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Magnetic susceptibility of some Lesser Himalayan rocks in central Nepal

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ABSTRACT

Variation in magnetic susceptibility (MS) along highways has been measured in rock outcrops within the Nepalese Lesser Himalaya in the following road sectors: Kathmandu-Mugling-Jugedi along the road that joins Kathmandu and Narayanghat, and Mugling-Pokhara-Ramdighat-Kerabari sector along Prithvi and Siddhartha highways. A pocket susceptibility meter (ZH Instruments SM30) was used to measure MS *in situ* on the flat surfaces at roadside or river/stream exposures of rocks that belong to Nawakot Complex, Kathmandu Complex, Sirkot Group, Kali Gandaki Super Group and Tansen Group in the inner and outer parts of the Lesser Himalaya. Site mean MS (average of 15 readings at each outcrop) data reveal the following characteristics: (i) A large range of average MS between (-0.003 to 5.1) x 10^{-3} SI; (ii) Lowest MS magnitudes (<0.1 x 10^{-3} SI) for quartzite, quartzose sandstone, limestone, dolomite, which are predominantly composed of diamagnetic minerals (quartz, calcite and dolomite); (iii) Intermediate range of (0.1-1.0) x 10^{-3} SI is found in most shales, diamictites, slates, phyllites, sandstones, schists; and (iv) High values (1.0–5.1) x 10^{-3} SI for amphibolite schists, metasandstones, sandstones with volcanic detritus, hematite-rich sediments and trachytes or trachyandesites. MS has good potential for finer-scale discrimination of geological formations represented by macroscopically similar lithologies, especially those composed by predominantly quartz or carbonate minerals, inability of whose objective identification has led to proliferation of formations in the geological literature.

Keywords: Physical properties, magnetic susceptibility, Nawakot Complex, Kathmandu Complex, Tansen Group, Kaligandaki Supergroup, Lesser Himalaya

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INTRODUCTION

Knowledge on the distribution of soils, sediments and rocks is a prerequisite for prospecting of the mineral resources, effective planning and execution of engineering geological works (e.g., selection of alignments for roads, powerlines and cable car, landslide mapping and prevention measures, hazard mapping, selection of sites for construction of large buildings and public infrastructures such as airports, convention facilities), groundwater exploration and so on. While geological traverses or aerial mapping of a particular area characterized by abundant fresh rock outcrops by geologists may be adequate for understanding the surficial geology, acquiring detailed knowledge on subsurface distribution of rocks/soils or mineral deposits or deciphering the structural details often requires supplementary field surveys and laboratory analyses using geochemical and geophysical methods of exploration utilizing sound knowledge of the geochemical characteristics (chemical composition, geochemical haloes, vertical soil profiles, etc.), physical properties (density contrasts among rocks and created by them variation of gravity in natural medium, electrical resistivity, magnetic susceptibility, acoustic impedance contrast or differences in velocity of propagation of seismic waves in natural media, radioactivity of rocks and ores, thermal conductivity and geothermal gradient, etc.) and the geophysical anomalies (caused by the physically contrasting media) detectable at the surface or along a borehole using appropriate sensors or logging devices.

Magnetic susceptibility (MS), one of the physical properties widely used in mineral and oil exploration, has been commonly used recently also for rapid assessment of quality and quantity of magnetically differentiable material in land, water and air systems in natural media or even for assessment of the degree of pollution or contamination by pollutants or heavy metals due to anthropological activities (Petrovsky and Elwood 1999; Gautam et al. 2000a, Gautam et al. 2004, 2005).

In this paper, we have presented data on *in situ* MS of the rocks from the Nepalese midlands both from the Outer and Inner Lesser Himalaya (*sensu* Sakai 1983). It aims to augment the sparse database of the physical properties of the

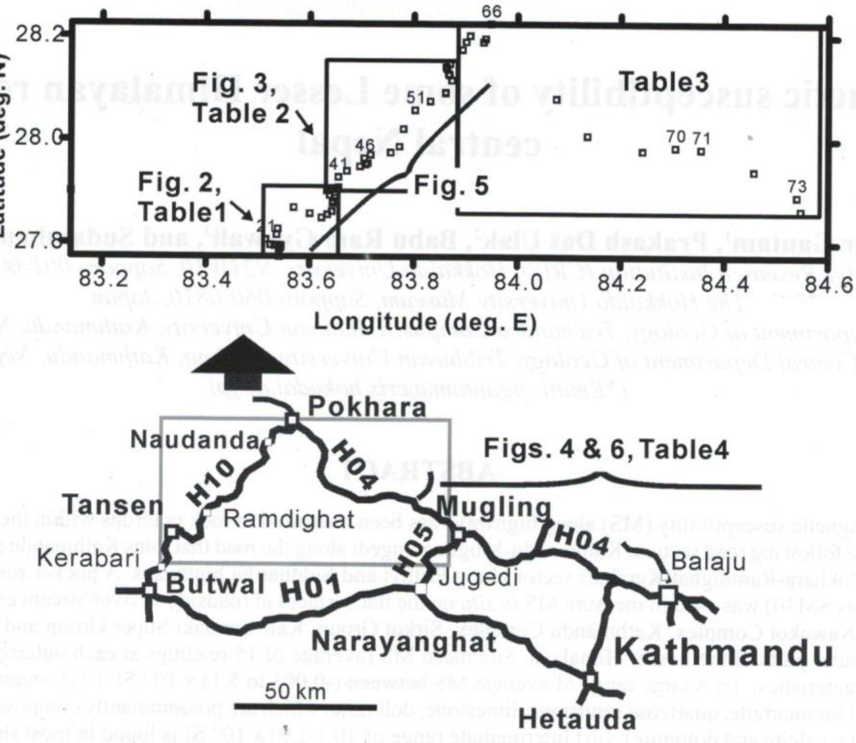

Fig. 1: Google Map® extracted segment within the central Nepal with the approximate traces of the major roads. Magnetic susceptibility (MS) traverses are related to the roads H04 (Kathmandu-Mugling-Pokhara: Prithvi Highway), H05 (Mugling-Narayanghat sector) and H10 (Siddhartha Highway; Pokhara-Butwal sector). The inset shows the MS measurement sites of the Lesser Himalayan rocks along the Kerabari-Ramdighat-Naudanda-Pokhara-Mugling road sector that falls within the rectangular area shown on the left side of the map. Sites within the smaller rectangles are detailed further in Figs. 2 and 3.

rocks and ores in the Nepal Himalaya (Gautam et al. 2000b; Rochette et al. 1992).

FIELD METHODOLOGY AND DATA PROCESSING

Field measurements of *in situ* MS were made along discrete sites along the major roads (H04: Kathmandu-Pokhara Highway, H10: sectors belonging mainly to Kerabari-Pokhara sector of Siddhartha Highway, and H05: Jugedi-Mugling road sector) using a SM 30 (ZH Instruments, Czech Republic) hand-held/pocket magnetic susceptibility meter (Fig. 1). Typical measurement was a road-side rock exposure, as fresh as possible in terms weathering and characterized by smooth surfaces/faces to which the susceptibility sensor could be firmly attached. At each site, at least 15 spot readings were taken on rock surfaces of macroscopically identical lithology distributed over an area of several square meters. MS measurement at each site was accompanied with GPS reading of the site and the outcrop characteristics such as rock type, structure, texture, color, degree of uniformity, degree of weathering. Each measurement site has been assigned commonly with a number and a 4-character index that incorporates the abbreviations for the formation name and the rock type (e.g. NpSs; Np = Nourpul Formation, Ss= sandstone).

Data processing involved calculating simple statistical parameters using a MS EXCEL worksheet: min, max, arithmetic average and standard deviation. Most measurement sites are identified in existing geological maps, and the susceptibility profiles plotted after projecting them into representative directions (Figs. 2 and 3) or as a function of the site longitude (Fig. 4), or just presented in diagrams that allow an appraisal of the range of MS variation by lithological composition (Figs. 5 and 6). In some cases, such as the presence of rhythmic alternation of layers of differing lithologies, MS was measured along short profiles with close spacing (e.g., every 25 cm; Fig. 3, right side). The measured dataset will be considered below according to the measurement sectors, for which detailed geological schemes are available.

RESULTS OF IN SITU MAGNETIC SUSCEPTIBILITY (MS) MEASUREMENTS

Kerabari-Ramdighat Section

The road in this area passes through the sedimentary rocks mapped into Tansen Group and Kali Gandaki Super Group (Sakai 1983, 1985). Fig. 2 (left) shows the site locations along an approximate road trace, along which the boundaries of formations (e.g., Kb=Kerabari, Si= Sisne, etc. following

Table 1: In situ magnetic susceptibility (MS) data derived from measurements at rock outcrops along the Kerabari-Aryaghat-Ramdighat sector of Siddhartha Highway

Site	Site coordinates		Magnetic susceptiblity				Formation name	Lithological index
	Latitude (deg. N)	Longitude (deg. E)	Mean	Min	Max	Stdev		
			(in 10^{-3} SI)					
Kerabari-Ramdighat Sector (Stratigraphic Nomenclature after Sakai 1983, 1985)								
1	27.7739	83.5410	0.000	0.015	0.247	0.004	Kerabari Fm.	KbLm
2	27.7821	83.5404	-0.014	0.021	0.184	0.009	Kerabari Fm.	KbLm
3	27.7865	83.5406	0.001	0.014	0.217	0.004	Kerabari Fm.	KbLm
4	27.7904	83.5428	0.121	0.218	0.085	0.027	Sisne Fm.	SiDm
5	27.7896	83.5418	0.098	0.179	0.127	0.020	Sisne Fm.	SiDm
6	27.7934	83.5447	0.156	0.226	0.179	0.022	Sisne Fm.	SiDm
7	27.7946	83.5443	0.089	0.260	0.158	0.043	Charchare Cglm. Mb.	ChCg
8	27.7946	83.5442	0.219	0.644	0.220	0.113	Taltung Fm.	TaSs
9	27.7953	83.5402	-0.005	0.233	0.114	0.080	Amile Fm.	AmQt(Fe)
10	27.7953	83.5402	0.022	0.243	0.154	0.064	Amile Fm.	AmQt(Ca)
11	27.7960	83.5326	0.064	0.102	0.008	0.011	Dumri Fm.	DuSs
12	27.7956	83.5326	0.227	0.336	0.000	0.031	Bhainskati Fm.	BhSh
13	27.7957	83.5328	0.896	2.000	0.097	0.361	Bhainskati Fm.	BhHm
14	27.7958	83.5328	0.136	0.331	0.066	0.062	Bhainskati Fm.	BhSh
15	27.7953	83.5324	-0.004	0.022	0.034	0.009	Amile Fm.	AmQt
16	27.7949	83.5319	0.531	1.020	0.042	0.142	Taltung Fm.	TaSs
17	27.7948	83.5318	0.204	0.440	0.078	0.075	Taltung Fm.	TaCg
18	27.7961	83.5246	0.545	1.660	0.041	0.283	Bhainskati Fm.	BhHm
19	27.7963	83.5243	0.018	0.065	1.340	0.012	Dumri Fm.	DuSh(pr)
20	27.7963	83.5243	0.057	0.080	0.302	0.007	Dumri Fm.	DumSh(rd)
21	27.8064	83.5148	0.093	0.137	0.116	0.012	Dumri Fm.	DuSs
22	27.8159	83.5361	0.144	0.262	0.162	0.033	Heklang Phyllite	HePh
23	27.8272	83.5379	0.003	0.047	0.028	0.012	Angha Khola Fm.	An?Qt
24	27.8686	83.5692	-0.003	0.016	0.011	0.005	Taltung? Qtz	TaQt
25	27.8569	83.6002	0.001	0.025	0.014	0.006	Amile? Qtz	AmQt
26	27.8493	83.6224	0.090	0.227	0.201	0.046	Dumri Fm.	DuSs
27	27.8551	83.6338	0.143	0.244	0.211	0.029	Sisne-diamict/shale.	SiDm/Sh
28	27.8613	83.6423	0.089	0.175	0.131	0.022	Chhappani white qtz	ChQt(wh)
29	27.8875	83.6479	0.085	0.149	0.115	0.016	Khoraidi dol	KhDl
30	27.8773	83.6442	0.048	0.139	0.103	0.027	Chhappani Fm.	ChQt(gr)
31	27.8810	83.6437	0.031	0.105	0.074	0.019	Khoraidi Fm.	KhDl
32	27.8926	83.6386	0.070	0.247	0.206	0.044	Ramdighat Fm.	RmSl
33	27.8905	83.6480	0.206	0.070	0.247	0.044	Saidi Khola Bds.	SKRh

Note: Statistics is based on 15 or more measurements on smooth surfaces randomly distributed at each outcrop. In the index given in the last column, the first two characters indicate Formation/Member name (Am: Amile; An:Angha; Be: Benighat; Bh: Bhainskati; Ca: Charchare; Ch: Chhappani; Du: Dumri; Dh: Dhading; He: Heklang; Kb: Kerabari; Kh: Khoraidi; Kn: Kunchha; Nd: Naudanda; Ng: Nayagaon; Np: Nourpul; Sk: Saidi Khola; Si: Sisne; So: Sorek; Ta: Taltung; Ri: Ripa), and the following two characters stand for predominant rock type (Cg: conglomerate; Dl: dolomite; Dm: diamictite; Hm: hematite-rich rock; Qt: quartzite (Fe: ferrugineous; Ca: calcareous; wh: white; gray)); Lm: limestone; Ph: phyllite; Rh: rhythmite; Sh: shale (pr: purple; rd: red); Sl: slate; Ss: sandstone;). The site locations are shown in Figs. 1-2 and profiles.

Sakai 1983) are shown. A MS plot along line A-A' into which the data presented in Table 1 are projected is given in the right side. Sites 1-21 in the southern limb of the Tansen syncline encompass limestone (Kerabari Formation), diamictite and shale (Sisne Formation), silt/sandstone with volcanic detritus of Taltung Formation with conglomerate known as Charchare, quartzite (Amile Formation), hematite-rich oölitic bed and red purple and black shales (Bhainskati Formation), and sandstone with variegated shales (Dumri Formation). Except for the Kerabari Formation that belongs to the Kali Gandaki Supergroup, the other formations constitute the Late Paleozoic to Oligocene or even Miocene Tansen Group (Gautam 1989, 1994; Hirayama et al. 1988; Sakai 1983). Sites 28-33 in the northern part represent the exposures of quartzite (Chhappani Formation), dolomite (Khoraidi Formation), slate (Ramdighat Formation), and rhythmite (Saidi Khola Formation), all belonging to the Kali Gandaki Super Group. Sites 22-23 are situated within the Palpa Klippe formed by the Kali Gandaki Super Group, whereas sites 24-27 belong to the northern limb of the Tansen Syncline. The Taltung Formation

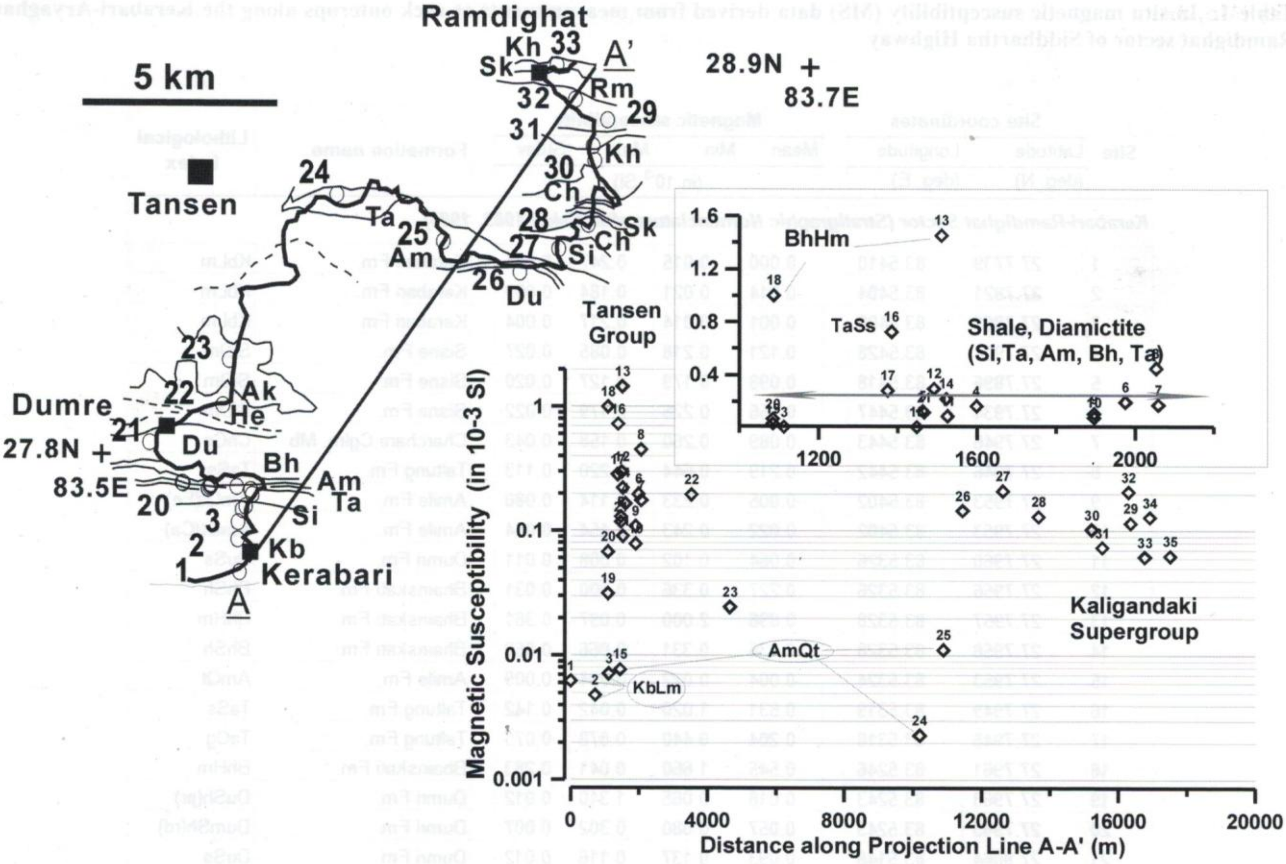

Fig. 2: Locations of the MS measurement sites along the Kerabari-Aryabhanjyang-Ramdighat road route of Siddhartha Highway plotted in the geological map by Sakai (1983, 1985). For MS data, refer to Table 1.

contains lenticular pockets of volcanic rocks, which are not exposed along this road, but boulders of the trachytic rocks found along the Tinau Khola just below the southernmost measurements site were measured for MS.

To be brief, measurements data (Table 1 and Fig. 2) from this area reveal that MS varies by >3 orders of magnitude. Kerabari Limestone has consistently low MS (for clarity, presented hereafter as number or the range without the measurement unit of 10^{-3} SI) below 0.007. Amile quartzite also has low MS range of 0.002-0.03. Rocks of the Kali Gandaki Supergroup have restricted MS range (0.006-0.02). High MS range (0.9-1.5) characterizes hematite-rich beds and siltstone with volcanic detritus of the Tansen Group. Trachytes of the Aulis volcanics possess the largest MS values (4.9-5.7).

Ramdighat-Naudanda road section

Geology of this area is known in detail as compiled and revised in the latest map by Dhital et al. (2002). Along the road section subjected to susceptibility measurements, we encountered the Sirkot Group (?Late Proterozoic) comprised by the Sorek Formation with Ripa Member, the Upper Nawakot Group (? Late Proterozoic) represented here by the Benighat Slates, and the Lower Nawakot Group (? Early to Middle Proterozoic) made up of Kuncha Formation, Naudanda Quartzite, Nayagaun Formation, Nourpul Formation, and Dhading Dolomite – most of which correspond to their counterparts in the Kathmandu region. The exposures of the Sorek Formation with Ripa Member at the southern end of the profile in the map of Dhital et al. (2002) adapted here mostly correspond to the Khoraidi Formation with Saidi Khola Beds of Sakai (1985).

The MS variation data presented in Table 2 and plotted along profile B-B' in Fig. 3 left clearly distinguishes dolomite from Dhading Dolomite and quartzite of Naudanda Formation as having the lowest range (0.001-0.01) from other rocks with high values reaching as high as 0.4. An excellent outcrop comprised by alternating beds of stromatolite-rich dolomites and dark colored siliceous beds with occasional chert bands available at site 36-7 has been measured in detail. Results reveal that the average MS magnitude for these two types of rocks (dolomites and siliceous rocks) has no appreciable difference judging from the average parameters for a dozen or more spot measurements. Measurements along a profile with closed spacing (25 cm), however, show that there is a clear quasi-periodic variation of MS along the profile (the inset at lower right corner of Fig. 3). It is desirable that this unique outcrop in the Nepalese Lesser Himalaya is subjected to detailed geochemical analyses including the isotopic signature to reveal its true paleoenvironmental significance.

Naudanda-Mugling road section

The rocks along this route are represented mostly by the low-grade metamorphic rocks comprised by phyllites (Kunchha Formation), dolomites (Dhading Dolomite), and quartzites or quartz phyllites which are attributed to the Lower Nawakot Complex. Quartzites and sandstones, which are difficult to assign to a particular lithostratigraphy are encountered occasionally. MS data obtained from sites 61-74 (see Fig. 1 for their locations) are presented in Table 3. Lowest MS range (0.01-0.03) is found in dolomites, whereas quartzites show large variation (0.0005-0.15). Phyllites exhibit variable MS (0.09-0.19), with the tendency to increase with the content of chlorite. Taking into account the rather high degree of weathering of these roadside rock outcrops, such minor variation in MS has limited value for detailing the individual rock formations in this sector.

Jugedi-Mugling-Kathmandu-Balaju road section

The area dealt with forms a part of 'the Kathmandu area and Central Mahabharat range' mapped around 1980 by J. Stocklin, K.D. Bhattarai and others at the Department of Mines and Geology (DMG 1980). Two major rock assemblages are recognized: i) Nawakot Complex: a part of the Lesser Himalayan sediments consisting almost exclusively of low grade (sericite chlorite) metasediments; and (ii) Kathmandu Complex: a part of the Lesser Himalayan crystallines consisting of relatively high grade metasediments (up to garnetiferous schists) but also including unmetamorphic or weakly metamorphosed sediments having fossils of early Middle Paleozoic age on top and containing granites and gneisses. A major discordance known as the Mahabharat Thrust (MT) separates the Nawakot Complex below from the Kathmandu Complex above. The Kathmandu Complex and Nawakot Complex constitute the core and peripheral part of the WNW-ESE trending structure: Mahabharat Synclinorium. As the geology of the area is detailed in numerous publications elsewhere, this paper identifies the locations of the sites measured for MS along an approximate

Table 2: In situ magnetic susceptibility (MS) data derived from measurements at rock outcrops along the Ramdighat-Naudanda sector of Siddhartha Highway

Site	Site coordinates		Magnetic Susceptiblity				Formation name	Lithological index
	Latitude (deg. N)	Longitude (deg. E)	Mean	Min	Max	Stdev		
			(in 10^{-3} SI)					
Ramdighat -Naudanda Sector (Stratigraphic Nomenclature after Dhital et al. 2002)								
34	27.8984	83.6556	0.062	0.019	0.184	0.055	Sorek Fm.	SoSl
35	27.8936	83.6510	0.129	0.058	0.217	0.048	Sorek Fm.	SoSl
36-7	27.9014	83.6582	0.063	0.049	0.085	0.011	Sorek Fm., Ripa Mb.	RiDl
39	27.9046	83.6615	0.108	0.064	0.127	0.014	Sorek Fm.	SoSl
40	27.9165	83.6719	0.127	0.085	0.179	0.030	Sorek Fm.	SoSl
41	27.9302	83.6849	0.128	0.095	0.158	0.016	Benighat Slates	BeSh
42	27.9483	83.7013	0.188	0.148	0.220	0.019	Benighat Slates	BeSh
43	27.9546	83.7073	0.067	0.043	0.114	0.018	Benighat Slates	BeSl
44	27.9569	83.7091	0.132	0.099	0.154	0.016	Benighat Slates	BeSh
45	27.9617	83.7134	0.003	0.000	0.008	0.003	Dhading Dolomite	DhDl
46	27.9691	83.7202	0.000	-0.008	0.000	0.004	Dhading Dolomite	DhDl
47	27.9906	83.7397	0.070	0.032	0.097	0.015	Nourpul Fm.	NpSs
48	28.0047	83.7528	0.033	0.016	0.066	0.013	Benighat Slates	BeSl
49	28.0269	83.7737	0.025	0.009	0.034	0.006	Dhading Dolomite	DhDl
50	28.0585	83.8019	0.028	0.013	0.042	0.008	Sorek Fm.	SoSs
51	28.0810	83.8228	0.059	0.026	0.078	0.016	Sorek Fm., Ripa Mb.	RiDl
52	28.1029	83.8428	0.024	0.007	0.041	0.010	Benighat Slates	BeSl
53	28.1054	83.8450	0.404	0.062	1.340	0.310	Nourpul Fm.	NpSs
54	28.1220	83.8602	0.215	0.156	0.302	0.040	Nourpul Fm.	NpSs
55	28.1270	83.8648	0.067	0.036	0.116	0.024	Nayagaun Fm.	NgSs
56	28.1277	83.8658	0.072	0.025	0.162	0.042	Nayagaun Fm.	NgSs
57	28.1315	83.8687	0.016	0.003	0.028	0.008	Naudanda Quartzite	NdQt
58	28.1332	83.8704	0.000	-0.007	0.011	0.005	Naudanda Quartzite	NdQt
59	28.1390	83.8754	0.003	-0.007	0.014	0.007	Naudanda Quartzite	NdQt
60	28.1481	83.8841	0.162	0.080	0.201	0.036	Kunchha Fm.	KnPh

Note: Statistics is based on 15 or more measurements on smooth surfaces randomly distributed at each outcrop. In the index given in the last column, the first two characters indicate Formation/Member name (Be: Benighat; Dh: Dhading; Kn: Kunchha; Nd: Naudanda; Ng: Nayagaon; Np: Nourpul; Ri: Ripa; So: Sorek), and the following two characters stand for predominant rock type (Dl: dolomite; Qt: quartzite; Lm: limestone; Ph: phyllite; Sh: shale; Sl: slate; Ss: sandstone). The site locations are shown in Figs. 1 and 3 and profiles.

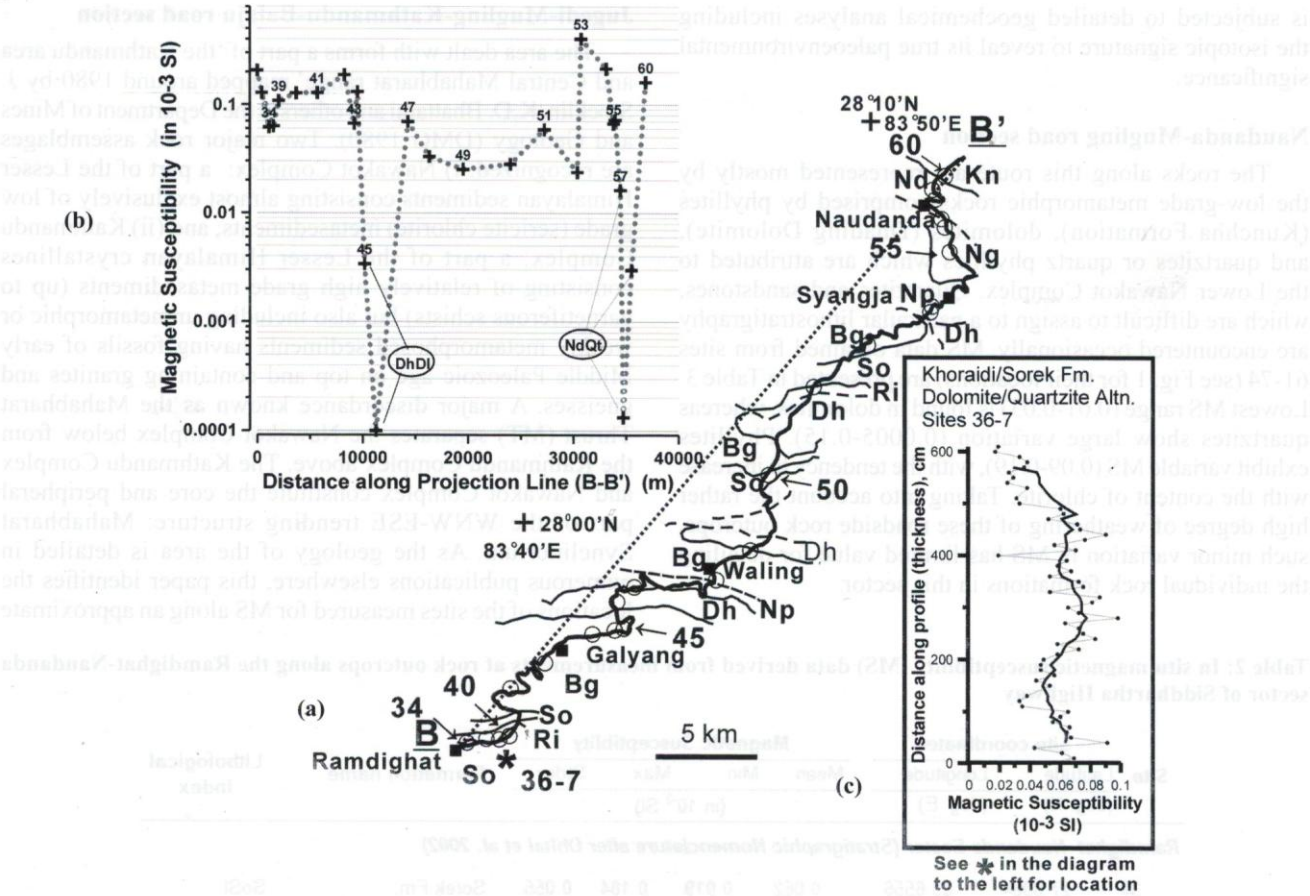

Fig. 3: (a) Locations of the MS measurement sites along Ramdighat-Naudanda road sector superposed on the geological map by Dhital et al. (2002). (b) Left: MS versus distance plot showing MS variation at each site. Note the very low MS values for dolomites and quartzites. For MS data refer to Table 1. (c) Right: a fine-scale MS profile across an overturned sequence of dolomite and siliceous rocks with chert layers at site 36-37. Note the quasi-periodic nature of the MS signal

road trace (Fig. 4, upper diagram) shown in latitude versus longitude plot.

Lithostratigraphic position of these sites is further given in Table 4 along with the statistics for the MS data. The MS profile in the lower part of Fig. 4 illustrates the significant constrasts exhibited by the different lithological units along the road sector. Minimum values (<0.1) are found in dolomites (Dhading Dolomite), quartzites (Fagfog, Purebesi) and limestones from Jogimara. MS of other lithologies ranges beween 0.07 and 0.3. Highest values are found in metasediments (Tistung and Sopyang formations), amphibolites (Robang Formation) and quartzose schists.

INTERPRETATION, DISCUSSIONS AND CONCLUSIONS

Summary of the MS data from Lesser Himalaya

Kerabari-Pokhara (Kerabari –Naudanda road sectors) area

In order to have a rapid appreciation of the considerable variation of MS among different lithologies, and also the varying range of MS in rocks belonging to the same lithology owing to difference in structure, texture, composition, degree of weathering etc., MS data are collectively shown in a special bi-plot (Fig. 5). In this plot, different sites with identical lithology are arranged adjacent to each other in such a way that the average MS magnitude, accompanied with ±standard deviation, increases from left to the right. It is clear from Fig. 5 that MS of carbonates and quartzites varies from negative values to ca. 0.1. Sandstones show rather a narrow range (0.02-0.15), whereas the other lithologies like slates, phyllites, diamictites, rhythmites exhibit even lower ranges. Magnetically most susceptible lithologies are the olive green siltstones/sandstones of Taltung Formation, the hematite-bearing beds of the Bhainskati Formation, and the trachytes of the Aulis Volcanics.

Mugling-Kathmandu (Jugedi-Balaju road sectors) area

A MS versus lithology plot summarizing the measurements in this area is shown in Fig. 6. In this diagram too, carbonates and quartzites show the widest range of MS, but unlike in the Tansen-Pokhara area, some impure quartzites are stronger by an order of magnitude. Metasandstones too

Table 3: In situ magnetic susceptibility data derived from measurements at rock outcrops along the Naudanda-Pokhara-Mugling road sector (Siddhartha and Prithvi highways)

Site	Site coordinates		Magnetic susceptiblity				Lithology	Lithological index
	Latitude (deg. N)	Longitude (deg. E)	Mean	Min	Max	Stdev		
			(in 10^{-3} SI)					
61	28.1750	83.8935	0.108	0.068	0.144	0.026	Gray phyllite w crenulation	KnPh
62	28.1900	83.9006	0.190	0.058	0.256	0.048	Phyllite, sst	KnPh
63	28.2019	83.9081	0.143	0.003	0.243	0.075	Greenish gr gritty phyllite w crenulation, sericite-rich	KnPh
64	28.1898	83.9339	0.094	0.063	0.116	0.015	Gritty phyllite	KnPh
65	28.1962	83.9382	0.144	0.029	0.314	0.100	Light grn gray ser phyllite, crenulated, high value on chl-rich parts	KnPh
66	28.2247	83.9479	0.148	0.086	0.407	0.077	Greenish chl gritty phyllite	KnPh
67	28.0805	84.0748	0.005	-0.008	0.023	0.007	White qtzite	??Qt
68	28.0089	84.1352	0.066	0.037	0.103	0.023	Dark grey sericitic phyllite/slate	??Ph/Sl
69	27.9795	84.2418	0.011	0.000	0.031	0.009	Light gray & smoky dolomite, brecciated	DhDl
70	27.9861	84.3047	0.029	0.015	0.046	0.010	White to smoky grey dolomite	DhDl
71	27.9829	84.3544	0.061	0.042	0.080	0.013	Silvery white green phyllite with soapy surface	??Ph
72	27.9403	84.4569	0.120	0.078	0.161	0.023	Quartzo-phyllite	Qt(Ph)
73	27.8915	84.5396	0.152	0.034	0.819	0.206	Gray quartzite	??Qt
74	27.8648	84.5471	0.092	0.068	0.140	0.019	Gritty phyllite with grn gray sst.	??Ph(Ss)

Note: Statistics is based on 15 or more measurements on smooth surfaces randomly distributed at each outcrop. In the last column, the first two characters indicate Formation/Member name (Dh: Dhading; Kn: Kunchha; ??: unknown), and the following two characters stand for predominant rock type (Dl: dolomite; Ph: phyllite; Qt: quartzite; Sh: shale; Ss: sandstone;). Site locations are indicated in the inset of Fig. 1.

exhibit wide variation between ca. 0.1 to 5. Other low-grade metasediments such as phyllites, schists, and the granite-gneiss lithologies exhibit rather stable MS varying narrowly between ca. 0.1 and 1.

Overall summary of the MS data

In order to characterize many different lithologies comprising the Lesser Himalayan rocks in central Nepal in terms of MS, a summary compilation that points to the importance of MS range rather than a fixed value is given in Table 5. Here, all the rock units are roughly grouped into 3 categories of differing MS ranges of high (>1.0), moderate (0.1-1.0), and low (<0.1). Such categorization is important while using MS to statistically discriminate the Lesser Himalayan lithostratigraphic units (in which the volume susceptibility is in practice a function of relative proportion of all dia, para and ferromagnetic minerals as well as structure and texture variation within the effective volume considered) from each other.

DISCUSSIONS ON THE POTENTIAL OF MS IN CORRELATION AND CONCLUSIONS

Geological mapping in Lesser Himalaya, especially in the Inner Lesser Himalaya, by several geological groups (e.g., Sakai 1983, 1985; Hirayama et al. 1988; Dhital et al. 2002) have contributed much to our understanding of the complex stratigraphic setup and the geological structure. However, the published literature reveals that mapping is not unequivocal in terms of assignment of rocks with similar lithologies to the various formations, often with different names, and hence the correlation of the proposed lithostratigraphic schemes with those in adjacent areas is not unique. For example, in a stratigraphic correlation scheme proposed by Dhital et al.

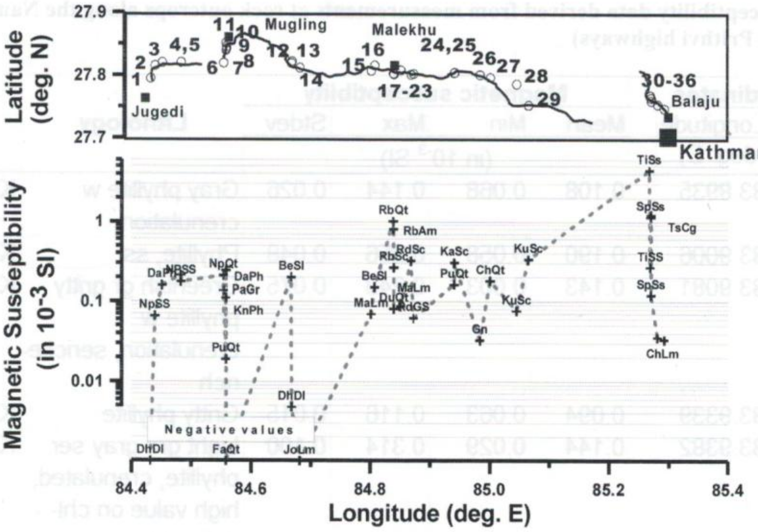

Fig. 4: Locations of the MS measurement sites along Jugedi-Malekhu-Kathmandu-Balaju road sector on the map by DMG (1985). The lower biplot shows the site-specific MS variation as a function of longitude. For MS data refer to Table 3. Note that the lowest values (<0.5x10^{-3} SI) are recorded by white quartzite, dolomite and limestones.

Table 4: In situ magnetic susceptibility data derived from measurements at rock outcrops along the Jugedi-Mugling-Kathmandu-Balaju road sectors

Site	Site coordinates		Magnetic susceptiblity				Formation name	Lithological index
	Latitude	Longitude	Mean	Min	Max	Stdev		
	(deg. N)	(deg. E)	(in 10^{-3} SI)					
1	27.7946	84.4316	-0.003	0.001	0.001	0.002	Dhading Dolomite	DhDl
2	27.8150	84.4388	0.066	0.040	0.100	0.019	Nourpul Formation	NpSs
3	27.8200	84.4510	0.159	0.096	0.271	0.045	Dandagaon Phyllite	DaPh
4	27.8204	84.4823	0.214	0.174	0.297	0.037	Nourpul Fm.	NpSs
5	27.8204	84.4825	0.176	0.095	0.244	0.034	Nourpul Fm.	NPSs
6	27.8194	84.5536	0.211	0.019	0.297	0.083	Nourpul Fm.	NpQt
7	27.8194	84.5536	0.137	0.046	0.322	0.083	Palung Granite	PaGr
8	27.8396	84.5575	0.019	0.002	0.122	0.036	Purebesi Quartzite	PuQt
9	27.8510	84.5576	0.111	0.037	0.201	0.072	Kunchha Phyllite	KnPh
10	27.8416	84.5580	0.243	0.175	0.285	0.031	Dandagaon Phyllite	DaPh
11	27.8452	84.5581	-0.005	0.001	0.001	0.003	Fagfog Quartzite	FaQt
12	27.8191	84.6675	0.201	0.013	0.824	0.204	Benighat Slate	BeSl
13	27.8222	84.6683	0.005	0.001	0.014	0.004	Dhading Dolomite	DhDl
14	27.8116	84.6817	-0.004	0.001	0.001	0.002	Jogimara Limestone	JoLm
15	27.8072	84.8010	0.070	0.026	0.096	0.022	Malekhu Limestone	MaLm
16	27.8158	84.8068	0.151	0.090	0.203	0.037	Benighat Slate	BeSl
17	27.8028	84.8380	1.007	0.011	10.000	2.299	Robang Fm.	RbQt
18	27.8028	84.8384	0.803	0.416	1.360	0.279	Robang Fm.	RbAm
19	27.8018	84.8391	0.265	0.001	0.638	0.168	Robang Fm.	RbSc
20	27.8014	84.8391	0.081	0.044	0.208	0.036	Dunga Quartzite	DuQt
21	27.8078	84.8505	0.087	0.054	0.120	0.019	Malekhu Limestone	MaLm
22	27.8009	84.8678	0.322	0.185	0.657	0.130	Raduwa Fm.	RdSc
23	27.8020	84.8721	0.062	0.018	0.177	0.048	Raduwa Fm.	RdGs
24	27.8038	84.9404	0.163	0.038	0.834	0.184	Kalitar Fm.	PaQt
25	27.8040	84.9408	0.306	0.237	0.438	0.055	Kalitar Fm.	KaSc
26	27.8006	84.9834	0.033	0.001	0.065	0.029	Gneiss	??Gn
27	27.7961	85.0005	0.181	0.027	1.240	0.281	Chisapani Quartzite	ChQt
28	27.7861	85.0445	0.076	0.033	0.208	0.047	Kulekhani Schist	KuSc
29	27.7522	85.0645	0.334	0.174	1.210	0.234	Kulekhani Schist	KuSc
30	27.7684	85.2673	4.386	0.062	14.100	3.570	Tistung Fm.	TiSs
31	27.7676	85.2687	0.269	0.100	0.407	0.093	Tistung Fm.	TiSs
32	27.7639	85.2697	1.138	0.244	3.030	0.847	Sopyang Fm.	SpSs
33	27.7639	85.2699	1.206	0.237	2.310	0.771	Tistung Fm.	TSCg
34	27.7591	85.2702	0.120	0.036	0.268	0.070	Sopyang Fm.	SpSs
35	27.7533	85.2809	0.035	0.024	0.066	0.011	Chandragiri Limestone	CnLm
36	27.7469	85.2922	0.033	0.023	0.048	0.008	Chandragiri Limestone	CnLm

Note: Statistics is based on 15 or more measurements. The site locations are shown in map and profile in Fig. 4. In the last column, the first two characters indicate Formation/Member name (Be: Benighat; Ch: Chisapani; Cn: Chandragiri; Da: Dandagaon; Dh: Dhading; Jo: Jogimara; Ka: Kalitar; Ku: Kulekhani; Kn: Kunchha; Ma: Malekhu; Np: Nourpul; Pa: Palung; Rd: Raduwa; Rb: Robang; Sp: Sopyang; Ti: Tistung; ??: unknown), and the following two characters stand for predominant rock type (Dl: dolomite; Gr: Granite; Gn: gneiss; Qt: quartzite; Lm: limestone; Ph: phyllite; Sl: slate; Ss: sandstone).

(2002), most formations other than the prominent Kerabari Formation of the Kali Gandaki Supergroup proposed by Sakai (1985) are regrouped into Sorek Formation correlated either to the upper part of the Lower Nawakot Group or much younger formations occurring in the Kathmandu area. It seems that regions with predominance of quartzites and carbonates with complex structural setting, with ubiquitous folding and truncation by faults, invite problems in accurate mapping and determining their affinity to particular lithostratigraphic units. Although these rocks are characterized by lowest susceptibilities, this roadside study indicates to the possibility of statistically distinguishing the individual units, even though they may be characterized by macroscopically similar lithologies, based on a large number of MS measurements. Rocks affected by various degree of weathering, secondary alterations, metamorphic grades are likely to exhibit significant variations in MS depending on the degree of breakdown of existing ferromagnetic minerals and subsequent transport resulting in their removal or addition of new minerals, *in situ* formation of secondary minerals, and so on. Despite possible fluctuations due to various causal factors, the summary data illustrated in Figs. 5, 6 and Table 5 show that MS reasonably discriminates various rock types within the Lesser Himalaya.

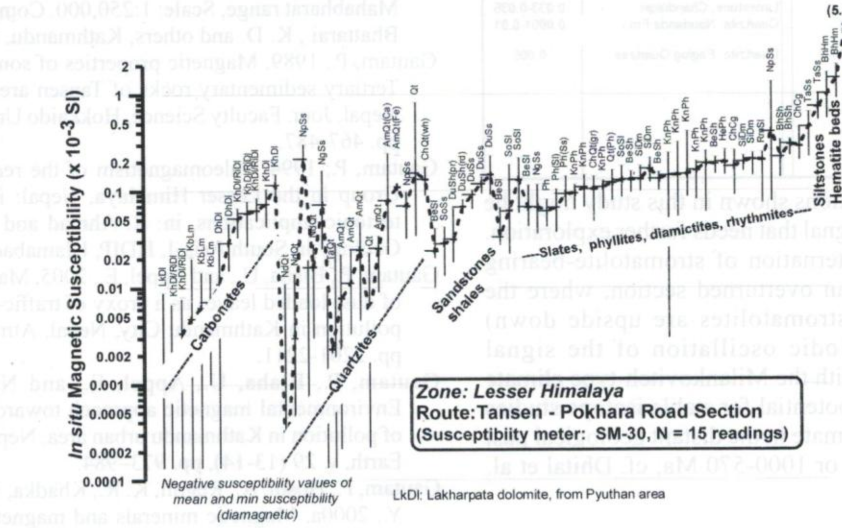

Fig. 5: MS data for the rocks from in Kerabari-Tansen-Syangja-Pokhara-Mugling road traverse. Locations of sites and their formation/lithology nomenclatures indicated commonly by 4 characters are shown in Figs. 1-3 and the captions of Tables 1-3, respectively.

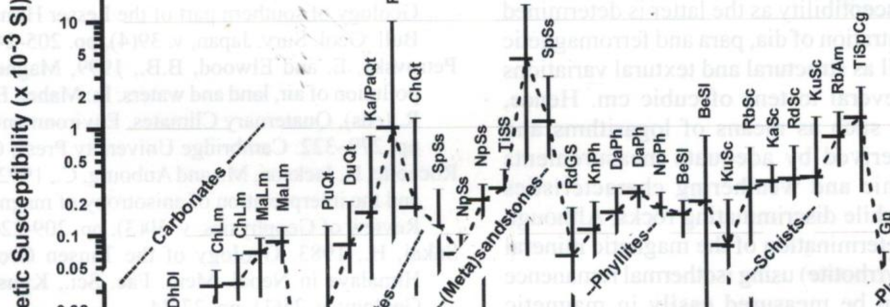

Fig. 6: MS data for the rocks in Jugedi-Mugling-Kathmandu-Balaju road sectors. Locations of sites and their formation/lithology nomenclatures indicated commonly by 4 characters are shown in Figs. 1,4 and the captions of Table 4, respectively.

Table 5: Summary of average magnetic susceptibility values/ ranges for rock formations in the central sector of the Nepalese Lesser Himalaya

Rock type(s), formation(s)	Mean value or range (in 10^{-3} SI)	Rock type(s), formation(s)	Mean value or range (in 10^{-3} SI)
1. High MS values (>1.0 x 10^{-3} SI)		*3. Low MS values (<0.1 x 10^{-3} SI)*	
Trachyte, Aulis Volcanics	4.6-5.5	Quartzite, Amile Fm.	0.008-0.1
Metasandstone, Tistung Fm.	4.4	Most sandstones, Dumri Fm.:	0.03-0.1
Hematitic beds, Bhainskati Fm.	1.0-1.453	Rhythmites /shales, Sorek Fm.	0.028-0.1
Conglomerate separating Tistung/Sopyang Fms.	1.2	Limestone, Malekhu Limestone	0.070-0.087
Metasandstone, Sopyang Fm.	1.1	Sandstone, Nayagaun Fm.	0.066-0.072
Amphibolite/schist, Robang Fm.	0.8-1.0	Dolomite, Sorek Fm, Ripa Mb	0.058-0.062
Sandstone, Taltung Fm.	0.5-0.7	Limestone, Kerabari Fm.	0.005-0.007
		Dolomite, Dhading Dolomite	-0.003-0.025
		Limestone, Chandragiri	0.033-0.035
2. Moderate MS values (0.1-1.0 x 10^{-3} SI)		Quartzite, Naudanda Fm.	0.0001-0.01
Most shales, diamictites, slates, phyllites, sandstones, schists (Sisne, Nourpul, Benighat, Raduwa, Kulekhani, Bhainskati, Dumri, Dandagaon, Sorek and Kunchha Fms.)	0.1-1.0	Quartzite, Fagfog Quartzite	-0.005

Certain periodic variations shown in this study might be related to paleoclimatic signal that needs further exploration. MS profile across the alternation of stromatolite-bearing dolomite and quartzite (an overturned section, where the subspherical to domal stromatolites are upside down) showing the quasi-periodic oscillation of the signal probably in accordance with the Milankovitch-type climate cycles. This outcrop has potential for stable isotope studies directed to the study of climate in the distant geological past (NeoProterozoic-Vendian or 1000-570 Ma; cf. Dhital et al. 2002, p. 54).

Thus, MS has high potential for discrimination of lithological units not just with relatively higher content of magnetic minerals such as the volcanic and red beds (e.g. hematite-rich beds) or metasandstones containing abundant magnetite and hematite, but also the weakly magnetic rocks such as dolomites and limestones. In general, however, different weakly susceptible rocks may have identical numerical values of susceptibility as the latter is determined by the types and concentration of dia, para and ferromagnetic minerals present as well as structural and textural variations within a volume of several to tens of cubic cm. Hence, statistical parameters, such as means of logarithms and standard deviation, derived by adequate measurements along with petrographic and weathering characteristics should be considered while discriminating rocks. Although not discussed above, determination of the magnetic mineral types (e.g. magnetite, pyrrhotite) using isothermal remanence characteristics that can be measured easily in magnetic laboratories may be further helpful when details are required. It is believed that use of MS measurements over areas characterized by complex distribution of rock formations will be useful for rapid and objective discriminations of the different geological units when used in combination with the existing geological observations. Hence, MS measurement deserves inclusion as a tool for geological mapping.

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