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Palaeomagnetic Constraints on Allochthony and Age of the Krol Belt Sequence, Garhwal Himalaya, India*

Chris T. Klootwijk[1] **, Arvind K. Jain[2] ***, and Rakesh Khorana[3]

[1] Research School of Earth Sciences, Australian National University, P.O. Box 4 Canberra A.C.T 2600, Australia
[2] Department of Geology and Geophysics, University of Roorkee, Roorkee 247672, India
[3] Geological Survey of India, Kashmir Circle, Rajbagh Srinagar, India

Abstract. Thermal demagnetization of 223 carbonate and sandstone samples from the Late Palaeozoic – Mesozoic Krol Belt sequence (Ganges section, Garhwal Lesser Himalaya) showed five magnetic components:

a) a magnetically soft component of recent origin;

b) a universally present secondary component of mixed polarity and of post-folding origin. Its NNW declination indicates an approximately 25° clockwise rotation of the sampled region with respect to peninsular Indo-Pakistan since Late Tertiary.

c) another universally present secondary component of mixed polarity and of pre-folding origin and with a NNW declination which indicates a clockwise rotation of the sampled region over approximately 45° since Early Tertiary.

d) an ENE to WSW directed secondary component of very shallow inclination and of mixed polarity, observed throughout the entire sample collection. This component may represent a low-temperature oxidation phase, aligned preferentially towards the foliation plane.

e) primary magnetic components could be determined only in the basal part of the sequence studied, i.e. in the Lower Blaini Diamictite, in the Blaini Limestone and in the Krol-A Limestone. Comparison of their rotation-corrected pole positions with the Indo-Pakistan apparent polar wander path (APWP) supports the disputed Permo-Carboniferous to Permian age of these rocks. The hish palaeolatitudes indicated by these primary components favour a glacial origin for the Blaini Diamictite.

Clockwise rotation of tectonic units within the Lesser Himalaya similar to the rotation described herein have been documented recently for the Kashmir nappe, and can be interpreted also from palaeomagnetic results from other regions of the NW Himalaya. If of regional consistency, such rotations may put constraints on the magnitude of intracontinental underthrusting along the Main Central Thrust (MCT).

Key words: Himalaya – Krol Belt – Palaeomagnetism – Tectonics

Introduction

Early Tertiary or earlier collision of Greater India with an island arc occurred at equatorial latitudes (Klootwijk 1981). The Indian plate has subsequently moved northwards over more than 3,000 km, with Eurasia undergoing hardly any latitudinal movement and only a slight clockwise rotation. This large-scale convergence has been accomodated not only by crustal shortening within South Central Asia (Molnar and Tapponnier 1975; Tapponnier and Molnar 1976), but also resulted in intracontinental underthrusting within extra-peninsular Indo-Pakistan and in telescoping of the sedimentary cover. The magnitude of underthrusting is a matter of debate, particularly after Powell and Conaghan (1973) revived Argand's (1924) hypothesis that Tibet's twice average crustal thickness represents doubling of the crust through large-scale underthrusting by Indo-Pakistan's continental lithosphere. This hypothesis conflicts with the established notion that buoyancy constraints would preclude large-scale continental subduction (McKenzie 1969; Dewey and Bird, 1970). Recent surface wave (Knopoff and Chang 1981) and deep seismic sounding studies of the Tibetan Plateau (Teng-Ji wen 1981; Teng-Ji wen et al. 1981) have been interpreted, however, in support of doubling of the crust. Estimates of thrust magnitudes within the Lesser Himalaya (Andrieux personal communication 1981) and along the MCT (Gansser 1974; Le Fort 1975) indicate a minimal underthrusting of 300–500 km.

The India-Asia convergence occurred nearly completely in a north-south direction. Palaeomagnetism can therefore be most usefully applied to quantifying and dating such a large-scale underthrusting, and on a more regional scale to determining the magnitude of rotational movement of individual thrust units. This formed the main objective for our ongoing palaeomagnetic project in extra-peninsular Indo-Pakistan (see reviews by Klootwijk 1979, 1981, Klootwijk and Radhakrishnamurty 1981). A second and closely related objective concerned further refinement of the Indo-Pakistan APWP and determination of its poorly constrained Palaeozoic and Tertiary segments. Rocks of those eras are not well developed in peninsular Indo-Pakistan. The present reconnaissance study of the Krol Belt region in the northwestern Himalaya has been carried out as part of this project, with as specific objectives:

1) To constrain the age range of the Krol Belt sequence through comparison with well-dated palaeomagnetic results from peninsular Indo-Pakistan.

2) To obtain more data on the controversial autochthonous or allochthonous position of the Krol Belt sequence.

3) To establish the palaeolatitude of deposition of the Blaini Diamictites, whose glacio-marine origin has been disputed.

Regional Geology and Sampling

Since the pioneering investigations of Auden (1934, 1937) in the Lesser Himalaya of Garhwal, who regarded their structure

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** *Present address.* Institute de Physique du Globe de Paris and U.E.R. des Sciences Physiques de la Terre, Universités Paris 6 and 7, 4 Place Jussieu, 75230 Paris Cedex 05, France

*** *Present address.* Geologisches Institut, Universität Karlsruhe, 7500 Karlsruhe 1, Federal Republic of Germany

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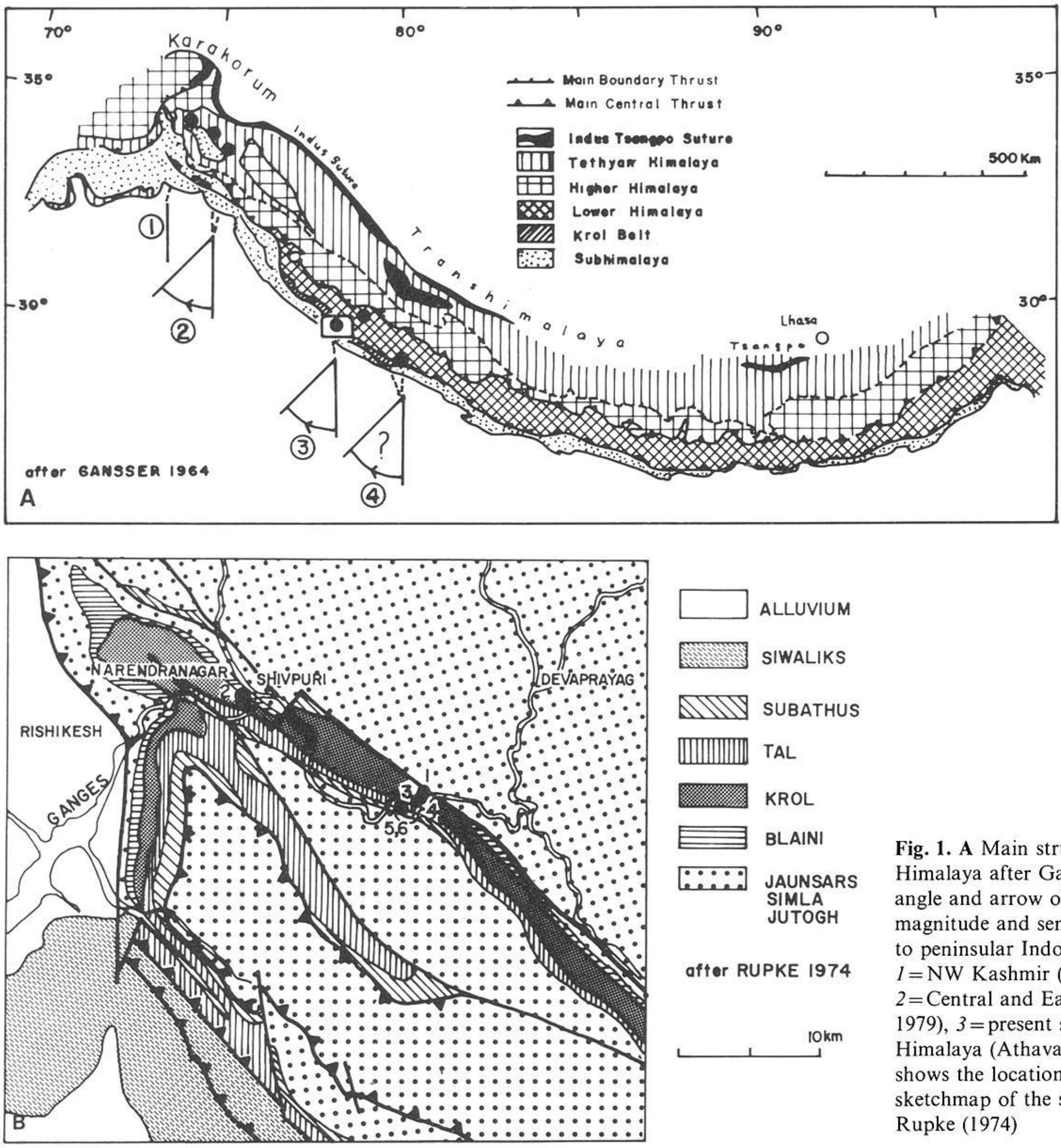

Fig. 1. A Main structural features of the Himalaya after Gansser (1964). The apical angle and arrow of the halfcones indicate magnitude and sense of rotation with respect to peninsular Indo-Pakistan (see text). *1* = NW Kashmir (Klootwijk 1979), *2* = Central and Eastern Kashmir (Klootwijk 1979), *3* = present study, *4* = Kumaon Lesser Himalaya (Athavale et al. 1980). The inset shows the location of **B**: a geological sketchmap of the sampled region after Rupke (1974)

as a telescoped pile of large-scale thrusts, controversies still persist regarding the chronostratigraphy and tectonics of this very complex region. A nearly complete absence of fossil records from these formations and a profusion of lithostratigraphical correlation schemes have hindered interpretation of the complicated tectonics. It is not surprising, therefore, that controversies have arisen on the regional tectonics and, in particular, on the allochthony of the Krol Belt sequence (Krol Nappe). Likewise, there is as yet no universal acceptance of a glacial origin for the Blaini diamictites of the Krol Belt sequence. This poses problems for dating the younger sequence of the Krol Belt, as the lithological correlation of the Blainis with the Permo-Carboniferous Talchir beds of peninsular Indo-Pakistan forms a keystone in dating the Krol Belt sequence. A probable Late Palaeozoic-Mesozoic age for this sequence is still contested.

It is beyond the scope of this paper to review the abundant literature and multitude of controversies on the Krol Belt, and we confine ourselves here to a description of the structural and stratigraphical outlines of the Krol Belt region as far as is relevant to our palaeomagnetic study.

The Garhwal Lesser Himalaya are made up of a pile of southwards directed nappes which are of higher metamorphic grade in the tectonically higher units (Fig. 1a, b). The cryptic roots of these thrusts probably emanate from the Main Central Thrust (MCT) in Garhwal and elsewhere in Himachal Pradesh and Nepal (Ravi Shankar and Ganesan 1972; Ashgirei et al. 1977; Andrieux et al. 1980; Brunel and Andrieux 1980). The main nappe units northwards and upwards of the autochthonous Siwaliks of the sub-Himalaya are: the Krol Nappe, mainly a lower greenschist metamorphism, and the Almora Nappe. The allochthony of the Krol Nappe was disputed by Ranga Rao (1968, 1970), Rupke (1974) and Fuchs and Sinha (1978), who interpreted the folded Krol-Tons thrustplane dissecting a basement of Simla slates and the unconformably overlying Subathu Formation as a pre-Eocene unconformity. Consequently, they doubted the tectonic window structures beneath the eroded parts of the Krol Belt, near Bhidalna and Pharat (Auden 1934, 1937, 1970, Jain 1972). The majority of workers favour, however, an allochthonous origin for the Krol Belt sequence (Auden 1934, 1937, 1970; Gansser 1964; Bhattacharya and Niyogi 1971; Jain 1972; Bhargava 1972; Valdiya 1973a, 1977; Kumar and Agarwal 1975; Ashgirei et al. 1975; Achariya and Shah 1975; Singh

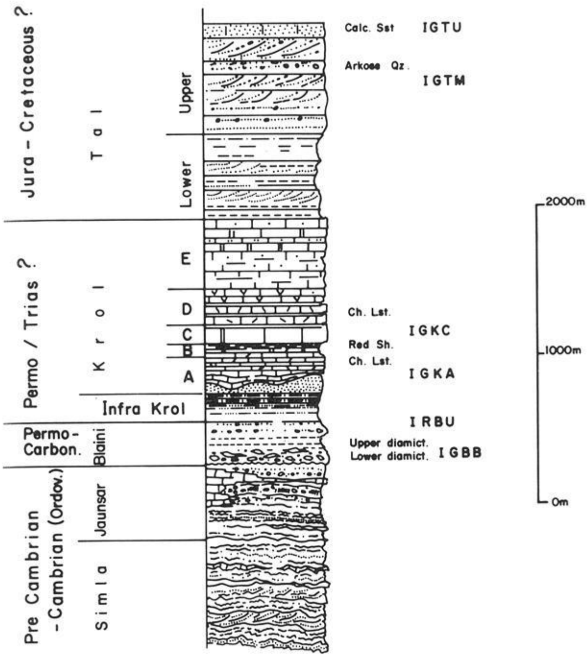

Fig. 2. Stratigraphical ideal column of the Krol Belt region after Gansser (1964)

1975a; Geological Survey of India, 1976; Ashgirei 1977; Sinha 1980; Prashra 1980)

Understandably, neither the magnitude nor the date of displacement of the Krol Nappe have been established accurately, though Auden (1937) and Prashra (1980) suggest minimal southward movements of 50 km and 60 km respectively. The youngest thrust movements of the Krol Nappe are of Plio-Pleistocene to Quaternary age as indicated by overriding of the Krol Belt sequence on the Siwaliks and Doon gravels of the sub-Himalaya. The general overthrusting of the Krol Nappe over an Upper Proterozoic to Lower Palaeozoic basement of low-grade metasediments of the Simla Group and unconformably overlying Tertiary sediments of the Subathu and Dagshai Formations (Figs. 1b, 2) indicates, according to Auden (1937), that the major south to southwestwards directed thrust movements and the subsequent folding of the thrustplane occurred during post-Burdigalian time and most probably during the Early Miocene diastrophistic phase of the Himalayan orogeny.

The base of the Krol Nappe is formed locally by the Jaunsars which are overlain unconformably by a Late Palaeozoic-Mesozoic succession comprising the Blaini Formation and the actual Krol Belt Formations, i.e. the Infra-Krol, the Krol limestone and shale and the Tal sandstone and limestone (Figs. 1b, 2).

The Blaini Formation is characterized by two main rock types, i.e. two diamictite horizons (lower horizon sampled, Table 1) and an upper succession of siliceous dolomitic purple limestone and silicified purple sandy shale (sampled, Table 1). The tillitic aspect of the diamictite has been disputed by Bhattacharya and Niyogi (1971), Valdiya (1973b), and Rupke (1974) who stressed the turbiditic character of the Blaini beds. The majority of recent sedimentological and geochemical studies have brought forth evidence for a glacial and most probably a glaciomarine origin of the Blaini Formation (Gaur 1971; Gaur and Dave 1974; Bhargava and Bhattacharya 1975; Singh 1975b; Bhatia and Prasad 1975, 1981; Ahmed 1975; Jain and Varadaj 1978; Jain in press 1981). The Blaini Formation is overlain by slate and sandstone of the Infra-Krol Formation (not sampled), which is succeeded by an up to 1,500 m thick succession of limestone and calcareous shale of the Krol Formation which is generally assumed to be of Permo-Triassic age. From the five members of the Krol Formation (A–E), only thin-bedded limestone of the Krol-A member and more massive dolomitic limestone of the Krol-C member were selected for sampling. The Tal Formation of a presumed Jurassic-Cretaceous age forms the highest lithostratigraphic unit of the Krol Belt. Sampling was carried out in white to pinkish coloured arkosic sandstone and shelly sandy limestone from the Upper Tal member (Table 1).

Treatment and Results

A total of 223 samples from the Blaini-Tal succession were obtained with a portable drill along the Ganges profile in the northeastern limb of the Lansdowne Syncline (Fig. 1b). The beds have a steeply southward to locally vertical dip, which facilitated sampling of stratigraphic profiles. Generally one sample was taken per bed (except for the Lower Blaini Diamictite). All samples were oriented with a magnetic and a solar compass.

Table 1. Sampling details Krol Belt region Ganges river section (30.2° N 78.4° E)

Formation	Locality (Fig. 1)	Age	Lithology	Section length	Samples (specimens)	Init. intensity 10^{-3} m. Am^{-1}	Bedding Strike (o)/ Dip (o)
Upper Tal Lst.	6	Jurassic-Cretaceous	oolitic arenaceous limestone	1 m	16 (21)	545– 3,725	100/ 54 S
Middle Tal Sst.	5	Jurassic-Cretaceous	pinkish to white sst., occ. cross-bedding	6.5 m	24 (25)	139– 2,290	95/ 55 S
Krol-C Lst.	4	Permo-Triassic?	grey thin-bedded dolomitic limestone	4.5 m	37 (68)	42– 1,763	134–140/ 67.5–79.5 SW
Krol-A Lst.	3	Permo-Triassic?	limestone, calcareous shale	15.5 m	40 (62)	29– 389	120–125/ 85 S
Blaini Lst.	2	Late Carboniferous-Early Permian	purple dolomites silicified red and grey sandy shales	14 m	62 (79)	46–102,964	83–93/ 73–81 S
Lower Blaini Diamictite	1	Late Carboniferous-Early Permian	grey boulder beds	11.5 m	34 (51)	88– 3,628	140–145/ 92–97 SW

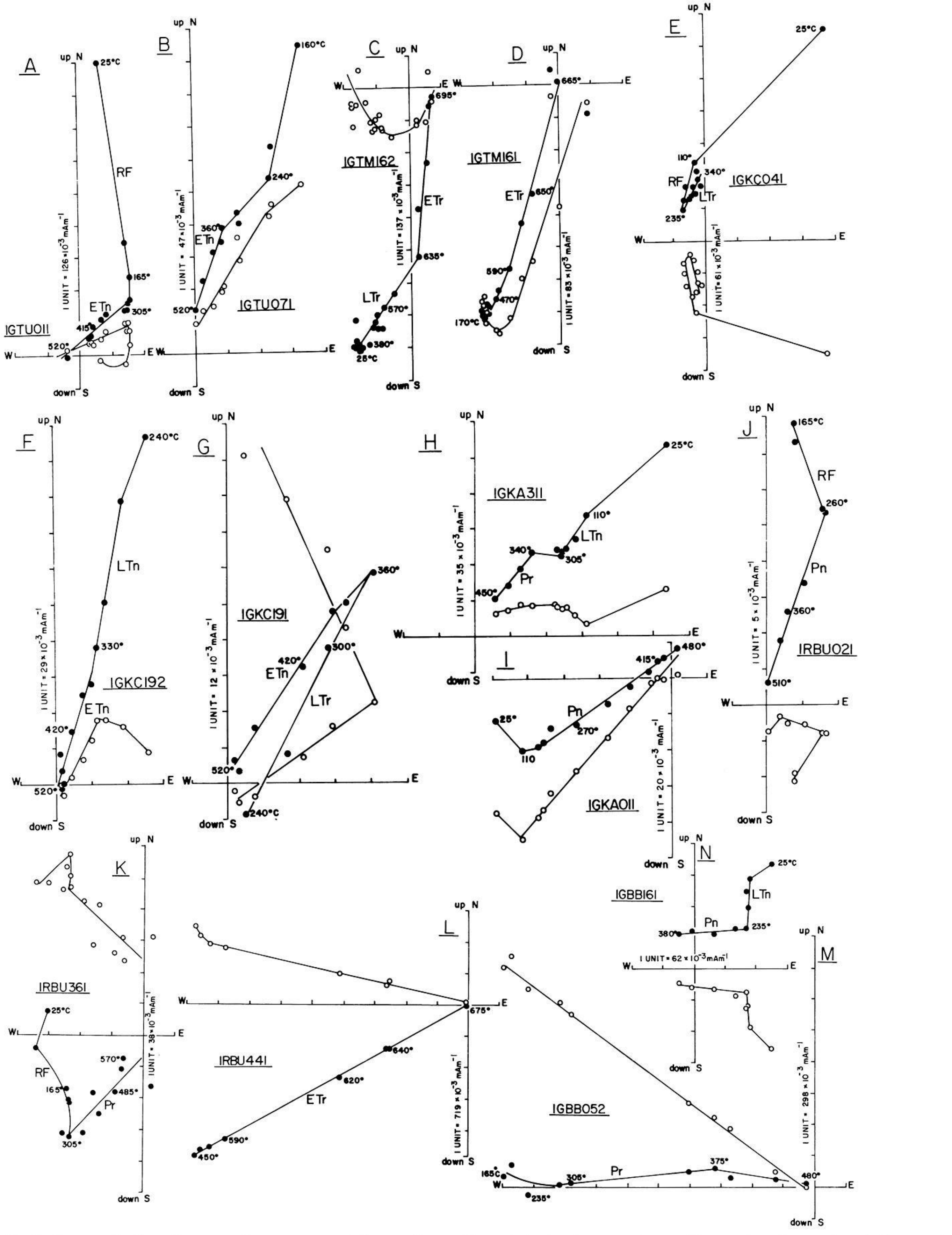

Fig. 3. Demagnetization diagrams of some representative specimens. The points denote successive positions – in orthogonal projection – of the end points of the resultant magnetization vector during progressive thermal demagnetization. *Open circles* denote projections on the vertical east-west plane, *dots* denote projections on the horizontal plane. *Numbers* denote successive peak temperature values. *RF*=recent field component, *LT*=Late Tertiary secondary component, *ET*=Early Tertiary secondary component, *P*=Primary component, *n*=normal polarity, *r*=reversed polarity. Results are not corrected for bedding. See Fig. 2 for sample codes

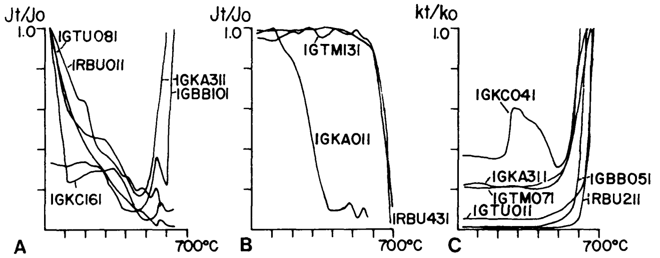

Fig. 4A–C. Representative normalized curves showing: **A, B** intensity decay of remanent magnetization and **C** changes in magnetic susceptibility during thermal treatment. See Fig. 2 for sample codes

Thermal demagnetization and analyses of the results were carried out following standard procedures described in detail elsewhere (Klootwijk and Bingham 1980; Klootwijk et al. 1981). All samples were rinsed in diluted HCl prior to measurement. Thermal demagnetization was carried out in large-size furnaces (McElhinny et al. 1971) with a feedback-controlled 10 coil Helmholtz system cancelling the ambient field to less than 10 gamma during the heating-cooling cycle (about 2 h). Measurements were taken on a two-axis United Scientific ScT cryogenic magnetometer interfaced with a Hewlett-Packard HP 2100 minicomputer. Magnetic components were identified from Zijderveld (1967, 1975) plots and directions were computed with an adapted version of Kirschvink's (1980) principal component analysis program. Fischer statistics were used throughout.

Analysis of results indicated the presence of five magnetic components:

a) A magnetically soft component representing up to 50% of initial natural remanent magnetization (NRM) was removed generally below 250° C. In samples from the Upper Tal and Blaini limestones, this component was aligned essentially along the ambient field direction (Fig. 3a, j, k). This component was, however, of a more viscous nature in the samples from most other formations and became realigned during storage in the laboratory (Fig. 3k).

b) A universally present secondary component of post-folding origin and of mixed polarity, with NNE to SSW pointing directions (Fig. 3c, e, g, n). This component showed a restricted blocking temperature range between 270° and 330° C (Fig. 4b), and represented 20–50% of initial NRM.

c) Another universally present secondary component of pre-folding origin and with NNE to NE and SSW to SW pointing directions (Fig. 3a–d, f, g, l). In the carbonate samples this component had a blocking temperature range between 360°–520° C, and represented 20–30% of initial NRM (Fig. 4a). The Upper Tal sandstone and the siliceous shale from the Blaini Limestone showed a restricted blocking temperature range for this component between 620°–670° C (Figs. 3l, b).

d) A primary magnetic component of mixed polarity and with somewhat dispersed directions, was determined only in the Lower Blaini Diamictite (Fig. 3h–k, m, n). Blocking temperatures ranged between 300° to 500° C.

e) A secondary component, WNW and ESE directed and close to horizontal. This component showed the best concentration of directions when corrected for bedding (Table 2). It was present in all formations studied and showed widely varying blocking temperature ranges (Table 2).

Interpretation

A primary or secondary origin of the five magnetic components described above, was ascertained on the basis of the fold test and on comparison of their pole positions with the Indo-Pakistan APWP. The magnetically harder secondary component *c* is of pre-folding origin as is clear from the improved concentration of formation mean directions after correction for bedding (Fig. 5b); the fold test is significantly positive at the 99% level (Tables 1, 2). The magnetically softer secondary component *b*, in contrast, is of post-folding origin (Fig. 5a), with a fold test significantly negative at the 99% level (Tables 1, 2). A comparison of the mean directions for both groupings with the Indo-Pakistan APWP (Fig. 6a, b) and with expected directions at the sampled region (Fig. 5d) indicates an appreciable clockwise rotation of the sampled tectonic unit with respect to peninsular Indo-Pakistan. This rotation has proceeded over approximately 45° since acquisition of the pre-folding component *c* and over about 25° since acquisition of the post-folding component *b*. Intersection of the loci of poles for these secondary components with the Tertiary segment of the Indo-Pakistan APWP indicates that components *b* and *c* were acquired between 40–50 m.y. ago and at about 20–30 m.y. ago, respectively.

The sampled region was restricted to the northeastern part of the Lansdowne Syncline (Fig. 1a). The relevance of this rotation for the wider Krol Belt region, has therefore, still to be established. In the absence of other constraining data, this rotation supports an allochthonous rather than an autochthonous origin of the Krol Belt region (Krol Nappe).

The secondary components *b* and *c* form part of a recently recognized pattern of Tertiary remagnetization in the wider Himalyan region (Klootwijk and Radhakrishnamurty 1981; Klootwijk 1981). Overprints of Early Tertiary age have so far been observed only in the internal zones of the Himalayan orogenic belt, and are evidently related to the later phase of the India-Asia collision along the Indus-Tsangpo suture zone. Early to Late Tertiary overprints, in contrast, have been observed in the more external zones and are most probably associated with thrust movements towards the Indian shield. The acquisition mechanism of these Tertiary overprints has not been studied in detail so far, but the observed wide range in blocking temperatures suggests a thermo-chemical process.

The secondary component *e* resembles overprints observed in Ladakh (Klootwijk et al. 1979) and in the Thakkhola region (Klootwijk and Bingham 1980), where a relation with the predominant foliation pattern was noted.

Mean directions for the primary magnetization components (*d*) of the Lower Blaini Diamictite, the Blaini Limestone and the Krol-A Limestone after correction for bedding, group closely to Late Palaeozoic-Early Mesozoic directions for Indo-Pakistan (Fig. 5c, d). This segment of the Indo-Pakistan APWP is so far based only on Permian to Permo-Carboniferous data from Gondwana sediments of peninsular India and on a result from north-eastern Baluchistan of an unspecified Permo-Carboniferous age. This APWP segment lacks sufficient detail to evidence improvement in grouping of pole positions when the Krol Belt results are corrected for the approximately 45° clockwise rotation (Fig. 6a, b). Yet, these rotation corrected primary pole positions may be instrumental in further constraining the Permo-Carboniferous loop in the Indo-Pakistan APWP.

This general agreement in pole positions clearly supports the disputed Permo-Carboniferous to Permo-Triassic age surmised for the Blaini and Krol Formations, so far based only on lithological correlation and scant palaeontological evidence. The high palaeolatitudes indicated by these three results (Table 2) likewise support the disputed glacial origin of the Blaini diamictite. It should be mentioned that the high palaeolatitude for the Blaini dolomitic limestone is in conformity with repeated

Table 2. Mean palaeomagnetic results, Krol Belt

Formation	Direction						Pole position (southpoles)					
	Decl (o)	Incl (o)	K	α_{95} (o)	N	Polarity	Lat (o)	Long (o)	dp (o)	dm (o)	E_{95} Palaeolat[a]	No Fig. 5, 6
A) *Recent field component*												
Upper Tal lst.	355	+41	31.5	10	8	N						1
Blaini Lst.	346.5	+42	21.5	9	13	N						2
B) *Late Tertiary secondary component, post-folding*												
Middle Tal sst.	203	−31.5	11	14.5	11	R	65 S	15.5 E	9	16.5		3
Krol-C Lst.	203.5	−40.5	34.5	3.5	50	R	68 S	1.5 E	2.5	4		4
Krol-C Lst.	18.5	+39	21.5	7.5	18	N	71.5 S	10 E	5.5	9		5
Krol-C Lst.	21.5	+40	29.5	3	68	N+R comb.	69.5 S	4.5 E	2	3.5		6
Krol-A Lst.	12.5	+43.5	8	12.5	20	N (+R:2)	78 S	9 E	9.5	15.5		7
Blaini Lst.	4	+30	9.5	10	25	N (+R:4)	75.5 S	63 E	6	11		8
Lower Blaini Diamictite	201.5	−40	22.5	14.5	6	R	69.5 S	4.5 E	10.5	17.5		9
Lower Blaini Diamictite	12	+44	26.5	8.5	12	N	78.5 S	8 E	6.5	10.5		10
Lower Blaini Diamictite	15	+42.5	25	7	18	N+R comb.	75.5 S	7.5 E	13.5	22		11
Mean pole	16	+38	97	7	5		∞73 S	14 E			6°	A
C) *Middle to Early Tertiary secondary component, pre-folding*												
Upper Tal lst.	29	+16	13	10	19	N	55 S	21.5 E	5.5	10.5		12
Middle Tal lst.	197	−28.5	11	12.5	14	R	68.5 S	28.5 E	7.5	13.5		13
Middle Tal lst.	18	+17	13.5	11	15	N	62.5 S	36.5 E	6	11.5		14
Middle Tal lst.	18.5	+22	11.5	8	29	N+R comb.	64.5 S	32 E	4.5	8.5		15
Krol-C Lst.	27.5	+34.5	18.5	5	46	N(+R:1)	62.5 S	6.5 E	3.5	5.5		16
Krol-A Lst.	27	+27	40	9	8	N	60.5 S	15 E	5.5	10		17
Blaini Lst.	233.5	−20.5	5	13.5	27	R	36.5 S	12 W	7.5	14		18
Blaini Lst.	25.5	+18	19.5	9.5	14	N	58.5 S	24.5 E	5	10		19
Blaini Lst.	224	−17	8	8.5	41	N+R comb.	43.5 S	6.5 E	4.5	9		20
Lower Blaini Diamictite	15	+15.5	13.5	26	4	N(+R:1)	63.5 S	43 E	13.5	26.5		21
Mean pole	27	+22.5	45	10	6		59.5 S	19.5 E			8.5	B
D) *Primary components*												
Krol-A Lst.	115	+71.5	10	18.5	8	R	12.5 N	109.5 E	28.5	32.5		22
Krol-A Lst.	317	−61	6	30	6	N	7.6 S	109 E	35	46		23
Krol-A Lst.	306.5	−67.5	8	15	14	N+R comb.	3.5 N	109.5 E	21	25		24
Blaini Lst.	89.5	+77	6.5	9	47	R	27.5 N	106.5 E	15.5	16.5		25
Blaini Lst.	270	−67	8.5	14	15	N	22.5 N	123 E	19	23		26
Blaini Lst.	269.5	−74.5	7	7.5	62	N+R comb.	26.5 N	116 E	12.5	13.5		27
Lower Blaini Diamictite	187.5	+62	8.5	16.5	11	R	16.2 S	72.5 E	20	25.5		28
Lower Blaini Diamictite	321	−79	7	18	12	N	13 N	92 E	32.5	34		29
Lower Blaini Diamictite	354	−72	7	12	23	N+R comb.	2.5 S	81.5 E	18.5	21		30
E) *Primary components, corrected for inferred rotation 45° clockwise*												
Krol-A Lst.	261.5	−67.5	8	15	14	N+R comb.	28 N	124 E	21	25	$50.5S^{33S}_{75S}$	24′
Blaini Lst.	224.5	−74.5	7	7.5	62	N+R comb.	47.5 N	108.5 E	12.5	13.5	$61\ S^{50S}_{74.5S}$	27′
Lower Blaini Diamictite	319	−72	7	12	23	N+R comb.	4 N	99.5 E	12.5	19	$57\ S^{41S}_{78S}$	30′
F) *East-west directed secondary component, all formations combined*												
Before bedding correction	289.5	− 8.5	4.5	10.5	54	N+R comb.						31
After bedding correction	286.5	− 1.5	7.5	7.5	54	N+R comb.						32

[a] Upper and lower limits corresponding to the apex of the 95% cone of confidence

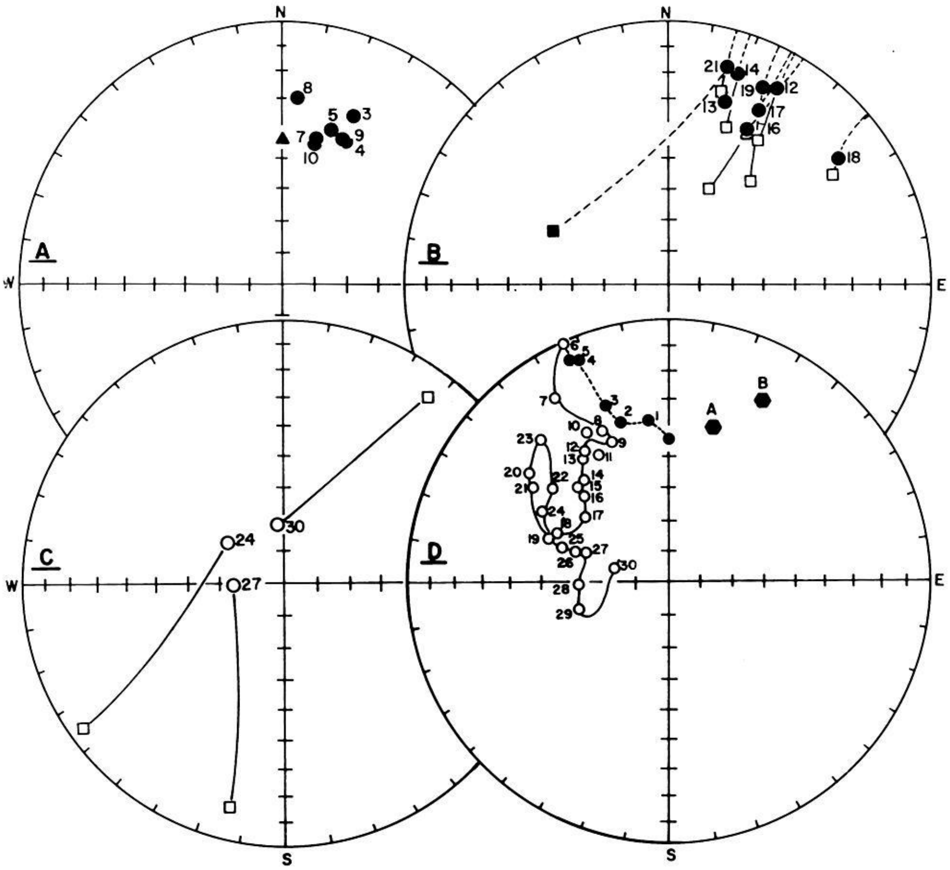

Fig. 5A–D. Formation mean directions not corrected for bedding. **A** For the secondary Late Tertiary component. The *triangle* represents the present field direction at the sampled region. **B** for the secondary Early Tertiary component. *Squares* indicate directions prior to bedding correction and *circles* thereafter; **C** for the primary component. Legend as for **B**. **D** expected directions in the sampled region according to palaeomagnetic data from the Indian plate: *1* = DSDP cores (20 my), *2* = DSDP cores (30 my), *3* = DSDP cores (40 my), *4* = DSDP cores (50 my), *5* = Sanjawi Lst. (Pal.-Eoc.), *6* = Brewery Lst. (Palaeoc.), *7* = DSDP cores (60 my), *8* = Deccan Traps, upper normal epoch (> 60–65 my), *9* = Deccan Traps, lower reversed epoch (> 60–65 my), *10, 11* = Tirupatti Sst. (Kl), *12* = DSDP cores (70 my), *13* = Satyavedu beds (Kl), *14* = Sylhet Traps (Kl??), *15, 16* = Goru Fm. – Parh Lst. (Kl–u), *17* = Rajmahal Traps (> 100–105 my), *18* = Loralai Lst. (Jm), *19* = Chiltan Lst. (Jm–u), *20, 21, 22* = Transferred directions for the mean pole positions from Australia (Jm), Australia (Jl) and Antarctica (Jm) respectively. *23* = Parsora beds (Tru), *24* = Pachmarhi beds (Tru), *25* = Kamthi beds (Pu–Trl), *26* = Mangli beds (Pu–Trl), *27* = Panchet beds (Pu–Trl), *28* = Kamthi beds (Pu–Trl), *29* = Talchir beds (P–C), *30* = Alozai Fm. (P–C). Hexagons *A* and *B* indicate the mean formation directions for the Late- and Early Tertiary secondary components respectively. All figures are in equal area projection. Full symbols denote downwards pointing directions and open symbols denote upwards pointing directions

observations on Precambrian glacial successions in particular, which are accompanied by substantial dolomitic sequences (Bhatia and Prasad 1981).

It is open to further study to what extent this approximately 45° clockwise rotation may be characteristic also for other regions of the Lesser Himalaya. The few palaeomagnetic results so far available, indicate that similar rotations can indeed be interpreted for other parts of the Lesser Himalaya (Fig. 1a). A similar clockwise rotation by about 45° of the Panjal nappe has been concluded from secondary post-folding components observed in Kashmir (Klootwijk 1979). Athavale et al. (1980) recently reported results for the Permo-Carboniferous Durgapipal volcanics and for the Siluro-Devonian Rudraprayag volcanics from the Kumaon Lesser Himalaya, and interpreted them as indicative of autochthony of the sampled regions. These regions are situated, however, directly to the north of the Main Boundary Thrust (MBT) and in the region of the Almora Thrust respectively (Fig. 1b). The assumed primary origin of the observed magnetic directions is, moreover, open to some doubt in view of the degree of metamorphism of the sampled regions, which is at least of greenschist facies (Raina and Dungrakote 1975; Kumar and Agarwal 1975). If these directions are indeed of primary origin, comparison of their pole positions with the Palaeozoic segment of the Indo-Pakistan APWP (Fig. 6b) can be interpreted in terms of a clockwise rotation of the sampled regions of a magnitude comparable to those observed in the present study and in Kashmir.

The importance of such clockwise rotations of the Lesser Himalayan nappes (Fig. 1a) for determination of the magnitude of intracontinental underthrusting of Greater India along the MCT (Powell and Conaghan 1973) remains to be studied. The similarity between the interpreted magnitude of rotations in this study and the azimuthal angle between the MBT and the reconstructed northern boundary of Greater India (Powell 1979; Fig. 7) may be more than fortuitous.

Conclusions

Comparison of Early and Late Tertiary secondary magnetic components from the Krol Belt region of the Garhwal Lesser Himalaya and the Indo-Pakistan APWP evidently indicates an approx-

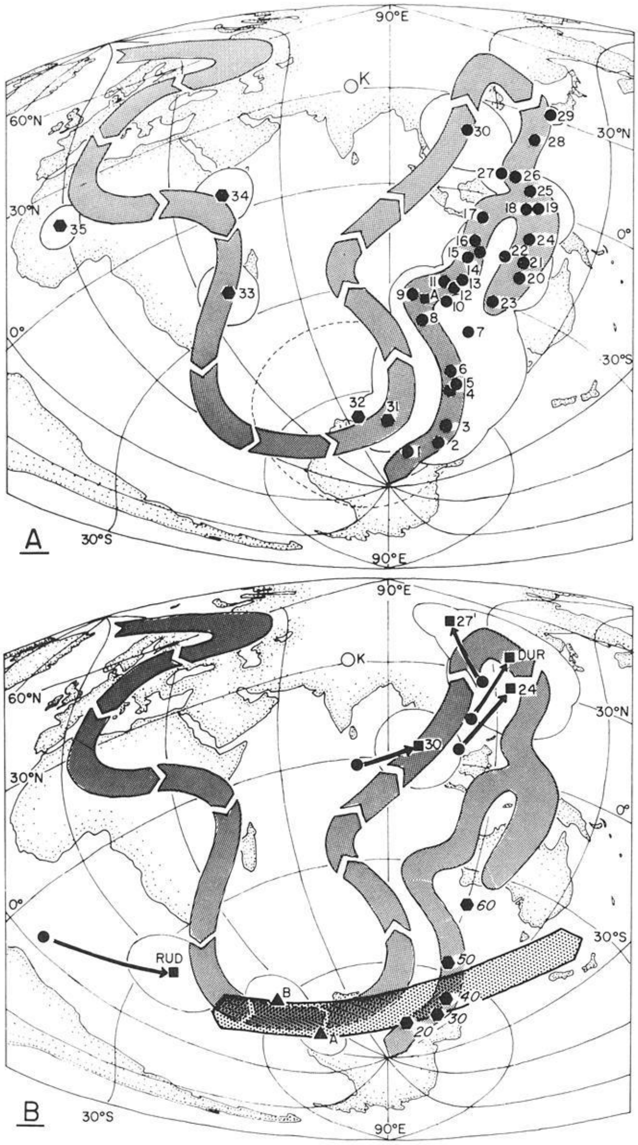

Fig. 6. A Phanerozoic APWP for Indo-Pakistan, based on (south) pole positions from the Indian plate (1–30, see legend to Fig. 5D) and transferred pole positions from south-east Australia (Goleby 1981; 31–35). *31*, *32*=Devonian, *33*=Silurian (M–U), *34*=Silurian (L–U), *35*=Ordovician (M–U). *A*=Panjal Traps. The latter result may represent a secondary (McElhinny et al. 1978) or possibly a primary magnetization. **B** Comparison of the Indo-Pakistan APWP as shown in Fig. 6a with the primary (Table 2: 24, 27, 30) and secondary mean pole positions (Table 2: A, B) obtained here for the Krol Belt region. The loci of the secondary mean positions (*A*, *B*) intersect the Tertiary part of the Indo-Pakistan APWP (ages indicated in m.y.) in the Early and Late Tertiary segments respectively (see text). Their offset indicates a clockwise rotation of the sampled region with respect to peninsular Indo-Pakistan which has proceeded over approximately 45° since the Early Tertiary (compare Fig. 5D). The primary pole positions have been corrected for this rotation (24′, 27′, 30′). The effect of a similar correction on palaeopositions obtained by Athavale et al. (1980) for the Permo-Carboniferous Durgapipal volcanics and the Siluro-Devonian Rudraprayag volcanics of the Kumaon Lesser Himalaya is shown for comparison. The hexagon (*K*) indicates the sampled region. Aitoff projection

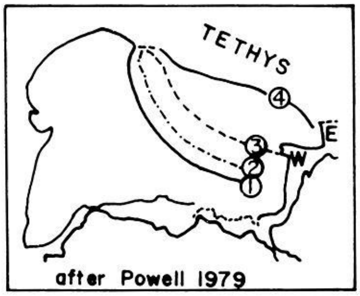

Fig. 7. A reconstruction of Greater India within Gondwana after Powell (1979). This figure displays the azimuthal orientation of the Main Boundary Thrust (*1*) with respect to the inferred outline of the maximum northern extent of Greater India. This extent is based on underthrusting of Greater India beneath Tibet up to the present Kun Lun – Astin Tagh – Nan Shan mountain front. Within a reconstructed East Gondwana this outline leads up to the Exmouth Plateau (*E*) off western Australia (4). *2*=Indus-Tsangpo suture zone, *3*=Inferred minimum northern extent of Greater India in an arc parallel to 2 and leading up to the Wallaby Plateau (W)

imately 45° clockwise rotation of the sampled region. This finding clearly supports the allochthonous nature of the Krol Nappe.

Comparison of the pole positions for the primary magnetic components of the Lower Blaini Diamictite, the Blaini Limestone and the Krol-A Limestone, with the Indo-Pakistan APWP supports a Permo-Carboniferous to Permian age of these formations. This strengthens the lithological correlation of the Blaini Formation with the Talchir boulder beds of peninsular India as has also been pointed out (Jain and Thakur 1975; Jain in press 1981) for other Late Palaeozoic diamictites. The observed high palaeolatitudes further support the glacial origin of the Blaini diamictites.

The presently emerging pattern of clockwise rotations in the northwestern Lesser Himalaya has to be tested further for consistency, as it may form an important constraint in determining the magnitude of intracontinental underthrusting along the MCT.

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