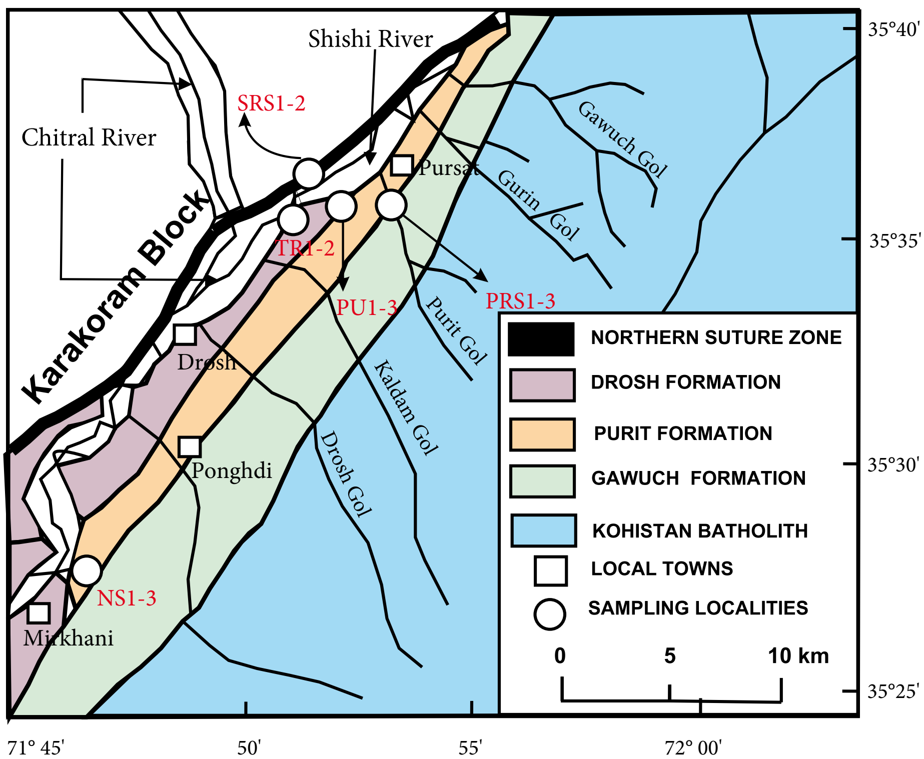

Figure 2. Geological map of the study area around the town of Drosh in western Kohistan. The sampled localities and sites (13) in the Purit Formation, Drosh Formation, and Northern Suture Zone are shown in red. Among the studied rocks, the Purit Formation is the farthest unit from the suture zone.

serpentinite in a matrix of strongly cleaved slate. The mélange has been interpreted by Pudsey (1986) as an olistostrome derived largely from the Kohistan Arc to the south. About 16 samples from red to dark-colored shale were collected at 2 sites from this rock unit. Further details about the studied sampling sites are given in Figure 2 and the Table.

3.2. NE Kohistan

A variety of sedimentary and volcanic rocks were studied to document magnetic mineralogical behaviors in the rocks of NE Kohistan from a 10-km strip south of the NSZ and within the arc. The Yasin Group in the type area near Yasin village is divided into a 2-km-thick upper unit and a >1-km-thick lower unit (Pudsey, 1986; Figure 3) with the upper unit (Sandhi Formation) made up of red, purple, green, and gray shales with interbedded greenstones. The lower unit is subdivided into 2 formations; the Taus Formation is mostly gray slate with some turbidite (up to 500 m thick), and the Chojalti Formation is composed of over 500 m of volcanic-lithic conglomerate, sandstone, tuff, slate, and limestone. Red and green sandstone and conglomerate of the Chojalti Formation are seen on the west side of the Yasin River; this unit is several hundred meters in thickness. This North-South stratigraphic order is followed by arc volcanics (Figure 3), which include a high proportion of volcaniclastics intercalated with a 500-m-thick metamorphosed limestone unit.

These Cretaceous-Tertiary sedimentary and igneous rocks were sampled at 16 sites from 3 localities on the south side of the NSZ (Figure 3). About 40 samples were collected at 4 sites from red and purple shale of the upper unit along Sandhi Gol stream on the east side of the Yasin River (36°30′47″N, 7335′30″E). This 200-m-thick section is composed of variably colored shale intercalated with volcanics. Another section located at the entrance of Naz Bar stream a few hundred meters west of Yasin village (36°22′46″N, 73°19′30″E) comprising red to purple-colored sandstones was sampled at 8 sites (70 samples).

Table. First column of this table shows names of rock formations used for this study. Locations, coordinates, rock type, number of sites/samples, and magnetic mineralogy of the studied samples are listed in the following columns. In NW Kohistan, the concentration of recently formed pyrrhotite increases towards the NSZ. In addition, the widespread presence of pyrrhotite is indicated in the rocks of NE Kohistan compared to NW Kohistan.

Formation name	Locality	Coordinates	Rock type	No. of sites/ samples	Magnetic mineralogy
NW Kohistan					
Purit (the farthest rock unit from the NSZ)	PRS: Near Pursat village	35°35′53″N, 71°51′24″E	Red sandstone	3/24	Hematite (both detrital and pigment) with minor presence of magnetite
	NS: Across from Nagar Fort	35°29′11″N, 71°44′43″E	Fine red calcareous shale	3/21	
Drosh	PU: Purgal village	35°36′26″N, 71°51′52″E	Fine red calcareous shale	3/18	Pigment hematite, magnetite, and minor pyrrhotite
	TR: Trang village	35°33′20″N, 71°40′12″E	Red to gray shale	2/14	
Mélange zone (NSZ)	SRS: Near Shishi village	35°38′07″N, 71°50′41″E	Fine red to dark shale	2/16	Pyrrhotite, magnetite, and recently formed hematite
NE Kohistan					
Upper Volcanic Unit	Sandhi Gol (stream)	36°30′47″N, 73°35′30″E	Red to purple-colored shale	4/40	Hematite with subordinate magnetite and pyrrhotite
Lower Sedimentary Unit	Near Yasin village along Nazbar stream	36°22′46″N, 73°19′30″E	Red to purple-colored sandstone	8/70	Dominant pyrrhotite with hematite and magnetite
Shamran and Western Volcanics	Baris village	36°17′40″N, 73°17′20″E	Volcanics intercalated with metasediments	4/32	Dominant pyrrhotite with subordinate magnetite

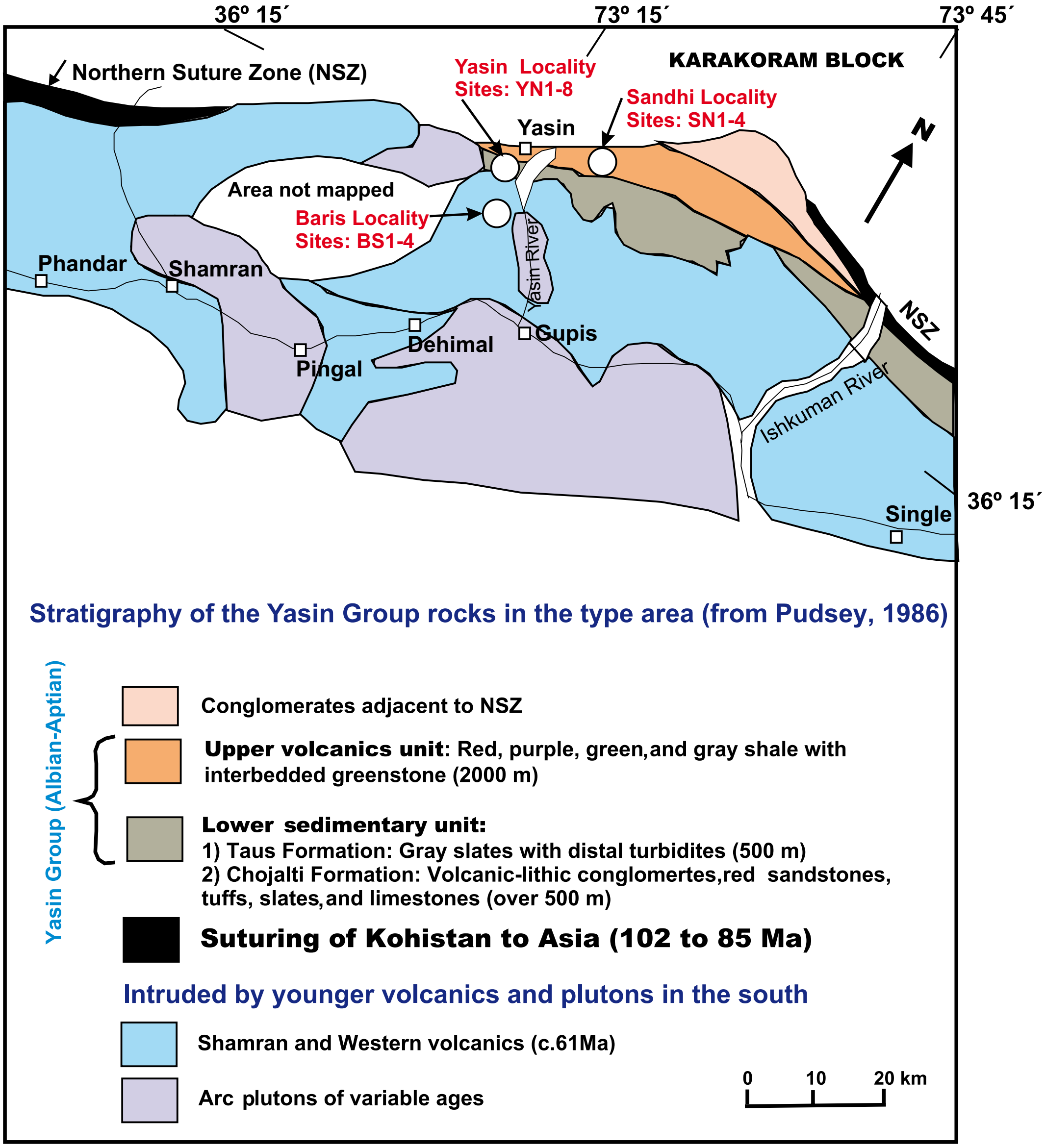

Figure 3. Geological map of the Yasin-Gupis area in NE Kohistan. Samples from the Sandhi, Yasin, and Baris localities (16 sites) are used for this study.

Towards the south on the Yasin-Gupis road, 32 samples were collected at 4 sites from arc volcanics near Baris village. These volcanics are intercalated with thin layers of metasediments and metamorphosed to lower green schist facies. The studied sampling sites are further described in the Table.

4. Field and laboratory procedures

Cylindrical specimens 2.5 cm in diameter and 2.2 cm in length were cored from each block sample and laboratory facilities at Kyoto University and Kobe University (Japan) used to analyze rock magnetic parameters. To detect mineralogical changes at high temperatures, low field magnetic susceptibilities were measured after each heating step using a Bartington MS-2 susceptibility meter. Thermomagnetic analyses were performed (both in air and argon environments) to observe magnetic behavior with increasing temperature using an automatic recording semihorizontal magnetic balance. Acquisition of isothermal remanent magnetization (IRM) and subsequent backfield procedures were applied to determine coercivity spectra. Composite IRMs of 1.3 T, 0.4 T, and 0.12 T (Lowrie, 1990) were applied to the NW Kohistan samples as hard, medium, and soft coercivity fractions along the z-, y-, and x-axes and then thermally demagnetized. Composite IRMs of 2.5 T, 0.4 T, and 0.12 T were applied to the NE Kohistan samples as hard, medium, and soft coercivity fractions, respectively. Magnetic minerals pyrrhotite, magnetite, and hematite exhibit transitions in magnetic properties at 34 K (–239 °C), 120 K (–153 °C), and 253 K (20 °C), respectively (e.g., Verwey, 1939; Morin, 1950; Rochette et al., 1990). To identify these low temperature phases, a transition quantum magnetic property measurement system was used and imparted an IRM of 1 T at 5 K before continuously warming up to 300 K. Optical microscopic observations of polished thin sections were conducted on selected samples under reflected and transmitted light to differentiate magnetic minerals (Zaman and Torii, 1999).

5. Results from NW & NE Kohistan

Results from the rock magnetic techniques indicate significant areal variations in magnetic mineralogy. Magnetic characteristics are compared here between NW and NE Kohistan and changes in magnetic behavior are also documented within a 10-km zone of northern Kohistan on the south side of the NSZ. Magnetic mineralogical results along with other parameters are listed in the Table.

5.1. Purit Formation (NW Kohistan)

Lithologies of the Purit Formation at the Pursat locality (about 7 km from the NSZ) range from red shale to fine-grained red sandstone. As illustrated in Figure 4a, the IRM acquisition curves indicate a gradual increase with applied field but without saturation up to a maximum field of 1500 mT. Backfield experiments (Figure 4a) show a high remanence coercive force (H_{cr}, 700 mT) indicating the presence of high coercivity hematite, most probably of detrital origin (Dekkers and Linssen, 1989). Composite IRM curves imparted at 120 mT, 400 mT, and 1300 mT in x, y, and z directions respectively also reveal high unblocking temperature hematite as the primary remanence carrier (Figure 4b). Microscopic observations (reported by Zaman and Torii, 1999) show detrital grains comprising hematite-ilmenite intergrowths with a fine-grained pigmentary hematite as a subordinate phase. Low temperature investigations (Figure 4c) reveal a magnetization peak at ~250 K (–23 °C) corresponding to the Morin transition of hematite and a minor presence of magnetite is indicated by a small phase transition at about 120 K (–153 °C). Thermomagnetic analysis identifies a Curie temperature at 680 °C (Figure 4d), again confirming hematite as a remanence carrier. The collective evidence is consistent with the published paleomagnetic data from the Pursat red beds recognizing a stable remanence carried by detrital specular hematite with pigmentary hematite likely responsible for secondary magnetization.

Red to brown-colored shale from the Nagar locality shows the presence of high unblocking temperature hematite from thermal demagnetization of composite IRMs (Figure 4e). Heating and cooling curves (Js-T in air) from thermomagnetic analysis are nearly coincident with a Curie temperature at ~680 °C (Figure 4f). As with the Purit locality, detrital specular hematite and pigmentary hematite are plausibly recognized as the cause of the primary and secondary magnetic carriers in these red beds.

5.2. Drosh Formation (NW Kohistan)

Samples from the Purgal locality are dark-reddish, fine-grained calcareous shale. A two-phased behavior is identified by IRM acquisition and backfield experiments, indicating the presence of both low and high coercivity magnetic minerals (Figure 5a). A dominant presence of hematite with subordinate magnetite is also clearly indicated by thermal demagnetization of the composite IRMs (Figure 5b). In contrast to the Purit Formation, thermomagnetic analysis reveals Curie temperatures around 575 °C and 680 °C, indicating magnetite and hematite, respectively (Figure 5c). Similar behavior is observed by low temperature analysis, with a sharp transition around 125 K (–148 °C) revealing the presence of magnetite and a peak around 240 K (–33 °C) indicating hematite (Figure 5d). Paleomagnetic results reported from these rocks also recognize the presence of hematite and magnetite as the remanence carriers from thermal demagnetization (Zaman and Torii, 1999).

Thermomagnetic analysis of dark to gray-colored shale from the Trang locality shows visible changes in magnetization at 250 °C, 580 °C, and 670 °C indicating the presence of pyrrhotite, magnetite, and hematite, respectively (Figure 5e). The composite IRM curves show the presence of hematite and magnetite/pyrrhotite as hard and soft coercivity fractions, respectively (Figure 5f).

5.3. Northern Suture Zone (NW Kohistan)

Samples from the Shishi locality are fine red to dark-colored shale. Coercivity spectra from IRM acquisition and backfield experiments identify fairly low coercivity hematite with minor change around 150 mT possibly indicating pyrrhotite or magnetite (Figure 6a). As noted by Dekkers and Linssen (1989), the presence of low coercivity hematite can be indicated by a ~500 mT coercive force and is most likely chemical in origin. The presence of hematite, magnetite, and pyrrhotite is also suggested by thermal demagnetization of the composite IRMs (Figure 6b). Thermomagnetic analysis in air shows no significant increase in intensity during cooling (Figure 6c). Thermomagnetic analysis in an argon atmosphere, however, shows a spectacular increase in magnetic intensity at about 600 °C during cooling (Figure 6d), indicating that magnetite has formed during heating due to a breakdown of iron sulfides, which are present here in veins and shear zones (Calkins et al., 1981). Microscopic observations (Zaman and Torii, 1999) recognize very fine-grained secondary hematite in the studied material and

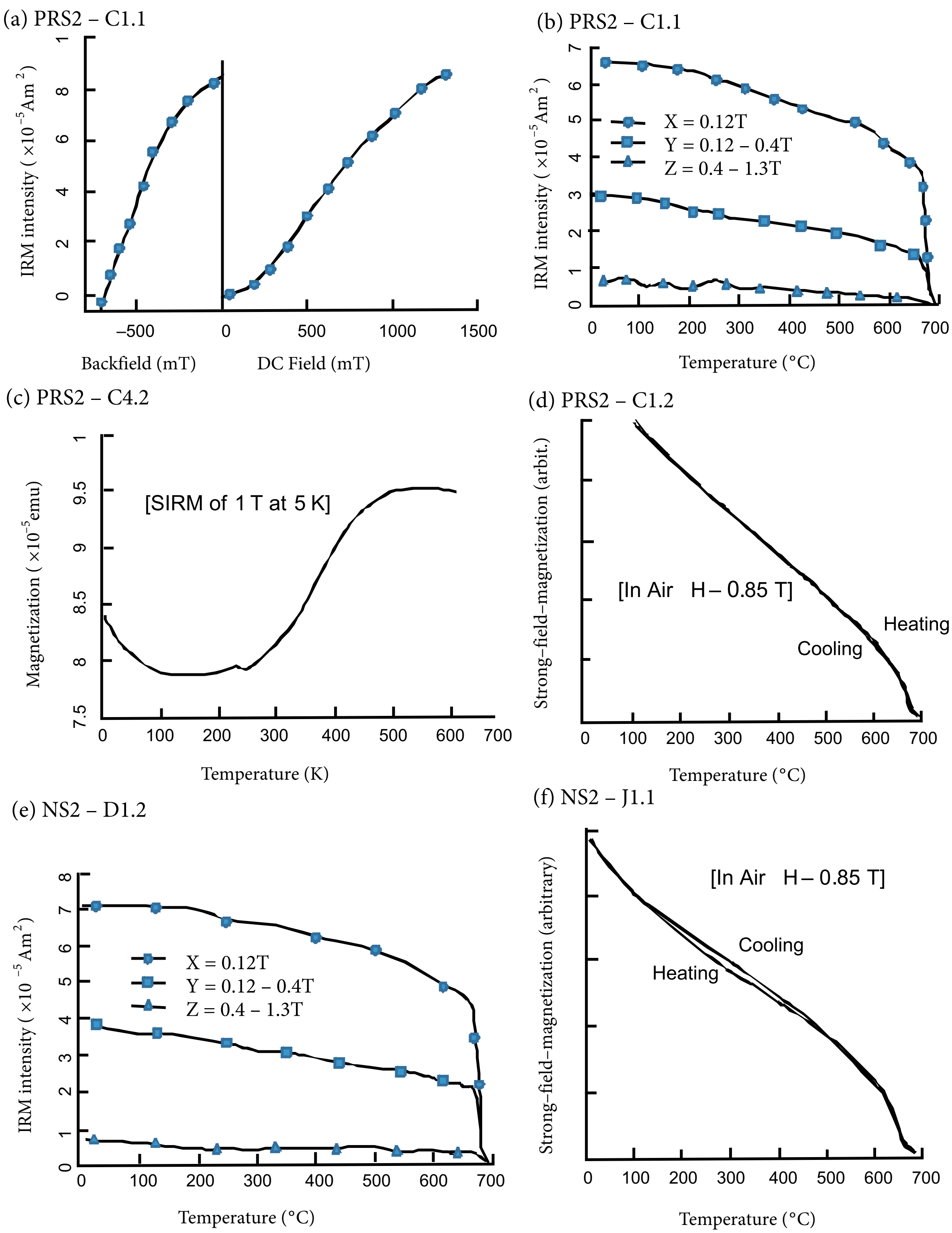

Figure 4. Magnetic characteristics of red bed samples from the Purit Formation in NW Kohistan. The diagrams include IRM acquisition and backfield curves (a), thermal demagnetization of three component IRMs (b, e), thermomagnetic analyses for Curie temperature determination (d, f), and low temperature measurements for determining magnetic transitions (c). All these diagrams indicate the dominant presence of hematite as a remanence carrier.

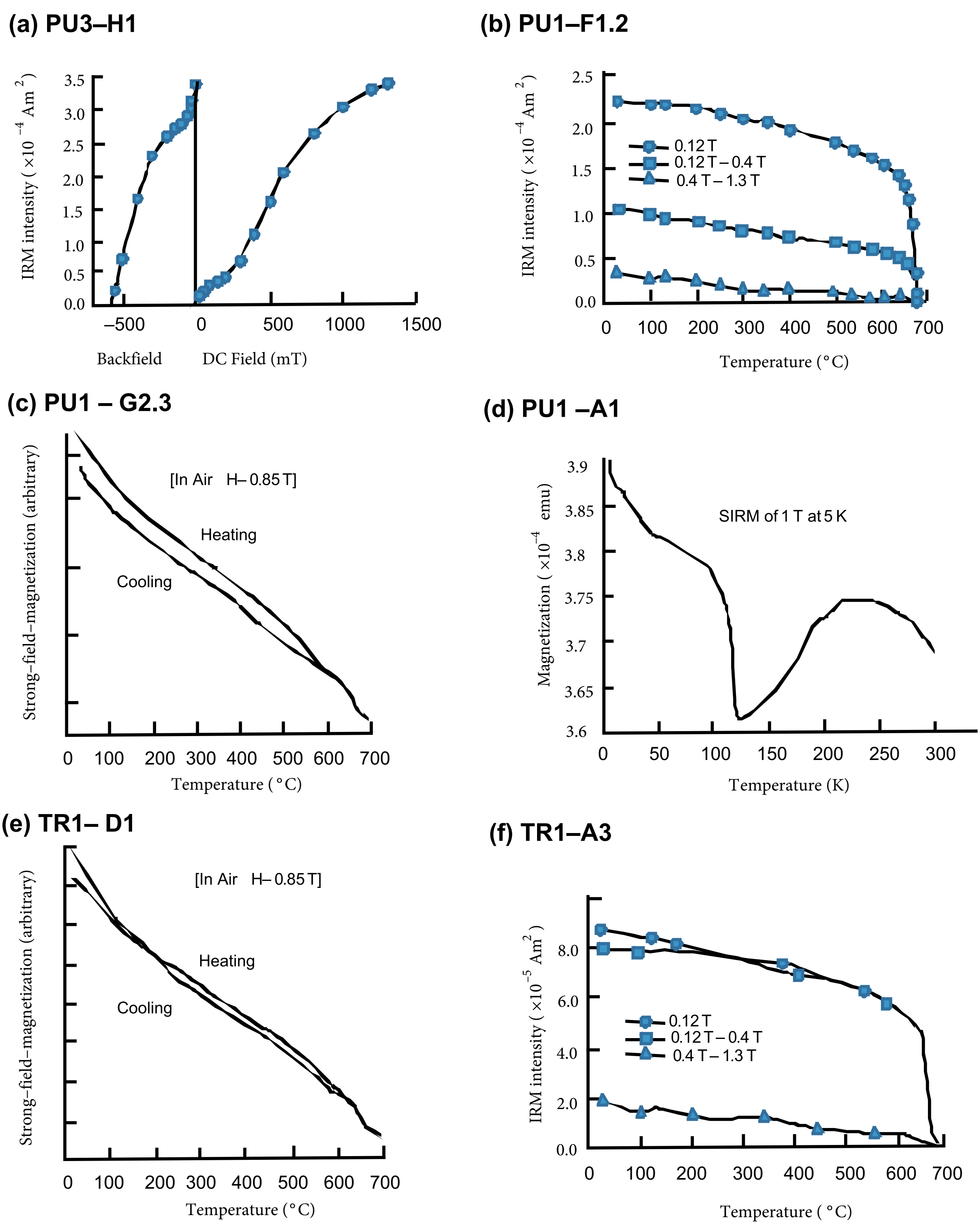

Figure 5. Magnetic characteristics of the red bed samples from Drosh Formation, NW Kohistan: IRM acquisition and backfield curves (a), thermal demagnetization of three component IRMs (b, f), thermomagnetic analyses for Curie temperature determination (c, e), and low temperature measurement for magnetic transition (d). In contrast to the Purit Formation, the presence of lower coercivity magnetic minerals such as magnetite is clearly visible in addition to hematite.

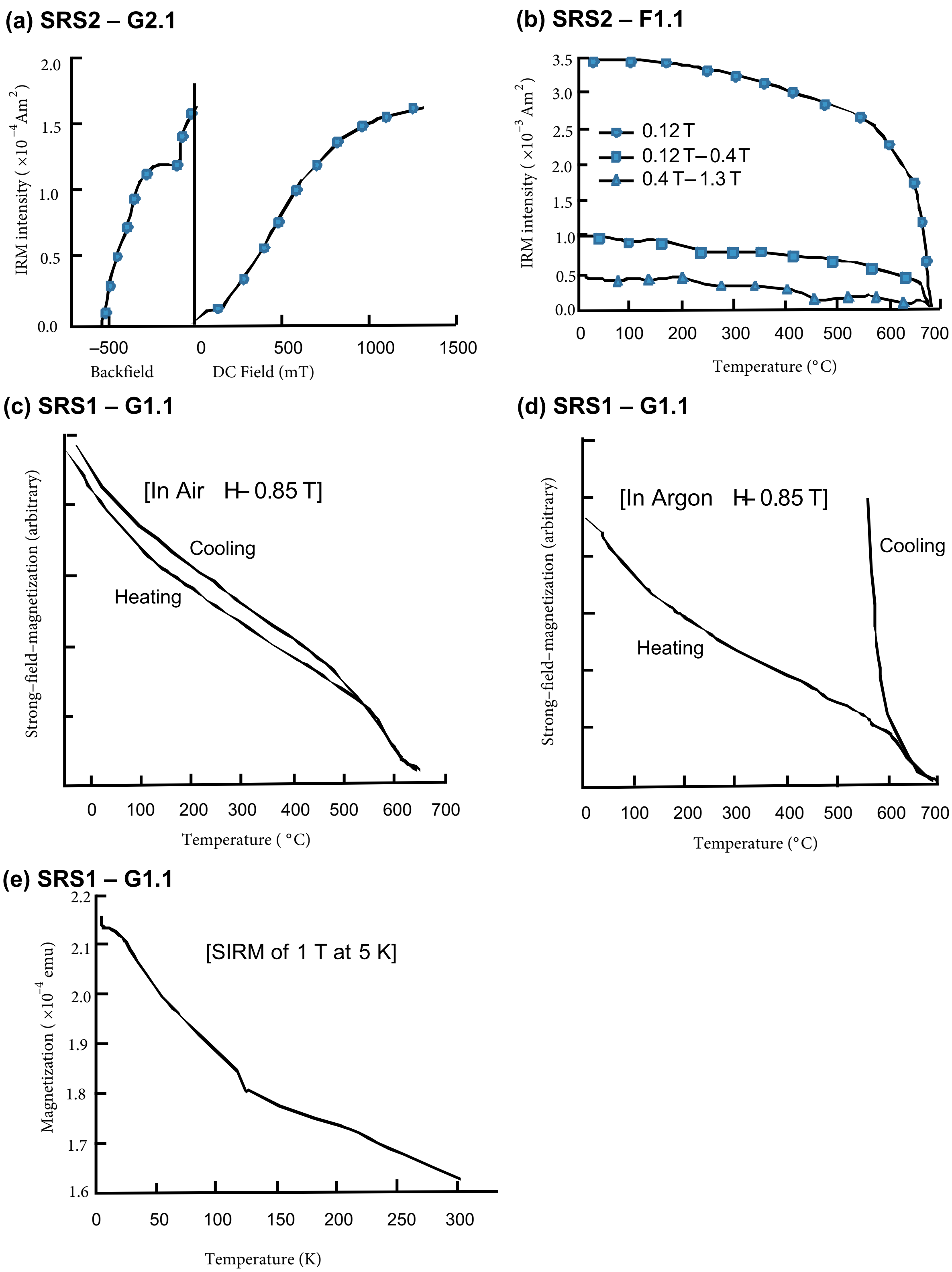

Figure 6. Magnetic characteristics of red bed samples from the Northern Suture Zone, NW Kohistan: IRM acquisition and backfield curves (a), thermal demagnetization of three component IRMs (b), thermomagnetic analyses for Curie temperature determination (c, d), and low temperature measurement for magnetic transition (e). In addition to magnetite and hematite, the presence of pyrrhotite is also indicated in these diagrams.

paleomagnetic directions reported from the same rock unit (Zaman and Torii, 1999) yield present-day geomagnetic field directions suggesting recent precipitation of hematite by enhanced thermochemical/metamorphic activity along the NSZ. The presence of magnetite is clearly indicated in low temperature analysis (Figure 6e) by a transition around 120 K (–153 °C); smaller amounts of pyrrhotite and hematite are indicated by changes around 34 K (–239 °C) and 220 K (–53 °C), respectively (Figure 6e).

5.4. Yasin locality (NE Kohistan)

IRM acquisition experiments on green-spotted purple-colored sandstones from the Yasin locality revealed two behaviors. In most samples, the IRM acquisition curves show two phases (Figure 7a), with the first comprising a steep increase in magnetization to 150 mT indicative of magnetite or pyrrhotite and the second being a gradual increase, but without saturation, to a maximum field of 2.5 T indicating hematite. Thermal demagnetization of composite IRMs reveals unblocking temperatures attributable to pyrrhotite, magnetite, and hematite (Figure 7b). Samples from other sites (YN3 and YN6) achieve complete saturation up to 100 mT, indicative of either magnetite or pyrrhotite (Figure 7c). Pyrrhotite and magnetite are confirmed by thermal demagnetization of composite IRMs (Figure 7d) while also showing a high temperature zone probably due to hematite formation in air during heating. Low field magnetic susceptibility of most samples measured at room temperature after each heating step shows a significant increase around 600 °C (Figure 7e), indicating formation of new superparamagnetic minerals during heating. However, specimens from sites YN3 and YN6 show a drop in magnetic susceptibility around 300 °C (Figure 7f), indicating mineralogical change within the unblocking range of pyrrhotite. The presence of this mineral with magnetite and hematite is evidence for multiple phases of diagenesis during the history of these rocks.

5.5. Sandhi locality (NE Kohistan)

IRM acquisition experiments on Sandhi Formation red beds also indicate two magnetic phases with steep increase in induced magnetization to 200 mT followed by gradual increase without saturation to 2400 mT (Figure 8a). Again the presence of pyrrhotite (or magnetite) and hematite (or goethite) as low and high coercivity phases is indicated and confirmed by thermal demagnetization of the composite IRMs (Figure 8b). Nearly identical behavior is observed in IRM acquisition and composite IRMs curves for an additional site (Figures 8c and 8d). In most samples, lowfield magnetic susceptibility increases significantly after 600 °C (Figures 8e and 8f), recording mineralogical changes during the heating.

5.6. Baris locality (NE Kohistan)

Low field magnetic susceptibility measured after each heating step reveals visible change around 300 °C indicative of alteration of pyrrhotite during laboratory heating (Figure 9a). IRM acquisition experiments on Baris volcanics show saturation variations from site to site. Samples from sites BS1, BS2, and BS3 (Figures 9b–9d) achieve saturation at ~200 mT, 50 mT, and 100 mT, respectively, and NRM intensity losses of ~90% by about 300 °C indicate pyrrhotite as a dominant magnetic mineral; the remaining 10% surviving to 580 °C is a signature of subordinate magnetite (Zaman et al., 2013).

6. Discussion

6.1. Pyrrhotite as an indicator of variable thermochemical activity

The iron sulfide pyrrhotite is found in basic igneous rocks, pegmatite, veins, and contact metamorphic rocks and has been observed as a magnetic carrier in magmatic, hydrothermal, and metamorphic rocks (Sagnotti, 2007). Pyrrhotite has been used as an index mineral in metamorphic belts to delineate isograds (Crouzet et al., 2001; Horng et al., 2012). Crouzet et al. (2001) reported a pyrrhotite-held postmetamorphic partial thermoremanent magnetization in metamorphic rocks acquired during postorogenic uplift. Pyrrhotite as a dominant magnetic mineral with subordinate goethite has been reported from the Hsuehshan Range of Taiwan (Horng et al., 2012), where it is interpreted to have undergone transformation from pyrite during regional metamorphism, with the latter the most common nonmagnetic iron sulfide in the younger nonmetamorphosed strata. In this example, the presence of goethite is interpreted as a weathering product of pyrrhotite.

Although variable in concentration, the widespread presence of pyrrhotite found in the rocks of northern Kohistan is likely attributable to thermochemical/metamorphic and uplift-related causes. Variation in pyrrhotite concentration in the study area is likely to be due to regional variations in these causes because the Kohistan Arc has experienced and continues to experience uneven deformation as a result of indentation of the Indian Plate into Asia. This variation is recorded in two ways: 1) a visible increase in pyrrhotite concentration as a result of enhanced thermochemical activities closer to the NSZ, and 2) an increasing impact of these effects from west to east along the northern margin of the Kohistan Arc, a likely consequence of the anticlockwise rotation of India that is accompanying the indention. Paleomagnetic results from this area (Zaman and Torii 1999; Zaman et al., 2013) report a remanence direction carried by pyrrhotite comparable to the present geomagnetic field direction, indicating acquisition in recent geological time and the

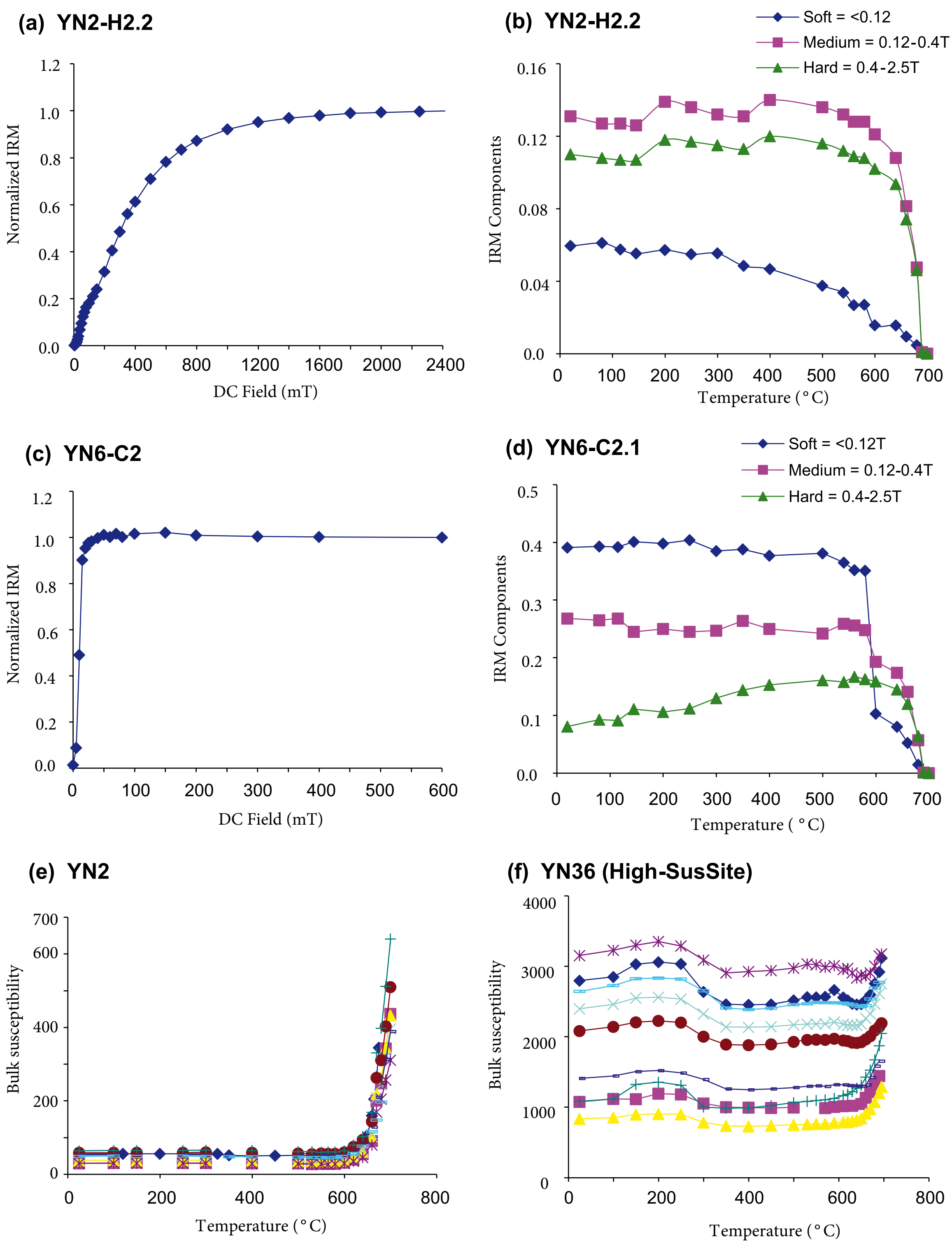

Figure 7. Magnetic characteristics of red bed samples from the Yasin locality, NE Kohistan: IRM acquisition curves for coercivity spectrum analyses (a, c), thermal demagnetization of three component IRMs (b, d), and magnetic susceptibility variation with temperature (e, f). In contrast to NW Kohistan, magnetic minerals in red beds of this locality are dominated by recently formed pyrrhotite and magnetite.

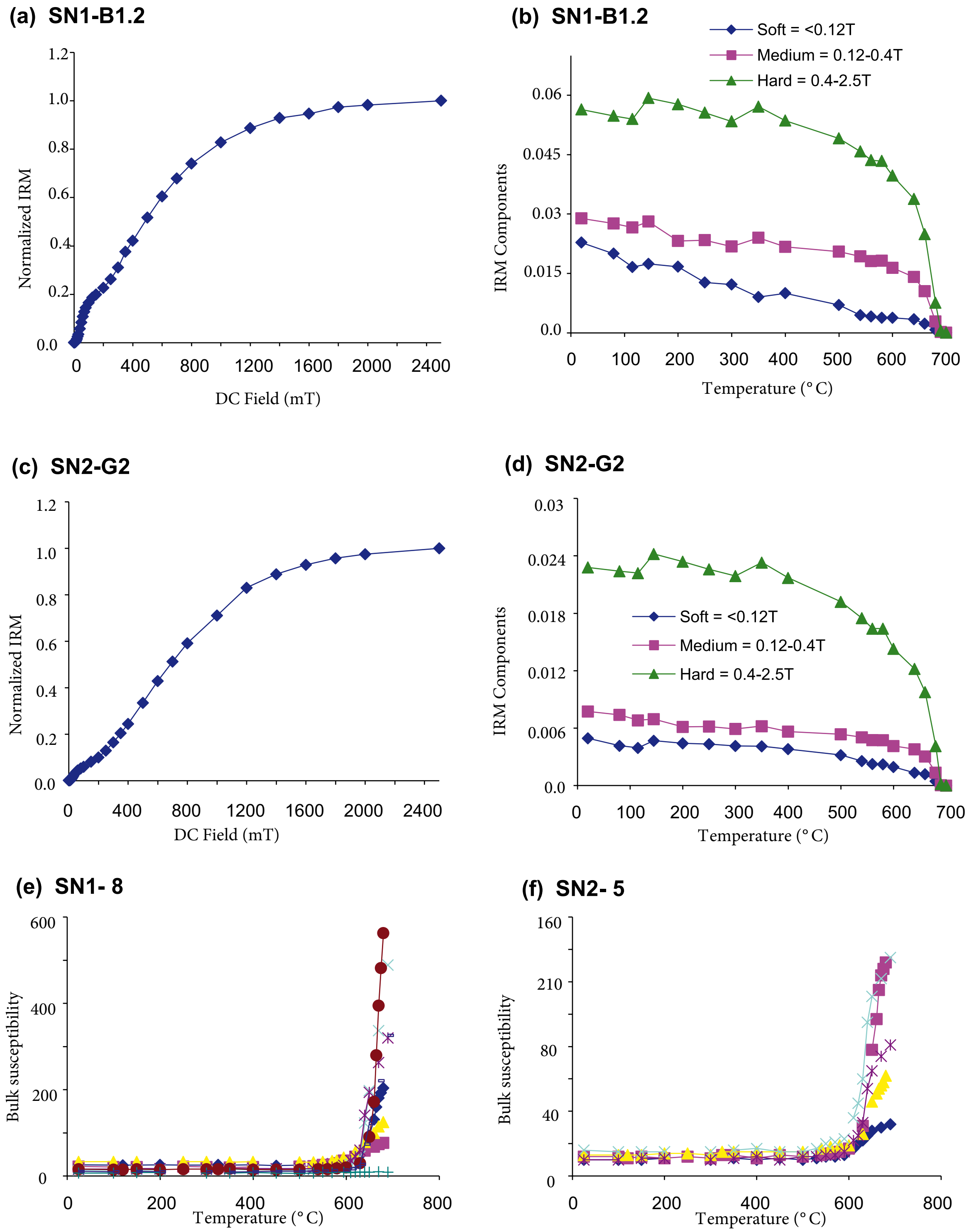

Figure 8. Magnetic characteristics of the red bed samples from the Sandhi locality, NE Kohistan: IRM acquisition curves for coercivity spectrum analyses (a, c), thermal demagnetization of three component IRMs (b, d), and magnetic susceptibility variation with temperature (e, f). In addition to hematite, pyrrhotite and altered magnetite are present as remanence carriers.

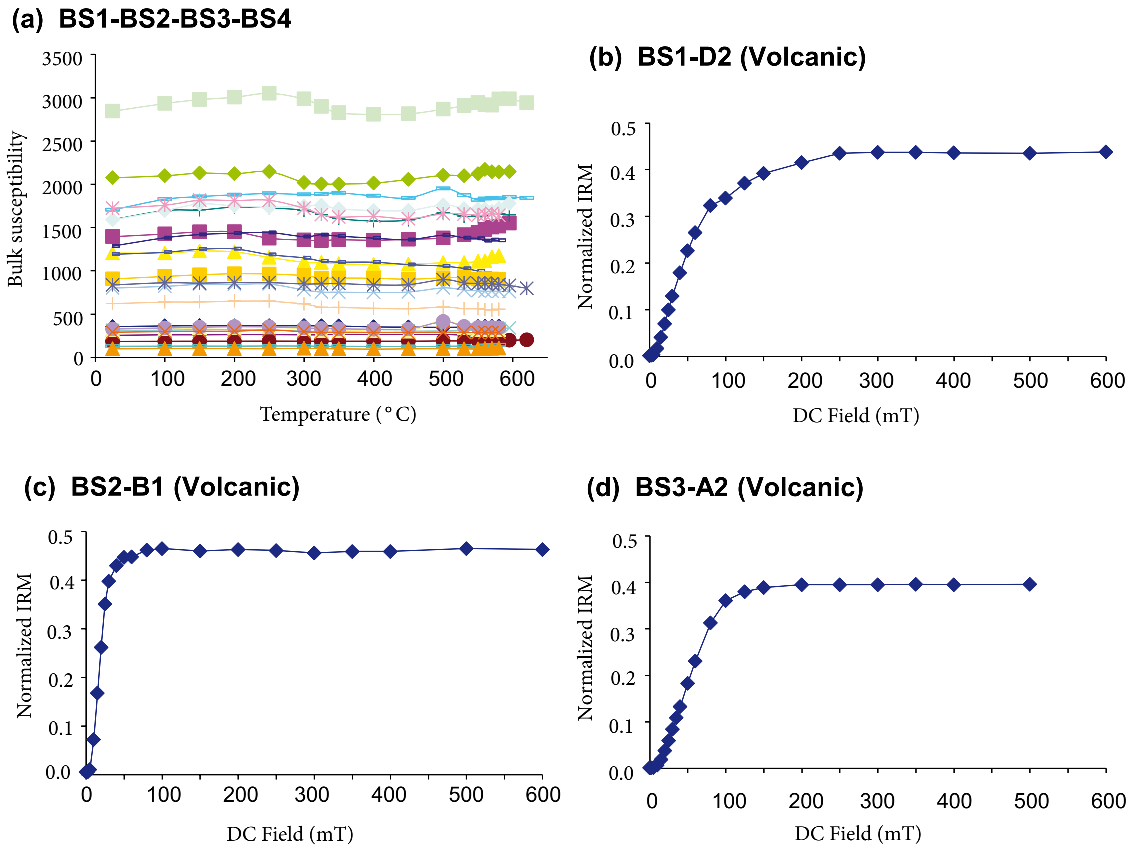

Figure 9. Magnetic characteristics of volcanic samples from the Baris locality, NE Kohistan. IRM acquisition curves for coercivity spectrum analyses (b, c, d) and magnetic susceptibility variation with temperature (a). Magnetic mineralogy of rocks from this locality is dominated by recently formed pyrrhotite and altered magnetite.

ongoing nature of thermometamorphic activity in the Kohistan Arc.

6.2. The magnetic signature of thermochemical activity in Kohistan deduced from paleomagnetism

The reported paleomagnetic signature from NW Kohistan (Zaman and Torii, 1999) indicates systematic decrease in stability of remanent magnetization approaching the NSZ. A high temperature component carried by hematite in red beds of the Purit Formation located at a maximum distance from the NSZ among the studied formations is the most stable magnetization (probably of primary origin). Rocks from the Drosh Formation located relatively closer to the NSZ reveal altered magnetite, pyrrhotite, and secondary hematite as remanence-carrying minerals indicating partial overprinting of the primary magnetic grains by the thermochemical activity. Magnetization in rocks of the NSZ is in turn clearly secondary in nature and acquired in recent geological times by hematite, which may record alteration of pyrrhotite and implies increasing thermochemical activity along the suture zone. From these characteristics in NW Kohistan, we interpret rocks at a distance from the suture zone as less intensely remagnetized compared with their counterparts in the NSZ and defining an increase in thermochemical/metamorphic activity towards the NSZ.

A combination of previous paleomagnetic data and the present rock magnetic results from NE Kohistan conform to the trend of magnetization observed in NW Kohistan, where secondary magnetization is stronger near the NSZ. Probable primary hematite is observed from rock magnetic and paleomagnetic investigations in NW Kohistan, indicating relatively low grades of thermochemical/metamorphic activity. The rocks of NE Kohistan are, however, significantly altered by such activity in the recent past as shown by widespread pyrrhotite carrying a record of the recent geomagnetic field and replacing a record of older magnetization in these rocks.

Due to the continued northward push of India into Asia a record of different paleomagnetic components indicates a divergence in declinations within the Kohistan Arc (Zaman et al., 1999, 2013), suggesting that this paleo-arc may not have acted as a rigid block following collision with India but may have been deformed by movement along localized shears and faults.

6.3. Variations in magnetic behavior towards the NSZ

Rocks of the Purit Formation from NW Kohistan (the farthest studied unit from the NSZ) carry a probable primary remanent magnetization residing in detrital specular hematite and implying a negligible effect of metamorphism on these rocks compared to those closer to the NSZ (Figure 10a). The rocks of the Drosh Formation located between the Purit Formation and the NSZ share a mixed ferromagnetic assemblage of secondary hematite, pyrrhotite, and magnetite. Formation of pyrrhotite and its partial conversion to magnetite and then to hematite is interpreted to be a result of enhanced thermochemical activity. In contrast to the Purit and Drosh formations, magnetic mineralogy of rocks in the NSZ is dominated by unstable domain structures in magnetic minerals such as pyrrhotite with subordinate magnetite and hematite. Paleomagnetic study of rocks from the NSZ (Zaman and Torii, 1999) reveals remanence directions near the present geomagnetic field direction and this young signature is taken as a sign of continuing thermometamorphic activity in the study area. The distribution of magnetic minerals in the study area and the link to variable thermometamorphic activity within a 10-km strip south of the NSZ is illustrated in Figure 10a. The arrow directions correspond to decrease in magnetic stability and presumed increase in thermometamorphic activity closer to the NSZ. This conforms with other studies reporting rocks along collisional margins to be more intensely remagnetized compared to their counterparts within the indenting tectonic blocks (e.g., Dekkers and Linssen, 1989; McCabe and Elmore, 1989; Katz et al., 1998; Rowan and Roberts, 2008; Meijers et al., 2011; Appel et al., 2012; Elmore et al., 2012; Van Der Voo and Torsvik, 2012).

6.4. Variations in magnetic behavior between NW and NE Kohistan

In addition to N-S variation, another magnetization trend is observed between NW and NE Kohistan (Figure 10b). In NW Kohistan magnetizations are generally stable compared to their counterparts in the NE, but this stability reduces towards NE Kohistan as indicated by secondary magnetizations in rocks of the Phandar area (Ahmed et al., 2001). Paleomagnetic results from Paleocene volcanic and plutonic rocks, exposed at some distance from the NSZ in central Kohistan, reveal secondary magnetite as the main magnetic carrier with optical observations showing a significant effect of low grade metamorphism (Ahmed et al., 2001) and remanence of secondary origin evident from the characteristic remanent magnetization in these rocks. Secondary magnetizations are also reported from an area across the NSZ at the longitude of the Karakoram Block (Klootwijk and Conaghan, 1979; Klootwijk et al., 1994).

Moving further towards the NE rock magnetic results from the Yasin valley area reveal a different picture. Red beds and volcanics here have been completely remagnetized at different stages in their history. Widespread presence of recently formed pyrrhotite may indicate an increase in the metamorphic grade and its associated thermochemical effects. In contrast to the Yasin-Gupis area of NE Kohistan, pyrrhotite is not generally identified as a main magnetic carrier in rocks of the Phandar and Drosh areas, a likely consequence of low degrees of thermometamorphic activity in central and NW Kohistan. The pyrrhotite-resident mean paleomagnetic direction from NE Kohistan is almost identical to the present geomagnetic field direction (Zaman et al., 2013), indicating acquisition by enhanced thermometamorphic activity in recent times.

6.5. Comparison of highly magnetized areas with metallic mineral zones in Kohistan

The metallic mineral potential of North Pakistan has been studied by some researchers. As reported by Calkins et al. (1981), the chlorite schist of the Gawuch Gol locality (Shishi valley, NW Kohistan) contains numerous sheared and altered zones, mostly related to the major faults in the area. These shear zones contain traces of galena, secondary malachite, and azurite. Their analyses of the ore-bearing quartz revealed the presence of silver, copper, lead, antimony, zinc, and vanadium. In the Kaldam Gol locality of Shishi valley, they found chalcopyrite, galena, pyrite, and secondary malachite in a brown-weathering breccia zone. From the surface exposures, the ore reserve has been estimated to be on the order of several hundred tons. They also reported many copper showings in the volcanic greenstone and amphibolites of the Drosh-Shishi area, which occur as chalcopyrite in small local veins and shear zones. On the Drosh-Chitral road, traces of chalcopyrite, pyrite, and malachite have been observed at the edges of thin quartz veinlets. In all these areas, the vein deposits were recognized along the fault zones as places of high metallic mineral potential. According to an unpublished report (Shakirullah, 2003), granitoid-hosted sulfide metals (copper-lead-antimony) occurred in various localities of the Drosh-Shishi area (NW Kohistan). Disseminated copper sulfides (copper-iron) have also been found as common minerals in a 4-km belt of the Dommel Nisar area, which the author considered a top priority target in NW Kohistan.

Due to very rough and inaccessible topography, no metallic mineral data are reported from the central parts of Kohistan. However, Sheikh et al. (2104) reported the widespread occurrences of base metal mineralization in the Golo Das and surrounding areas of the Ishkuman valley (NE Kohistan), which is not far from our study area in NE Kohistan. As per their observations, the rocks just south of the NSZ are highly deformed and metamorphosed (greenschist to amphibolites facies); however, the volcanic rocks at some distance from the NSZ are relatively

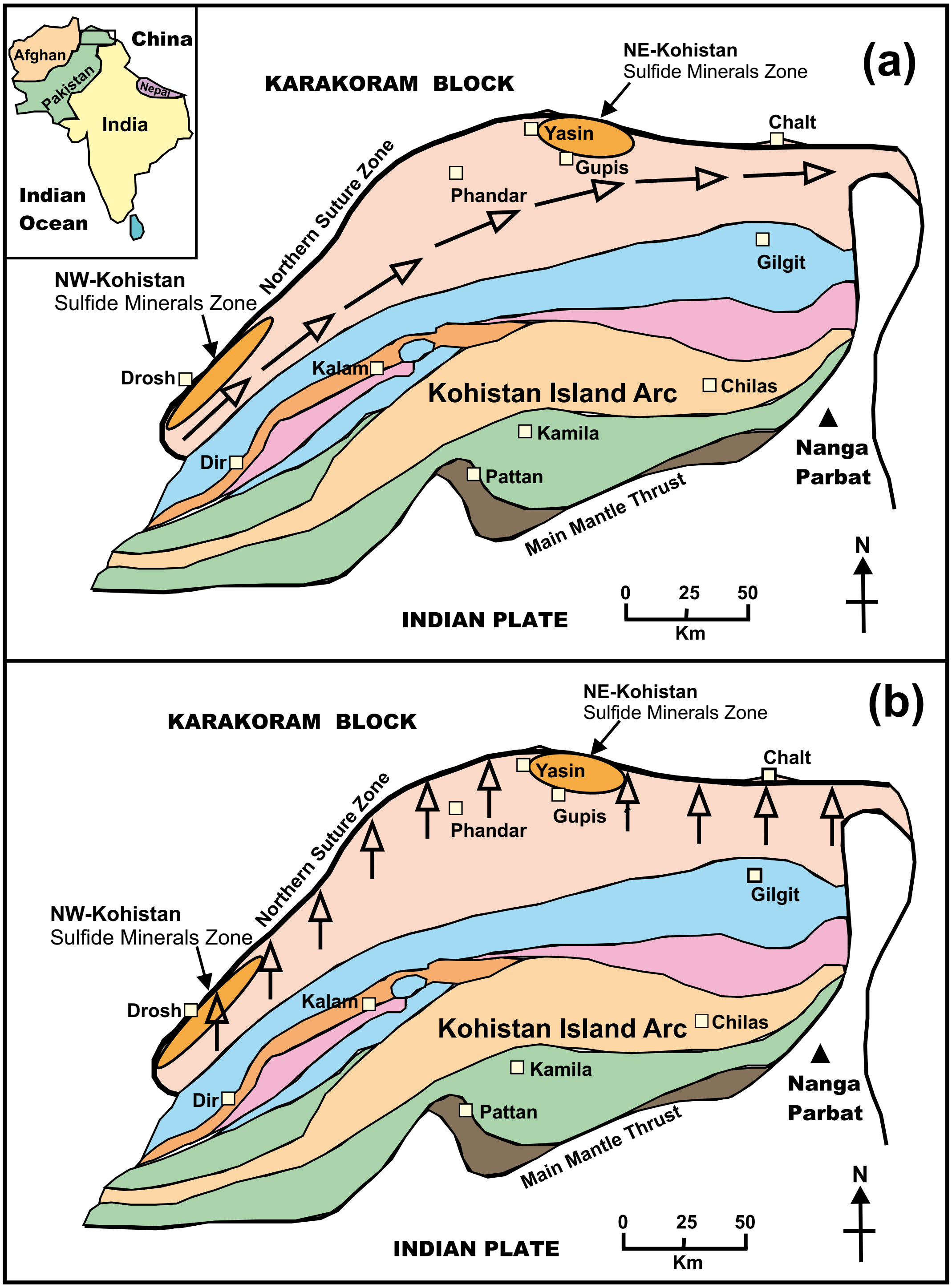

Figure 10. Proposed models to demonstrate changes in the level of remagnetization caused by variable thermotectonic metamorphic activity in a zone adjacent to the Northern Suture Zone in Kohistan Arc. (a) An increase in thermometamorphic grade is indicated by the arrow direction between NW and NE Kohistan, where a significant increase is observed in the NE. (b) Another trend of such activity is shown by arrow direction from south to north, reaching its maximum level in the suture zone area. The golden-colored ellipses near the Drosh and Yasin areas indicate the reported sulfide mineral zones in NW and NE Kohistan, respectively.

compact, less deformed, and less metamorphosed. They found numerous sulfide-bearing alteration zones along the sheared zones formed by faulting. In addition, the leaching of pyrite and chalcopyrite to malachite, azurite, and hematite is found to be ubiquitous along these zones, while iron ores (e.g., magnetite, hematite, specularite, and ilmenite) formed by skarnification are commonly observed in the calcareous rocks. The enrichment of Cu, Co, Au, and Ag and depletion of Pb, Zn, Ni, and Cr in the sulfide-bearing sheared zones have also been detected, attributed to hydrothermal alteration and leaching in the area.

As reported by Sagnotti (2007), pyrrhotite is usually associated with chalcopyrite, pyrite, pentlandite, sphalerite, galena, magnetite, and arsenopyrite. The widespread presence of pyrrhotite predicted by our rock and paleomagnetic studies thus matches well with the reported chalcopyrite- and pyrite-dominated sulfide zones in the study area (Figure 10). In addition, comparison of the highly magnetized zones in NW and NE Kohistan with the metallic minerals zones in the study area support our interpretation of stronger hydrothermal/thermochemical activity in the areas along the NSZ compared to those inward in the Kohistan Arc.

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