

## A Paleomagnetic Study of Tertiary Formations From the Kyrgyz Tien-Shan and Its Tectonic Implications

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As part of a general investigation of Cenozoic deformation in Central Asia, we studied the paleomagnetism of Tertiary red beds and lava flows from intermontane basins in the Tien-Shan region of Kyrgyzstan. We collected 532 cores and hand samples from 78 sites at 12 localities and progressively demagnetized them, thermally or with alternating fields. For most sites, there are magnetic components with unblocking temperatures higher than 600°C. We infer that the magnetic carriers are mainly hematite and magnetite. For most localities, the high-temperature component appears to predate tectonic folding. For all localities, mean inclinations are shallower than expected from apparent polar wander paths. Inclination anomalies range from  $16^{\circ} \pm 5^{\circ}$  for the Issyk-Kul basin, to  $26^{\circ} \pm 7^{\circ}$  for the Fergana basin. If due to changes in latitude, these anomalies imply at least 2000 km of northward displacement of the Tien-Shan during the Tertiary, for which there is no tectonic evidence. We thus consider that the paleomagnetic reference directions cannot be directly compared with our Tertiary data. We explored other possible reasons for this anomaly, which has also been reported from other parts of the Alpine belt, but we could not find a satisfactory explanation. Absolute rotations cannot be accurately determined, because of problems with the reference direction. Nevertheless, the mean declination for the Fergana basin lies counterclockwise by  $20^{\circ} \pm 11^{\circ}$  from the mean declination of the Issyk-Kul basin. This result is consistent with the counterclockwise rotation inferred for the Fergana basin from the pattern of Cenozoic faults and folds. It suggests a Cenozoic right-lateral displacement of  $110 \pm 60$  km on the Talas-Fergana fault.

### INTRODUCTION

Argand [1924] compiled a tectonic map of Eurasia. He inferred that northward motion of India and its subsequent collision ("affrontement") with Asia were responsible for Cenozoic reactivation of earlier structures and for anomalous relief throughout much of Central Asia. Recent work has done much to confirm and quantify these ideas. Crustal shortening within Tibet was attributed to reactivation of earlier structures by Dewey and Burke [1973]. Seismicity and studies of fault traces on satellite imagery confirmed the extent of active deformation within Central Asia [Molnar and Tapponnier, 1975]. From magnetic anomalies in the Indian Ocean, India is estimated to have collided with Eurasia about 55 Ma ago [Patriat and Achache, 1984]. Since then, paleomagnetic and structural evidence suggests that there has been a further convergence of about 2000 km between India and Eurasia [Achache et al., 1984; Savostin et al., 1986].

Still not clear is the style of deformation within Central Asia over the last 55 Ma. Molnar and Tapponnier [1975] drew attention to the importance of strike-slip faulting. Tapponnier et al. [1982] suggested that strike-slip faulting could have led to significant eastwards extrusion of large blocks, with accompanying rotations. Peltzer and Tapponnier [1988] further suggested that eastward extrusion of Tibet accounts for

about 50% of the convergence between India and Asia, the rest being taken up by crustal thickening. In contrast, England [1982], Houseman and England [1986] and Dewey et al. [1989] have argued that crustal thickening accounts for almost all of the convergence.

Davy and Cobbold [1988] and Cobbold and Davy [1988] compared analogue models of continental indentation with the pattern of Cenozoic faults in Central Asia (Figure 1a). They concluded that lateral extrusion accounts for somewhere between 20% and 45% of convergence, the rest being taken up by thickening. Such thickening must attenuate laterally across wrench zones, left-lateral in the west and right-lateral in the east. Cobbold and Davy [1988] found structural evidence for left-lateral wrenching, not only on the edges of thickened areas, but also in a long strip, running from the Gulf of Oman, through the Pamirs, to Lake Baikal and beyond. This belt, they argued, is responsible for some eastwards extrusion of Central Asia. On structural evidence, wrenching is partially accommodated by rotation of fault blocks and antithetic strike-slip faults, domino style. Rotations were inferred to be counterclockwise in the Gulf of Oman-Pamirs-Baikal wrench zone, clockwise in eastern Tibet. The Fergana basin in the Tien Shan was inferred to have rotated about  $30^{\circ}$  counterclockwise in the Cenozoic [Cobbold and Davy, 1988]. Bakirov [1960] had already made a rather similar suggestion, but he thought the rotation occurred during the Late Paleozoic.

Using the active velocity field, England and Molnar [1990] calculated that clockwise block rotation in eastern Tibet currently accommodates nearly all the northeastward motion of Tibet and that no eastward or southeastward motion of China or Indonesia are necessary. Jolivet et al. [1990] suggested that the opening of the Japan Sea was a consequence of counterclockwise rotation of blocks at the northeastern end of the Gulf of Oman-Pamir-Baikal wrench zone.

Paleomagnetism appears to be an excellent technique for measuring block rotations; but little work has been done so far to demonstrate Cenozoic rotations in Central Asia. Bazhenov

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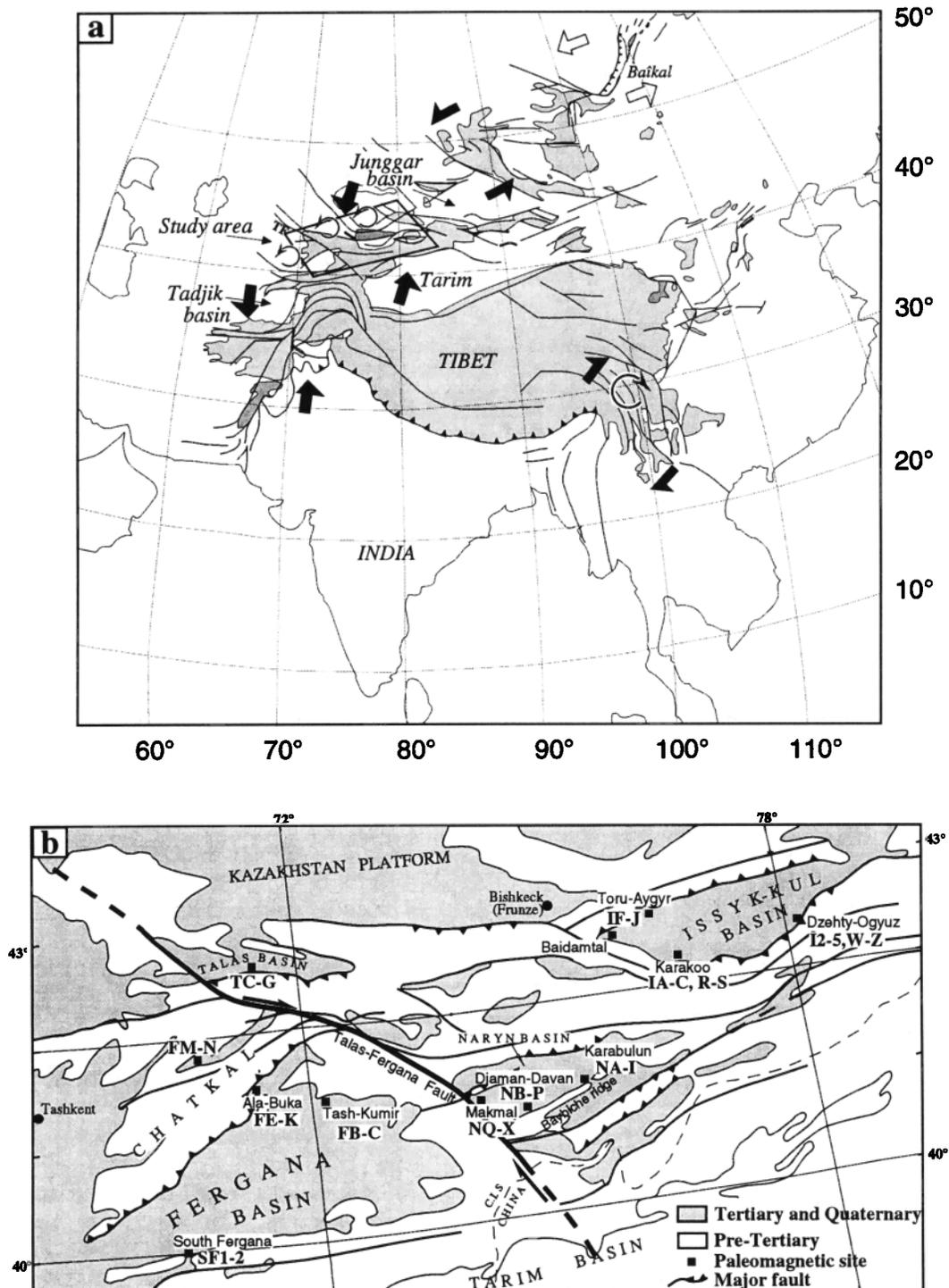


Fig. 1. (a) Cenozoic deformation in Central Asia [after *Cobbold and Davy, 1988*]. Map shows traces of major faults, areas with elevation greater than 2 km (hatched) and inferred Cenozoic displacement pattern. Pairs of arrows indicate horizontal displacement gradients (solid for contractional, open for extensional). solid half arrows indicate dominant wrenching in Altai and eastern Tibet; asymmetric solid arrows, convergent wrenching in Hindu-Kush and Tien-Shan; asymmetric open arrows, divergent wrenching in Baikal; round arrows, rotations relative to stable Asia. (b) Structural map of the Kirghiz Tien-Shan, showing main faults, Tertiary basins and paleomagnetic sampling localities.

and *Burtman* [1986] were able to demonstrate rotations in the area of the Pamir-Punjab syntaxis; *Chen et al.* [1991] found paleomagnetic and structural evidence for small rotations of the Tarim and Junggar blocks in Western China; and *Pozzi and Feinberg* [1991] proposed a significant counterclockwise rotation of part of the northern Tadjik basin.

To study rotations throughout the Gulf of Oman-Pamirs-Baikal strip, a paleomagnetic project was set up between the Centre National de la Recherche Scientifique (CNRS) and the Geological Institute of the Academy of Sciences (Moscow). In the summer of 1989, *Bazhenov, Burtman, Cobbold, Perroud* and *Sadybakasov* took part in a 1-month expedition to the

Tien-Shan region of Kyrgyzstan. The objectives were to sample Tertiary red beds and lavas and to test for rotations between individual basins and even within them.

#### GEOLOGICAL SETTINGS

In the Tien-Shan region of Kyrgyzstan, mountain ranges several kilometers high alternate with intermontane basins (Figure 1b). Paleozoic and older rocks form the ranges whereas Mesozoic and Cenozoic sediments fill the basins. Mesozoic sediments are common throughout the large Fergana basin but are rare in the other basins. The Paleogene succession is continental and only a few hundred meters thick, to the north of the Talas-Fergana fault; but it is marine and more than 1 km thick, to the south of the fault. The Neogene succession is several kilometres thick in the major basins and is entirely continental. On the ranges, there are old erosion surfaces with remnants of Paleogene sediments. Erosion surfaces and sediments have been folded and faulted, as a result of Cenozoic tectonics [Schulz, 1948; Sadybakasov, 1972, 1991]. Anticlinal ranges are commonly thrust over neighboring synclinal basins.

The general strike of the Tien-Shan ranges is East-West, but there are significant deviations, especially near the major Talas-Fergana fault, which separates the Western Tien-Shan from the Central and Eastern Tien-Shan (Figure 1b). This strike-slip fault originated in the Paleozoic and has been active in the Cenozoic [Burtman, 1961; Wallace, 1976; Tapponnier and Molnar, 1979]. Most of the displacement on it has been right-lateral. The Quaternary offset is more than 10 km. The total offset since the Permian is about 200 km [Burtman, 1980]; but so far it has not been possible to determine how much of this is Cenozoic and how much is older [Tapponnier and Molnar, 1979].

#### SAMPLING LOCALITY

We sampled Tertiary sediments and lavas in several basins throughout the Northern, Central and Western Tien-Shan. We collected a total of 408 cores and 124 hand samples at 78 sites (6-8 samples per site) from 12 localities within Eocene to Miocene rocks. Both solar and magnetic compasses were used for orientation; when both were present, calculated declinations differed from the present day-field declination by less than 1° or 2°.

As a base map, we used the 1:1,000,000 Operational Navigation Chart (sheet F6), published by the U.S. Defense Mapping Agency. For convenience, place names quoted in this paper have been taken from this map wherever possible. We used Landsat satellite images, geological maps at 1:200,000 and 1:500,000 [Ministry of Geology of the USSR and Kyrgyz Academy of Sciences, 1978] and detailed topographic maps. We carefully recorded the attitudes of bedding, folds and other structures. From these data, we constructed geological sections. We used a portable navigational instrument (Magellan GPS NAV 1000™) to locate each paleomagnetic site on the ground with an accuracy of 30 m.

#### Northern Tien-Shan

Here we sampled Tertiary sediments and lavas on the edges of two east-west trending basins: Issyk-Kul and Talas (Figure 1b).

In the Issyk-Kul basin, we mainly sampled the Kokturpak

formation (Eocene) and the Dzhety-Ogyuz formation (Oligocene-Miocene). At the northern edge of the basin (Toru-Aygyr locality), the Kokturpak formation consists of reddish sandy marls, sandstones and clays, of lacustrine and subaerial origin, resting upon a basalt flow (or flows) 12 m thick. Only a few meters above the basalt, the sediments have yielded mammalian and reptilian remains (*Deperetella* and *Prothyreodon* sp.) attributed to the Middle to Late Eocene [Turdukulov, 1980]. The basalt has yielded a radiometric age of 55-Ma whole-rock K-Ar date [Krilov, 1960]. Underlying sandstones have been baked over a thickness of 1 m. We sampled four sites (IF to IJ) in the basalts and underlying sandstones. On average, the succession here dips gently southwestwards, but locally it is folded. Basalts and sediments of the Kokturpak formation were also sampled at four sites (IN to IQ) at the Baidamtal locality (western end of Issyk-Kul Basin), where the succession dips gently southwestward.

The Dzhety-Ogyuz Formation consists of red sandstones and conglomerates. Remnants of an Oligocene tortoise have been found at the type locality of Dzhety-Ogyuz [Sidorenko, 1972]. The formation is here more than 1000 m thick and the top may be Lower Miocene. The bedding dips gently to the NNW. We sampled 12 sites, seven near the base of the formation (IT to IZ) and five near the top (I1 to I5). Seven randomly oriented pebbles were sampled at one of the sites, in order to perform a conglomerate test.

At the Karakoo locality, on the southwestern edge of the Issyk-Kul basin, Paleogene sediments dip gently westward. We sampled two sites (IA, IB) in Paleogene red beds and three sites (IC, IR and IS) in Miocene grey to yellowish-grey sediments.

At the southern edge of the Talas basin (Talas locality), the bedding dips gently southward. We sampled seven sites (TA to TG) in red Paleogene detrital sediments of continental origin, similar to those of the Kokturpak Formation of Issyk-Kul basin.

#### Central Tien-Shan

The Tertiary stratigraphy of the Naryn basin is less well known. At all localities, we sampled red sandstones close to the underlying Paleozoic basement. The sandstones are similar to those of the Kokturpak Formation of the Issyk-Kul basin.

On the southern edge of the Naryn basin is the ENE-trending Baybiche ridge (Figure 1b). On geomorphological and stratigraphic evidence, this ridge was uplifted in the Quaternary [Sadybakasov, 1991]. Its Paleozoic core is overlain by Cenozoic sediments, dipping northwestwards on average. In detail, the Baybiche ridge is made up of en-echelon folds striking east. We sampled nine sites (NA to NI) in the Karabulun and Karabuk valleys (grouped as Karabulun locality) and seven sites (NJ to NP) at Djaman-Davan locality, where the Baybiche ridge locally trends EW. At both localities, the red sandstones are drape-folded, sometimes strongly, over underlying basement faults.

In the NW corner of the Naryn basin, at Makmal locality, we sampled eight sites (NQ to NX) on the slopes of the Ak-Shirak ridge. Here the red sandstones dip gently southeastward.

#### Western Tien-Shan

We investigated Paleogene sedimentary rocks on the northern and northwestern edges of the Fergana basin and in the Lower Chatkal basin.

On the northern edge of the Fergana basin, near the town of Tash-Kumyr, we sampled three sites (FA to FC) in mudstones and sandstones of the Massaget Formation, which has marine fauna of Oligocene age [Sodorenko, 1972]. The bedding at this locality dips steeply southward.

On the northwestern edge of the Fergana basin, in the foothills of the Chatkal ridge, is the Ala-Buka syncline, asymmetric and southeasterly verging. On its northwestern limb, where the bedding dips steeply southeastwards, we sampled four sites (FH to FK) in the Massaget Formation; and on the southeastern limb, where the bedding dips gently northwestward, we sampled another four sites (FD to FG) in pink marls of marine origin, attributed to the Eocene [Sidorenko, 1972].

The intermontane Chatkal basin is situated within the Chatkal ranges. This basin is an open syncline trending NE. We sampled six sites, four on one limb (FL to FO), two on the other (FP and FQ), all in continental Paleogene sediments (marls and sandstones).

Near the southern edge of the Fergana basin, pale-red calcareous siltstones were sampled from the basal member of the Massaget Formation (Late Oligocene to Miocene) on both limbs of an EW trending syncline (sites SF-1 and SF-2). Hand samples, oriented with a magnetic compass, were taken along sections across about 15 meters of true stratigraphic thickness, on each limb.

#### PALEOMAGNETIC STUDY

The samples were studied at Rennes paleomagnetic laboratory. Remanent magnetization was measured with either a cryogenic magnetometer (LETI) or a Schonstedt spinner flux gate magnetometer. We isolated characteristic directions of remanent magnetism after progressive thermal demagnetization or alternating field demagnetization, performed with Schonstedt equipment. In general, we found thermal cleaning to be more efficient for sediments. At each step in the demagnetization process, we measured bulk susceptibility. We determined paleomagnetic directions by principal component analysis, within a graphical interactive system [Perroud, 1985], and we used the statistics of Fisher [1953]. We studied one specimen from each core and two specimens from each hand sample. We considered as reliable any site which presented consistent magnetic behavior from at least three samples.

Fold tests were carried out in two ways, according to McElhinny [1964] and McFadden and Jones [1981]. For some localities, the number of sites which yielded acceptable results was rather limited and so we had to use sample directions. The algorithm, on which is based the test of McFadden and Jones [1981], was used in three different ways. First, we compared mean directions from different localities within a single basin, to see if the differences were statistically significant (the consistency test). To perform the fold test *sensu stricto*, we sorted the sampling sites into groups of similar bedding orientation, irrespective of location. Finally, the reversal test was carried out for data from each basin, again irrespective of site location.

#### Magnetic Mineralogy

For most sedimentary samples, natural remanent magnetization (NRM) intensities range from  $5 \cdot 10^{-4}$  to  $10^{-2}$  A m<sup>-1</sup>, whereas basalts and some sediments (sites IA, IB, IW,

IF, IJ, IS and FB), including those from zones of contact with basalts, have higher intensity of magnetization, from  $10^{-2}$  to 5 A m<sup>-1</sup> (Figure 2a). A similar difference is also observed in weak field susceptibility, with values between  $10^{-5}$  and  $10^{-3}$  SI units for most of the sediments and values between  $10^{-3}$  and  $10^{-2}$  SI units for the other sedimentary sites and the basalts (Figure 2b).

Isothermal remanent magnetization (IRM) was given in about 20 steps to one sample from each site. The most common progressive acquisition curves illustrate two stages (Figure 2c): first, for applied fields up to 200 mT, the IRM intensity increases rapidly; then, from 200 mT up to 1.2 T, the intensity increases more slowly, indicating that the sample did not reach saturation. For a few samples, IRM was acquired more gradually (Figure 2c) and saturation was still not reached at 1.2 T.

To further explore the magnetic mineralogy of our rocks, we conducted an additional experiment on seven samples, from sites IC, IR, IS, IY, IZ, I2 and I5, following a method suggested by Lowrie [1990], in which different coercivity fractions of IRM are magnetized in successively smaller fields, along three orthogonal directions, and then thermally demagnetized. The three-component IRMs were produced in fields of, first, 1.2 T along the Z axis; then, 0.15 T along the X axis; and finally, 0.05 T along the Y axis. These fields were chosen so as to evaluate the influence of hematite and goethite for the Z axis, single-domain magnetite for the X axis and low-coercivity magnetite for the Y axis. In two samples (grey sandstones from sites IC and IR), the IRM appears to be dominated by magnetite (Figure 2d). In the other five samples, both hematite and magnetite are indicated in various proportions, with hematite usually prevailing (Figures 2e and 2f).

For the basalts, thermomagnetic curves, obtained with the automated vertical Curie balance at Rennes, show a clear inflection point at about 350°C (probably due to maghemite) and a Curie point at 580°C (due to magnetite, the main carrier of magnetization).

#### Anisotropy of Magnetic Susceptibility

To check for a possible bias in paleomagnetic directions, due to anisotropy of our samples, we measured the anisotropy of magnetic susceptibility (AMS) for all sites which gave paleomagnetic results, using the enhanced Digico apparatus at Rennes. The basalt samples reveal no anisotropy. Sediments from all basins, except Issyk-Kul, display randomly oriented ellipsoids and very low anisotropy ratios. For the Issyk-Kul basin, anisotropy ratios are also low, but AMS ellipsoids are either triaxial or prolate ( $k_{int}/k_{min} > k_{max}/k_{int}$ ), with a vertical minor axis and a major axis along the trend of the Issyk-Kul basin (Figure 3). This AMS may be of purely sedimentary origin, or it may result from a combination of a sedimentary fabric and tectonic shortening in a NW-SE direction. Nevertheless, the degree of anisotropy is usually lower than 5%.

From the combined IRM experiments discussed above, for most red samples from the Issyk-Kul basin, we think that hematite is the main carrier of magnetization, even though magnetite is present in various amounts. The domination by hematite on the IRM suggests that it should also dominate the susceptibility. If so, we can infer that its anisotropy mainly reflects the distribution of hematite particles in our samples.

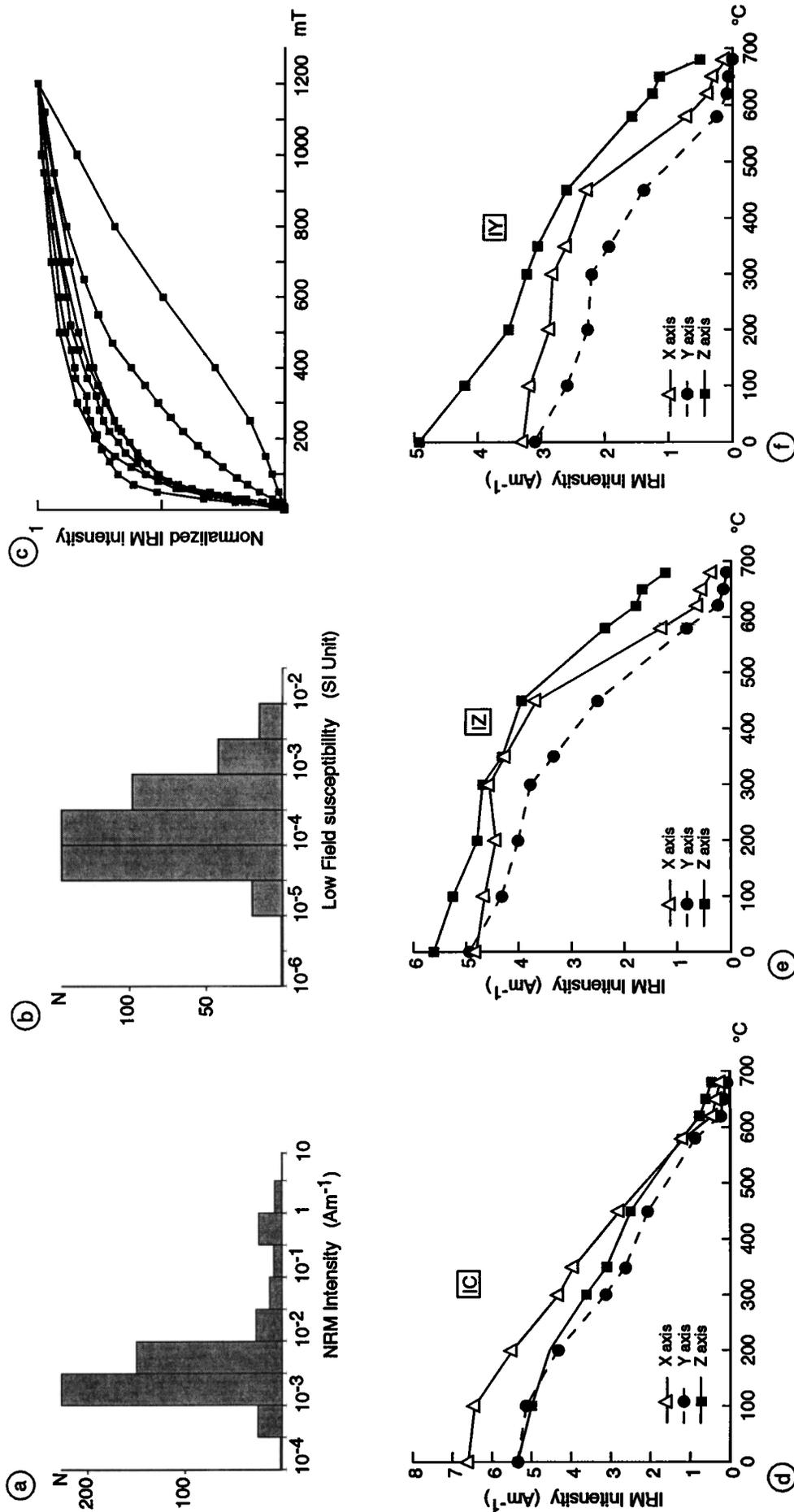


Fig. 2. Rock magnetic study. Histograms of (a) NRM intensity and (b) low field susceptibility for the entire collection; (c) representatives normalized IRM intensity curves for sediments. IRM demagnetization data after Lowrie (1990) (compare text): (d) gray sandstone, (e) and (f), red sandstones.

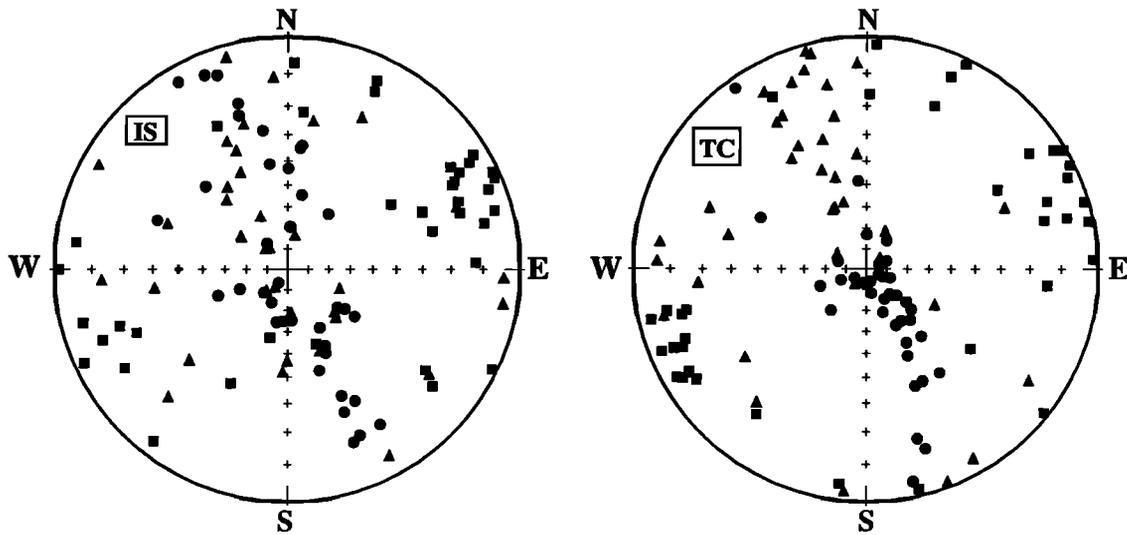


Fig. 3. AMS data for the Issyk-Kul basin. Stereographic projection shows attitude of maximum (squares), intermediate (triangles) and minimum (circles) principal axes of susceptibility. In stratigraphic coordinates, susceptibility ellipsoid is prolate with a vertical minor axis and a major axis along the trend of the Issyk-Kul basin.

#### Paleomagnetic Results

**Issyk-Kul basin: Dzhetey-Ogyuz.** At six sites (I1, I3, I4, IT, IV and IX) where samples were the most coarse-grained, we were not able to isolate consistent paleomagnetic directions. During thermal demagnetization, samples from these sites had an erratic behaviour for temperatures higher than 350°-400°C. We had similar problems with a few samples from other sites too. However, on the remaining samples from five sites (I2, I5, IW, IY and IZ), thermal cleaning revealed two magnetic components (Figure 4). The first was usually removed below 350°C. In geographic coordinates, this low-temperature component (LTC) clusters well around the present-day magnetic field direction ( $I = 61^\circ$ ). This LTC is therefore interpreted as a recent overprint. Between 350°C and 680°C, a second component was isolated. This high-temperature

component (HTC) exhibits both polarities (Table 1), and its in situ mean direction is far from the present-day dipole field. No fold test is possible here since the dip of the bedding ranges only from 33° to 41° northwards. The tilt-corrected HTC mean direction is  $D=0^\circ$ ,  $I=+44^\circ$ ,  $\alpha_{95}=11^\circ$ . From the conglomerate layer, five out of the seven pebbles display a well-defined magnetization, but their directions are randomly distributed, eliminating the possibility of blanket remagnetization of the whole sequence.

**Issyk-Kul basin: Karakoo.** Four sites (IA, IC, IR and IS), out of the five sampled, provided good results. The LTCs are rather scattered, especially for sites with reverse polarity; whereas the HTC are rather well determined on all samples. In stratigraphic coordinates, both polarities are present, with nearly antipodal directions (Table 1). The dip of the bedding

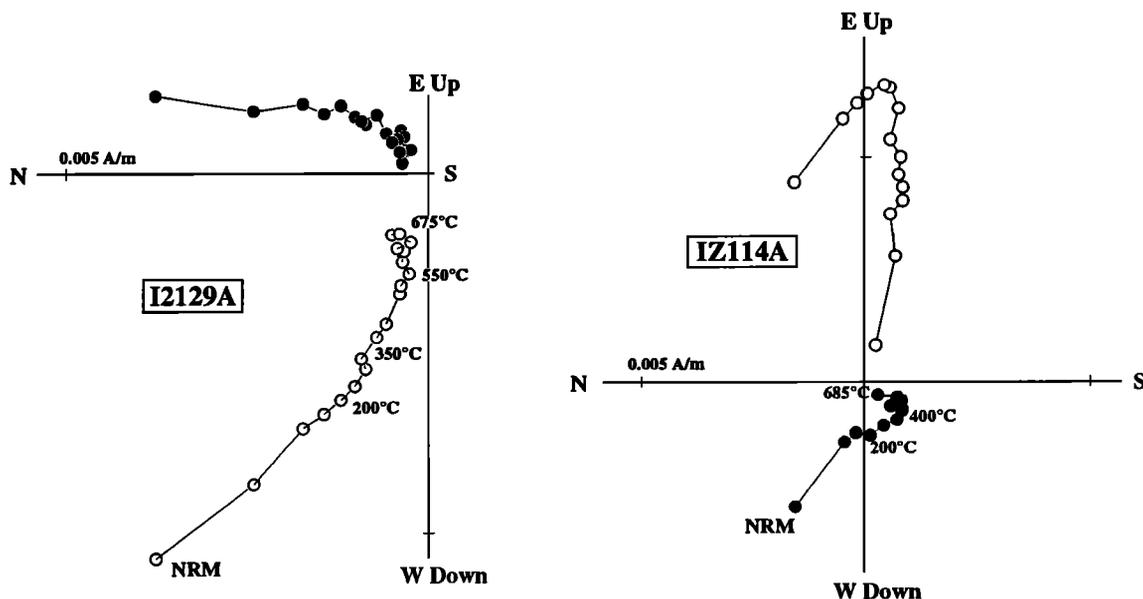


Fig. 4. Thermal demagnetization for two sites (I2 and IZ) from Issyk-Kul basin. Orthogonal vector projections in geographic coordinates show changes in magnetization with temperature, from initial attitude (NRM), toward full demagnetization at the origin. Solid (or open) symbols are in horizontal (or vertical) plane. Low-temperature components (LTC) are close to the present field (unblocking temperature around 350°C), whereas high-temperature components (HTC) are of both polarities.

TABLE 1. Paleomagnetic Data for Issyk-Kul basin

Site	Latitude, (°N)	Longitude, (°E)	Bedding	n/N	AF/TH	In Situ		Tilt Corrected		k	α <sub>95</sub>	Litho	Age
						D	I	D	I				
<i>Dzhety-Ogyuz</i>													
IW	42.334	78.234	264/41	6/7	TH	078	78	11	46	58	9	S	Oligo-Miocene
IY	42.334	78.234	264/41	6/7	TH	356	80	354	39	35	12	S	Oligo-Miocene
IZ	42.344	78.231	256/37	7/7	TH	251	-88	169	-53	38	10	S	Oligo-Miocene
I2	42.356	78.225	241/33	4/7	TH	45	76	352	51	30	17	S	Oligo-Miocene
I5	42.357	78.224	261/33	6/7	TH	20	61	7	30	78	8	S	Oligo-Miocene
<i>Karakoo</i>													
IA	42.183	76.725	206/14	6/6	TH	19	58	0	54	90	7	S	Paleocene
IC	42.203	76.675	088/53	6/6	AF/TH	176	-16	173	-68	19	16	S	Miocene
IR	42.200	76.670	337/11	4/4	TH	334	54	349	53	38	15	S	Miocene
IS	42.200	76.670	337/11	5/5	TH	165	-63	185	-59	33	13	S	Miocene
<i>Toru-Aygyr</i>													
IF	42.621	76.385	135/10	16/16	AF+TH	209	-37	206	-47	45	6		
IG	42.625	76.389	215/10	6/7	AF+TH	190	-37	184	-32	506	3	B	Eocene
IH	42.625	76.389	259/03	7/7	AF+TH	192	-46	191	-43	312	3	B	Eocene
IJ	42.632	76.392	145/32	24/24	AF+TH	200	-26	178	-52	95	3		
<b>Mean</b>													
				N		In Situ		Tilt Corrected		k	α <sub>95</sub>		
						D	I	D	I				
Dzhety-Ogyuz				5		33	78	0	44	47	11		
Karakoo				4		354	49	357	59	50	11		
Toru-Aygyr				4		198	-36	190	-49	11	29		
All sites				13		12	57	2	49	50	10		
										48	10		
										10	12		
										42	6		

Top part of table gives localities, site numbers, site location, site stratification, number of samples used for statistics (n), number of samples measured (N), method of demagnetization (AF for alternating field, TH for thermal), mean declination (D) and mean inclination (I) for high-temperature component of samples, Fisher statistics (k for grouping parameter, α<sub>95</sub> for radius of circle of confidence at 95% probability level), rock type (B for basalt, S for sediment) and approximate stratigraphic age. Bottom part of table gives number of data used for calculation (N), mean declination (D) and inclination (I) for each locality, and Fisher statistics for high-temperature component (HTC).

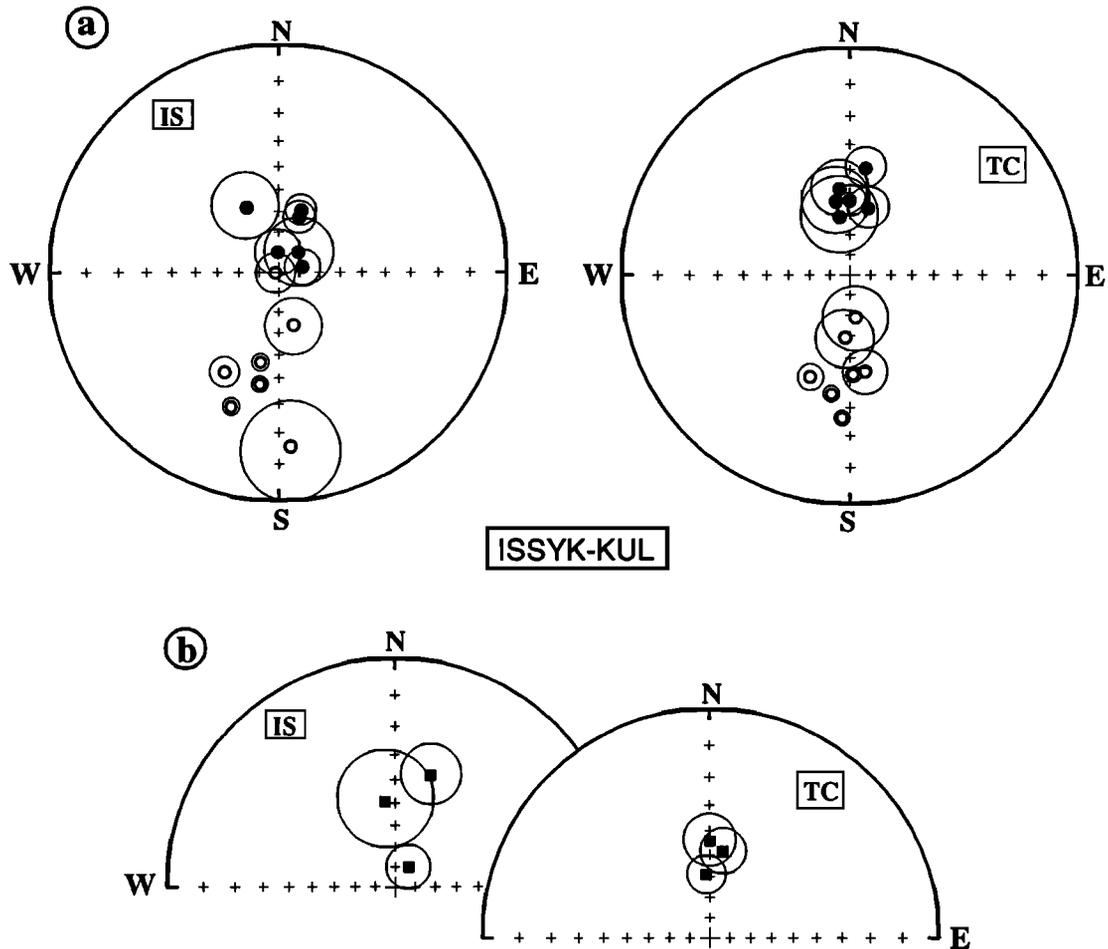


Fig. 5. (a) Stereographic projection of mean directions for sites from Issyk-Kul basin. (b) Stereographic projection of mean directions for the three localities of Issyk-Kul basin. Solid (or open) circles are projections in the lower (or upper) hemisphere. Coordinates are either geographic (IS) or stratigraphic (TC).

ranges from  $11^{\circ}$  to  $53^{\circ}$  and the fold test after *McElhinny* [1964] is positive at the 99% confidence level. The tilt-corrected mean direction is  $D=357^{\circ}$ ,  $I=+59^{\circ}$ ,  $\alpha_{95}=9^{\circ}$ .

**Issyk-Kul basin: Baidamtal.** This locality provided good results only on the lava flow of site IQ, but the attitude of this flow could not be measured accurately. Thus we excluded this result from further analysis.

**Issyk-Kul basin: Toru-Agyr.** For two of the four sites sampled in the basalts, we also collected underlying sediments in the contact zones (sites IF and IJ). As discussed previously, the intensity and susceptibility of these sediments are unusually high and their magnetization is dominated by magnetite. Furthermore, mean directions from sediments and volcanics are quite similar. From these magnetic properties, the sediments appear to have been totally remagnetized during lava emplacement. To determine the mean direction of these two sites, we therefore decided to combine the results for both sediments and volcanics. The four final site-mean directions (Table 1) are well clustered both before and after tilt correction, with a tilt-corrected mean at  $D=190^{\circ}$ ,  $I=-49^{\circ}$ ,  $\alpha_{95}=10^{\circ}$ .

**Issyk-Kul basin: Entire basin.** The site mean directions for the entire Issyk-Kul basin are presented in Figure 5a, both before and after tilt correction. The dip of the bedding (Table 1) ranges through about  $90^{\circ}$ , from about  $40^{\circ}$  toward the north,

to about  $50^{\circ}$  toward the south. For the consistency test (Table 2), the calculated F statistic slightly exceeds the critical value; but it is mainly due to the steeper bedding dip at Karakoo locality, where the rocks are slightly younger. However, the mean declinations from all three localities are statistically identical (Figure 5b). For all 13 site means from all localities, the fold test according to *McElhinny* [1964] is positive at the 99% confidence level. At the scale of the entire Issyk-Kul basin, the fold test according to *McFadden and Jones* [1981] is positive too (Table 2); however, two results (site IJ from Toru-Agyr and site IC from Karakoo) have deviating bedding attitudes and cannot be incorporated into the test. Finally, for all 13 tilt-corrected site means, the reversal test is positive (Table 2). We conclude that the Issyk-Kul basin acquired its synformal structure later than its magnetization. The overall mean paleomagnetic direction for the Issyk Kul basin is  $D=2^{\circ}$ ,  $I=+49^{\circ}$ ,  $\alpha_{95}=6^{\circ}$ .

**Talas basin.** A characteristic magnetization was isolated in samples from four sites out of the seven sampled. Both polarities are observed (Table 3). In geographic coordinates, the mean direction for the locality is far from that of the present field. A fold test is not significant, but the dip of the bedding ranges only from  $25^{\circ}$  to  $39^{\circ}$  southward. The tilt-corrected mean direction for the basin is  $D=343^{\circ}$ ,  $I=+54^{\circ}$ ,  $\alpha_{95}=22^{\circ}$ . Because the data set is of limited reliability, we

TABLE 2. Results of Field Test Application

Test	L	DF	CV	IS	TC
<i>Issyk-Kul Basin</i>					
Consistency	site	4,20	2.9	8.7	3.3
Fold*	site	4,16	3.0	12.5	1.6
Reversal	site	2,22	3.4		0.7
<i>Naryn Basin</i>					
Consistency	site	4,26	2.8	3.9	2.6
Fold	site	4,26	2.8	8.4	1.0
Reversal	site	2,28	3.3		0.8
<i>Ala-buka Locality</i>					
Fold	sample	2,52	1.9	102.0	0.4
<i>Fergana Basin</i>					
Consistency	sample	4,86	2.5	7.2	2.1
Fold	sample	8,82	2.1	56.0	1.9
Reversal	sample	2,88	3.1		1.5
<i>Fergana and Chatkal</i>					
Consistency	sample	6,104	2.2	9.4	2.4

Consistency test is the comparison of locality mean directions; fold test is performed for the entire data set from a basin with bedding attitudes being regrouped irrespective of locality if necessary; reversal test is performed for tilt-corrected data for each basin separately with data being divided into polarity groups irrespective of locality and bedding attitudes; L is the level at which the tests are performed; DF is the number of degrees of freedom; CV is the 95% critical value, IS and TC are in situ and tilt-corrected calculated values of field statistics, respectively.

\* Two sites with deviating beddings were not incorporated into any group.

decided not to consider it for the final tectonic interpretation.

*Naryn basin.* Three kinds of behavior were observed during demagnetization. Some samples had a single well-defined component, with unblocking temperature around 670°C (Figure 6a). Other samples had two magnetic components: an LTC near the present field direction, which we interpret as a partial recent overprint (Figure 6b and 6c), and an HTC with unblocking temperature higher than 655°C, showing both polarities. Finally, other samples had a single very well-defined component with unblocking temperature less than 570°C, whose direction was close to the present field (Figure 6d), suggesting complete recent remagnetization.

*Naryn basin: Karabulun.* This locality provided seven reliable sites out of nine (Table 4). All except NI have a reverse component of magnetization. However HTCs are rather scattered within three sites (ND, NC and NG), leading to rather large confidence circles around the mean directions. Although the dip of the bedding ranges from 33° SE to 25° NW, a fold test is not significant at the 95% level, according to

*McElhinny* [1964]. The tilt-corrected mean direction is  $D=358^\circ, I=+30^\circ, \alpha_{95}=14^\circ$ .

*Naryn basin: Djaman Davan.* Six sites out of seven provided reliable results. One site (NN) shows a large degree of scatter, but the others do not. Most sites show normal polarity (Table 4). The mean directions are better clustered after tilt correction than in situ, but a fold test [McElhinny, 1964] is inconclusive. The tilt-corrected mean direction is  $D=26^\circ, I=+46^\circ, \alpha_{95}=17^\circ$ .

*Naryn basin: Makmal.* Out of eight sites, only five provided acceptable results and two of these (NW and NQ) show a large degree of scatter (Table 4). The fold test according to McElhinny [1964] is again inconclusive. The tilt-corrected mean direction is  $D=355^\circ, I=+36^\circ, \alpha_{95}=31^\circ$ .

*Naryn basin: Entire basin.* When the data are considered at the scale of the entire Naryn basin (Figure 7a), there is some within-site scatter, but site means are rather consistent, except for two sites (NO, Djaman Davan, and NW, Makmal) which

TABLE 3. Paleomagnetic Data for Talas Basin

Site	Latitude, (°N)	Longitude, (°E)	Bedding	n/N	AF/TH	In Situ		Tilt Corrected		k	$\alpha_{95}$	Litho	
						D	I	D	I				
TC	42.499	71.550	95/30	4/8	TH	180	-29	177	-59	13	26	S	
TE	42.499	71.550	90/25	4/6	TH	155	-10	150	-33	12	27	S	
TF	42.499	71.550	85/39	6/6	TH	166	-33	151	-71	62	9	S	
TG	42.500	71.535	97/26	6/6	TH	359	34	354	59	44	10	S	
						In Situ		Tilt Corrected					
						N	D	I	D	I	k	$\alpha_{95}$	
						4	350	27	343	54	27	18	
											20	22	

Same symbols as in Table 1. At all sites, sediments are of undifferentiated Paleogene age.

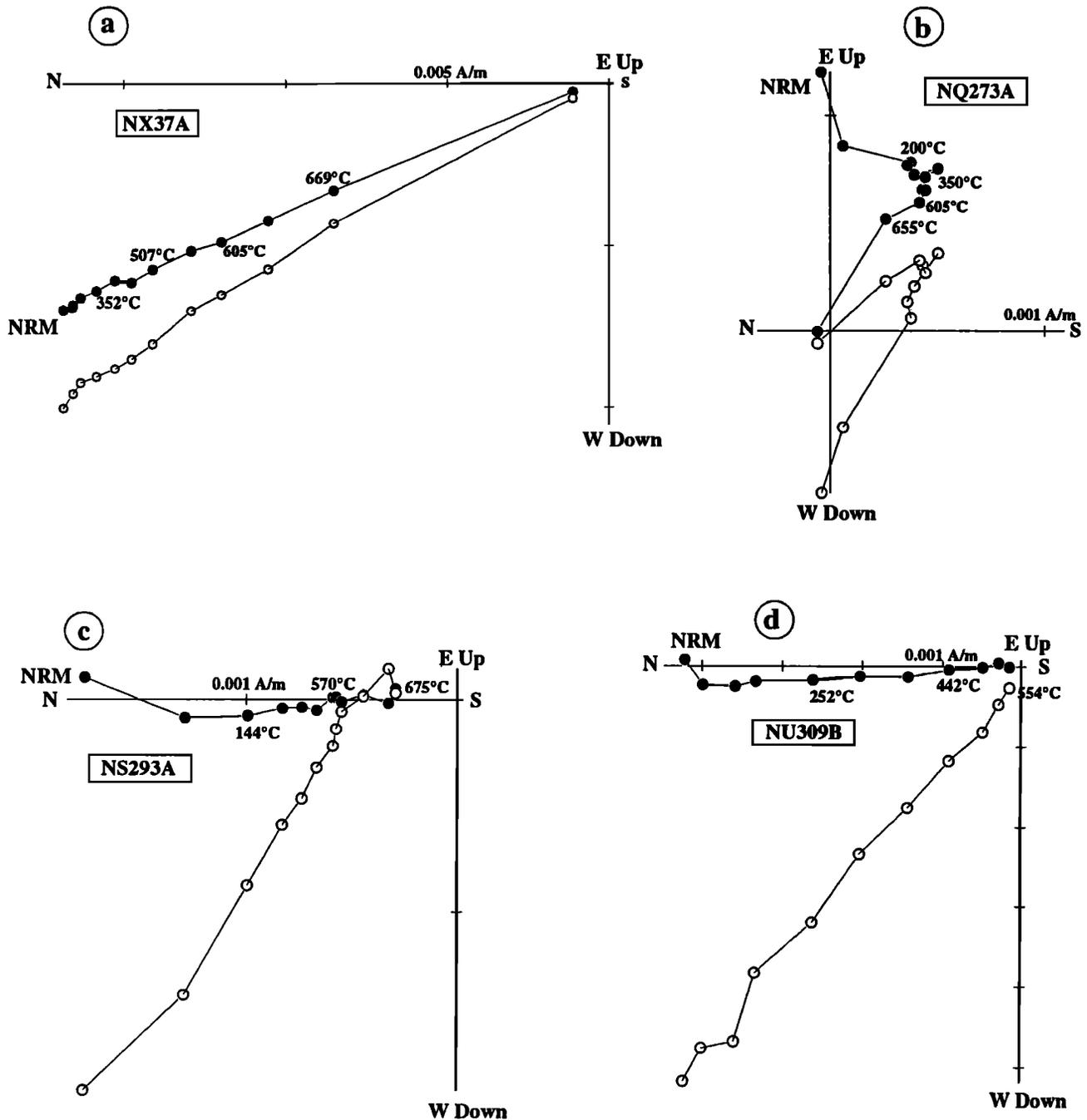


Fig. 6. Orthogonal vector projections of representative thermal demagnetizations for the Naryn basin. For site (a) NX, magnetization is carried by hematite. For sites (b) NQ and (c) NS, LTCs show unblocking temperatures around 350°C and are near the present field in geographic coordinates; whereas HTCs present both polarities, with unblocking temperature higher than 655°C. For site (d) NU, there is one component of magnetization, close to the present field in geographic coordinates and probably a complete overprint. Symbols and conventions are as for Figure 3.

deviate strongly (more than 40°) from the overall mean. After their omission, the three tilt-corrected locality means are statistically identical (Figure 7b) and the overall mean for the Naryn basin ( $D=5^\circ$ ,  $I=+37^\circ$ ,  $\alpha_95=11^\circ$ ) agrees well with the mean direction for the Issyk-Kul basin. After data regrouping, although the fold test according to *McElhinny* [1964] is not conclusive due to large dispersion, the fold test according to *McFadden and Jones* [1981] is positive, as is the reversal test (Table 2).

**Fergana basin.** Most samples show two components of magnetization (Figure 8). The LTCs are rather close to the present field direction and have unblocking temperatures between 200°C and 350°-400°C. Unblocking temperatures for HTCs are generally around 680°C, except for site FH, where they are below 580°C, suggesting that magnetization could be carried by magnetite (Figure 8).

**Fergana basin: Tash-Kumyr.** Data from site FA are highly scattered and so we discarded them. For the remaining two sites

TABLE 4. Paleomagnetic Data for Naryn Basin

Site	Latitude, (°N)	Longitude, (°E)	Bedding	n/N	AF/TH	In Situ		Tilt Corrected		k	α <sub>95</sub>	Litho
						D	I	D	I			
<i>Karabulun</i>												
NA	41.280	75.373	66/33	4/6	TH	182	20	181	-10	23	19	S
NB	41.280	75.373	170/13	6/6	TH	201	-10	198	-17	38	11	S
NC	41.280	75.373	32/15	3/6	TH	176	-43	191	-51	28	23	S
ND	41.277	75.359	241/19	3/6	TH	176	-55	169	-37	11	40	S
NE	41.277	75.359	210/18	7/7	TH	167	-40	159	-27	26	14	S
NG	41.221	75.226	266/21	5/7	TH	186	-47	184	-26	12	23	S
NI	41.221	75.226	219/14	7/7	TH	351	47	344	36	17	16	S
<i>Djaman-Davan</i>												
NJ	41.067	74.779	257/31	4/7	TH	47	68	14	44	60	12	S
NL	41.067	74.779	270/32	6/7	TH	73	75	23	51	44	10	S
NM	41.067	74.779	270/32	7/7	TH	222	-53	27	-26	26	12	S
NN	41.044	74.795	160/37	8/8	TH	45	3	39	36	8	35	S
NO*	41.047	74.791	143/50	6/7	TH	50	26	42	76	41	10	S
NP	41.047	74.791	143/50	5/7	TH	41	23	19	70	119	7	S
<i>Makmal</i>												
NQ	41.224	74.077	31/25	5/8	TH	138	-20	143	-44	9	27	S
NS	41.224	74.077	31/25	3/6	TH	357	1	0	15	115	12	S
NT	41.233	74.096	63/25	5/7	TH	19	20	30	36	21	17	S
NW*	41.220	74.080	43/22	5/6	TH	315	-3	315	19	8	28	S
NX	41.230	74.100	50/21	6/6	TH	338	20	342	40	19	16	S
<hr/>												
Mean					N	In Situ		Tilt Corrected		k	α <sub>95</sub>	
						D	I	D	I			
Karabulun					7	1	33	358	30	8	22	
Djaman-Davan					5	46	45	26	46	7	25	
Makmal					4	348	17	355	36	9	28	
All sites					16	10	34	5	37	6	16	
<hr/>												

Same symbols as in Table 1. At all sites, sediments are of undifferentiated Paleogene age.

\* These two sites were not incorporated in the localities mean direction as basin mean direction (compare text).

(FB and FC, Table 5), statistics were calculated at sample level, giving a tilt-corrected mean direction of D=170°, I=-26°, α<sub>95</sub>=13°. The bedding dips uniformly for both sites and so a fold test is not significant.

**Fergana basin: Ala-Buka.** Five sites out of eight provided reliable results. Demagnetization usually revealed two components. In geographic coordinates, HTC's are all far from the present field (Table 5). The bedding dips either steeply to the SE or gently to the NW. After tilt correction, both polarities are observed, with roughly antiparallel directions. The fold test according to McElhinny [1964] is positive at site level. So is the test according to McFadden and Jones [1981], but at sample level due to the small number of sites (Table 2). The tilt-corrected mean direction, calculated at site level, is D=337°, I=+36°, α<sub>95</sub>=15°.

**Fergana basin: South Fergana.** Samples from the southern limb (SF-2) responded well to thermal cleaning and a characteristic (HTC) component was isolated above 350°. We found directions of both polarities and they are nearly antipodal. The data from the other limb (site SF-1) show more scatter and HTC directions were recovered from three samples only. For this locality, the fold test according to McElhinny

[1964] is positive at the sample level. The mean direction is D=340°, I=+40°, α<sub>95</sub>=10°.

**Fergana basin: Entire basin.** Recovered paleomagnetic directions for Fergana basin are presented in Figure 9a, both before and after tilt correction. At the scale of the entire basin, the fold test according to McElhinny [1964] is positive at site level. Because the number of accepted sites from each locality is limited, we performed other tests at sample level. For all three localities, the consistency test (Figure 9b), the fold test according to McFadden and Jones [1981] and the reversal test are all positive (Table 2). The mean direction for the basin is D=342°, I=+34°, α<sub>95</sub>=9°.

**Chatkal basin.** Samples from three sites showed no stable endpoint demagnetization. For sites FM and FN only, where bedding dips gently to the NW, we determined HTC directions, showing both polarities of the Earth's magnetic field, roughly antiparallel in stratigraphic coordinates (Figure 10 and Table 5). The tilt-corrected mean direction, calculated at sample level, is D=352°, I=+42°, α<sub>95</sub>=9°. Combining Chatkal and Fergana data sets led to calculated statistics somewhat larger than the critical values for the consistency test (Table 2).

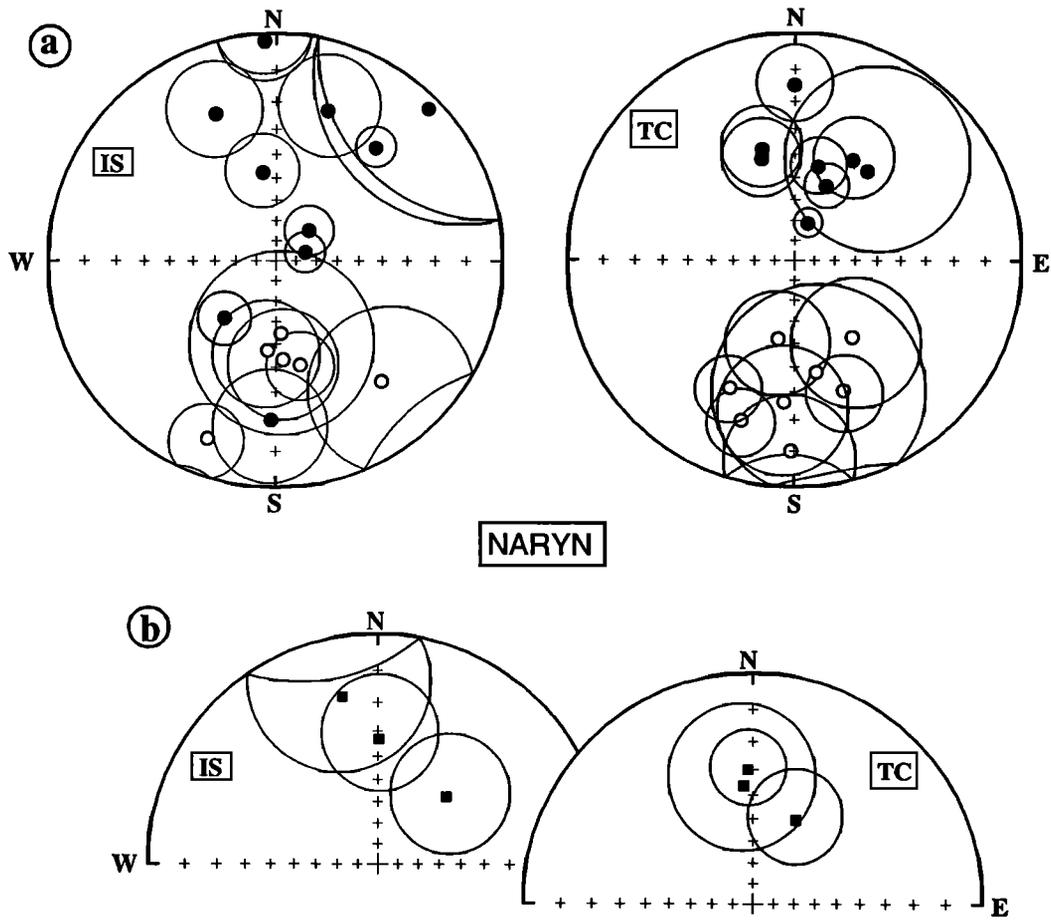


Fig. 7. (a) Stereographic projection of mean directions for sites from Naryn basin. (b) Stereographic projection of mean directions for the three localities of Naryn basin. Symbols and conventions as for Figure 4.

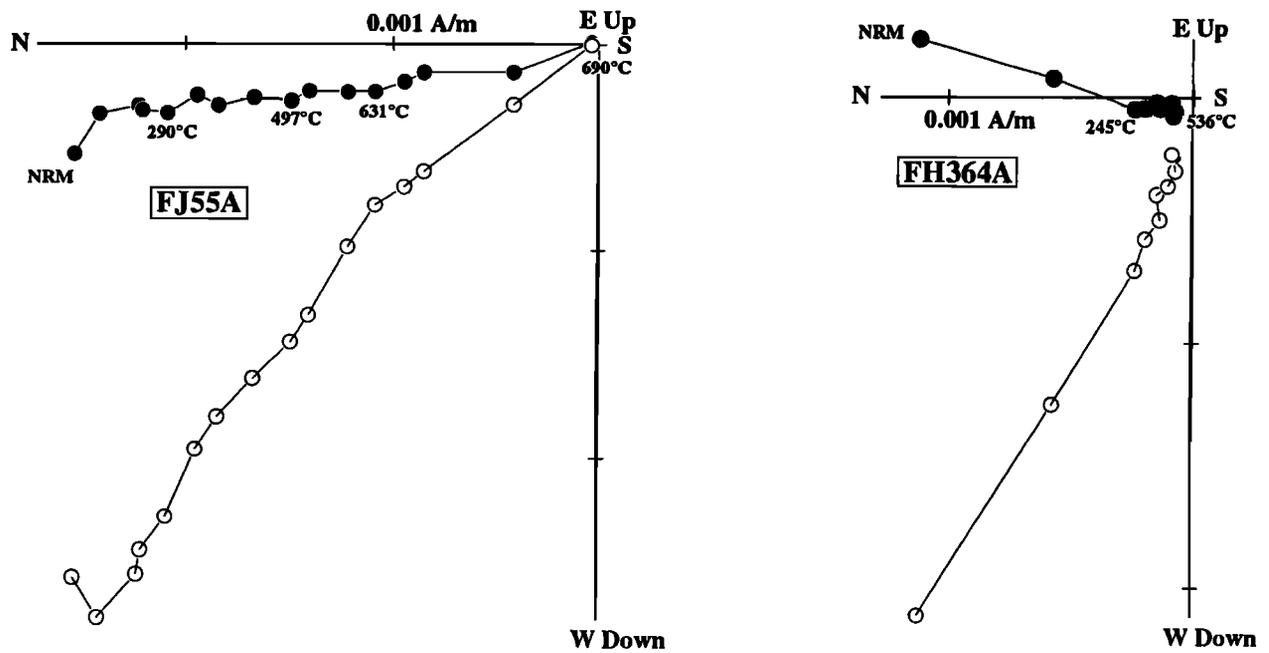


Fig. 8. Orthogonal vector projections of representative thermal demagnetizations for Fergana basin. There are two components of magnetization. For site (a) FJ, the HTC has an unblocking temperature of 690°C and is carried by hematite; whereas for site (b) FH, the HTC has an unblocking temperature of 570° and is probably carried by magnetite. Symbols and conventions are as for Figure 3.

TABLE 5. Paleomagnetic Data for Fergana and Chatkai Basins

Site	Latitude (°N)	Longitude, (°E)	Bedding	n/N	AF/PH	In Situ		Tilt Corrected		k	α95	Litho	Age
						D	I	D	I				
<i>Tash-Kumir</i>													
FB	41.328	72.200	78/71	3/7	TH	343	-46	344	24	35	21	S	Oligocene
FC	41.328	72.200	79/71	6/7	TH	178	42	177	-29	18	16	S	Oligocene
<i>Ala-Buka</i>													
FE	41.396	71.294	40/83	8/8	TH	162	42	158	-33	12	16	S	Paleogene
FG	41.396	71.294	44/81	5/6	TH	158	30	163	-44	15	20	S	Paleogene
FH	41.390	71.357	232/32	5/6	TH	347	69	333	38	27	15	S	Paleogene
FJ	41.390	71.357	218/24	4/6	TH	350	31	343	12	73	11	S	Paleogene
FK	41.390	71.357	208/23	6/7	TH	347	68	324	49	40	11	S	Paleogene
<i>South Fergana</i>													
SF-1	40.0	70.1	91/45	3/6	TH	351	-17	351	28	31	15	S	Oligocene
SF-2	40.0	70.1	265/29	6/6	TH	305	70	333	46	46	9	S	Oligocene
<i>Chatkai</i>													
FM	41.685	71.709	253/28	6/8	TH	3	64	354	37	22	15	S	Paleogene
FN	41.691	70.699	227/12	4/7	TH	180	-60	169	-51	47	14	S	Paleogene
<hr/>													
Mean													
<i>Tash-Kumir</i>													
				N		In Situ		Tilt Corrected		k	α95		
				9*		D	I	D	I	21	11		
				5		173	44	170	-26	18	13		
<i>Ala-Buka</i>													
				9*		74	86	337	36	3	45		
				9		332	47	340	40	4	50		
<i>South Fergana</i>													
				9		345	-14	342	34	3	-		
<i>Entire Fergana basin</i>													
				10*		2	62	352	42	33	9		
<i>Chatkai</i>													
										31	8		
										25	9		

Mean direction for the Fergana basin is calculated at the site level. Same symbols as in Table 1.  
\* Statistics on sample level.

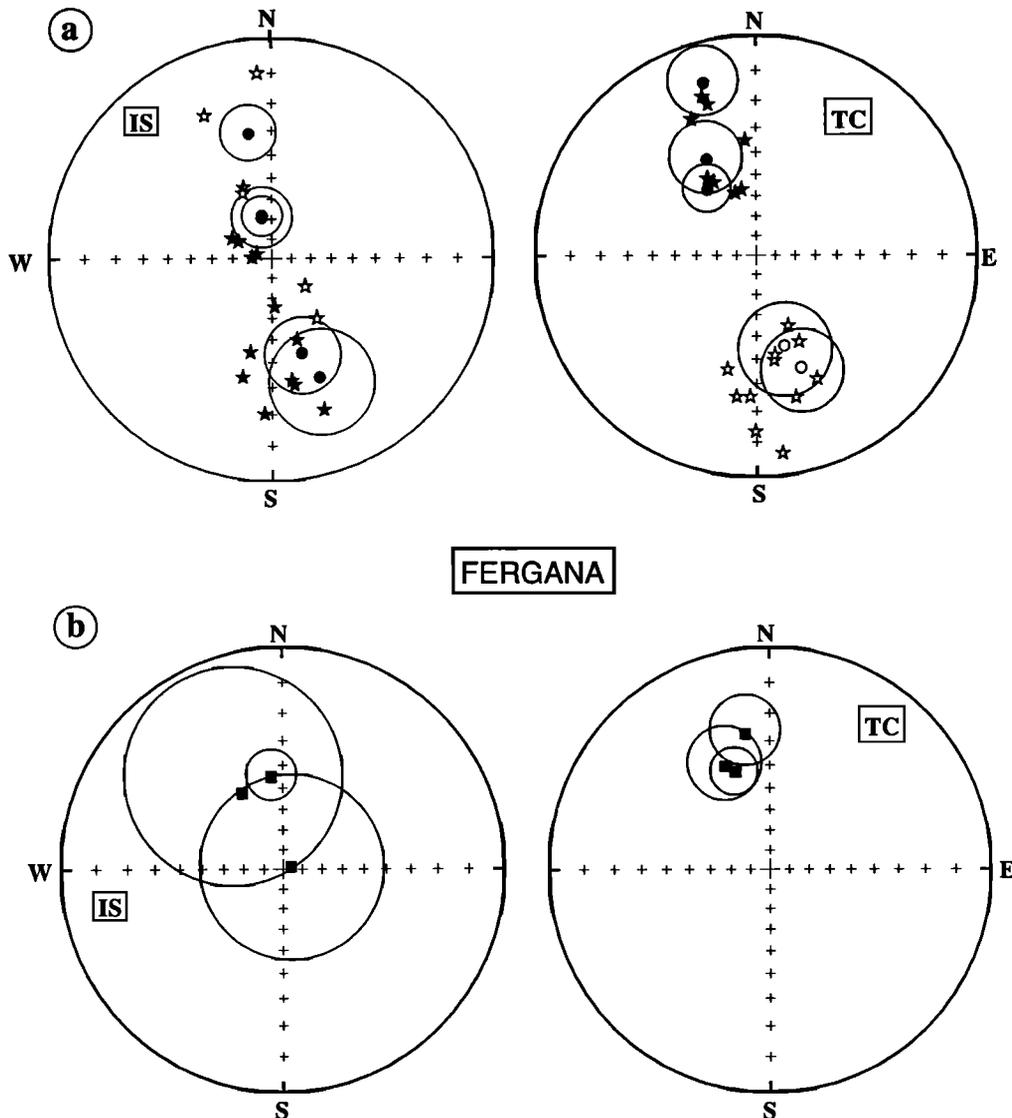


Fig. 9. (a) Stereographic projection of samples directions (stars) and sites mean directions (circles) from Fergana basin. (b) Stereographic projection of mean directions for the three localities of Fergana basin. Symbols and conventions as for Figure 4.

However, we cannot be sure that this discrepancy is significant, because of the small size of the Chatkal data set.

#### DISCUSSION

##### Timing of Magnetization

For most of our samples, demagnetization provided well-determined HTC's, consistent at basin level. The reversal test is also positive for the three basins, as well as the conglomerate test at Dzhety-Ogyuz locality. Fold tests were positive for all localities where they could be applied. For every basin, a fold test was also positive. We therefore conclude that magnetization was acquired before folding.

For the Tien Shan as a whole, deformation started in the Paleogene, became more rapid in the Neogene and has continued to the present day [Schulz, 1948; Sadybasov, 1991], the evidence being provided by crustal thickening, uplift, erosion of ranges and deposition of molasse sediments. Because the formations studied are Eocene to Oligocene (sometimes Early Miocene) and the various field tests are

positive (Table 2), we conclude that the HTC's were acquired early in the rock history. We shall therefore consider them as the primary magnetizations in these rocks.

##### Interpretation

**Inclination.** In interpreting any anomaly in the direction of magnetization, one of the main considerations is to separate rock magnetic factors from tectonic factors. Apparent polar wander paths (APWPs) for the Eurasian plate have been calculated by Irving and Irving [1982] and by Westphal *et al.* [1986]. Recently, Besse and Courtillot [1991] have calculated a new APWP; however, its Cenozoic part does not differ significantly from those published earlier: the Eurasian pole is almost stable between 40 Ma and 10 Ma. Hence any interpretation is almost independent of the reference data and the age of magnetization. Under these conditions, we have chosen as a reference the pole at 40 Ma (latitude = 80°N, longitude = 145°E,  $A95 = 4^\circ$ ) according to Besse and Courtillot [1991].

Our paleomagnetic results show shallower inclinations

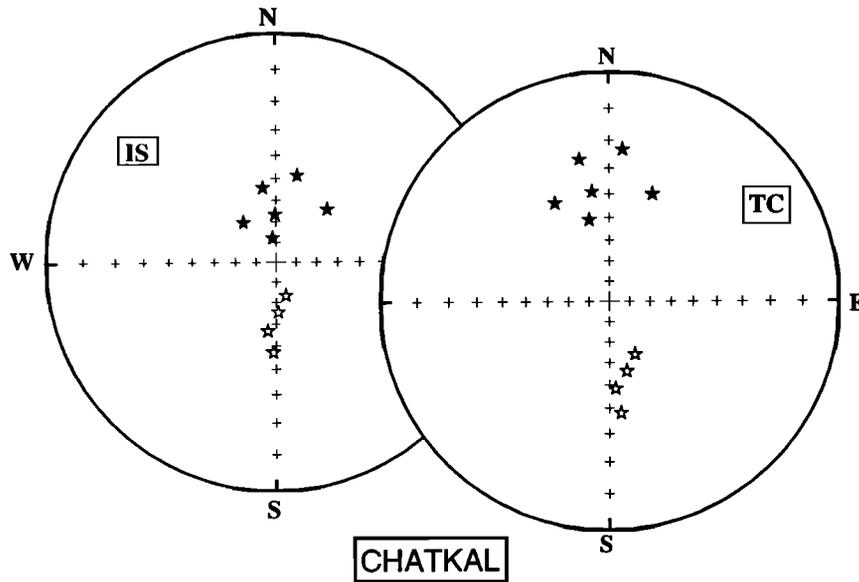


Fig. 10. Stereographic projection of mean direction for samples from the two sites of the Chatkal basin. Symbols and conventions are as for Figure 4.

than those predicted by the reference pole at 40 Ma (Figure 11), the differences ranging from  $16^{\circ} \pm 5^{\circ}$  for Issyk-Kul to  $26^{\circ} \pm 7^{\circ}$  for Fergana (Table 6). Furthermore, the inclination for Issyk-Kul is influenced by the steep vectors from the Karakoo locality where some data are from younger rocks; without this locality, this inclination difference for Issyk-Kul is still larger ( $20^{\circ} \pm 6^{\circ}$ ).

A long-term nondipole field may induce errors in reference data. Recently, *Schneider and Kent* [1990] have suggested that positive axial quadrupole terms, around 3% or 4% of the dipole term, have been present throughout the entire Tertiary. However, this leads to a negligible difference in inclination ( $1.5^{\circ}$  at  $40^{\circ}$  latitude) in comparison with a pure dipole.

Very few paleomagnetic data apart from ours are available for Central Asia for the Cenozoic. *Bazhenov and Burtman* [1986] studied Paleogene sediments in the Northern Pamirs. Among five localities, inclinations range between  $29^{\circ}$  and  $40^{\circ}$ , with a mean value of  $35^{\circ}$ . These values are in good agreement with our own and such a coherence reinforces the suggestion that inclination was not modified by local deformation or by magnetic anisotropy. Unfortunately, other

existing paleomagnetic results are of inadequate quality, mainly because of poor cleaning. Still more unfortunately, there are no data on volcanic rocks, usually regarded as more faithful recorders of geomagnetic field.

Tectonic deformation or compaction can modify the magnetic fabric and thus the paleomagnetic inclination. *Blow and Hamilton* [1978] have shown with analogue models that a 60% compaction of varved clays can induce a  $15^{\circ}$  shallowing of inclination. On this basis, if compaction reaches 50%, as it can indeed in some red beds, the inclination shallowing could be between  $10^{\circ}$  and  $15^{\circ}$ . Nevertheless, compaction experiments on red beds have yielded negligible inclination shallowing [*Stamatakos et al.*, 1989]. Except for two sedimentary sites from Baidamtal locality, which yielded no results, we found no evidence for strong compaction or penetrative deformation in our samples. Instead, the rocks are simply folded. Moreover, the main body of our data are from sandstones, which are not liable to noticeable compaction [e.g., *Meade*, 1966]. As shown above, anisotropy of susceptibility is lower than the 5% level required to alter significantly the paleomagnetic vector [*Nagata*, 1961].

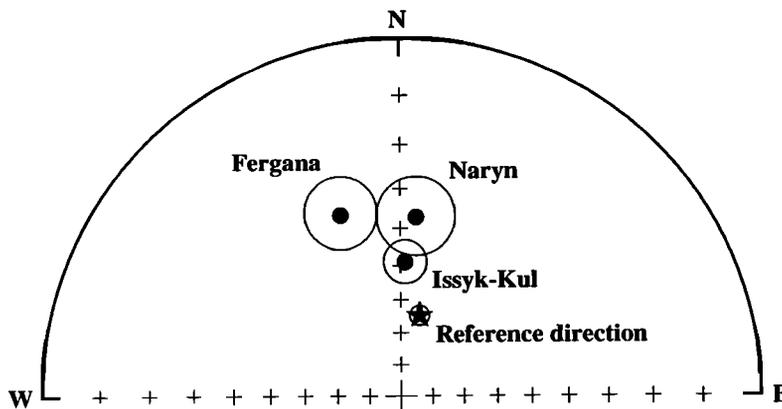


Fig. 11. Stereographic projection of mean paleomagnetic directions measured for the three main basins and reference direction computed from 40 m.y mean pole of *Besse and Courtillot* [1991]. No significant inclination difference is observed between the basins, whereas the reference direction (star) is significantly steeper. Other symbols and conventions are as for Figures 3 and 4.

TABLE 6. Poles and Associated Paleomagnetic Directions for Eurasia at 40 Ma, Compared With Our Measured Data

Pole (40 Ma)	Latitude (°N)	Longitude (°E)	A95	Direction	
				D	I
<i>Besse and Courtilot</i> [1991]	80	145	3.8	13	62
<i>Irving and Irving</i> [1982]	78	159	6.0	16	60
<i>Westphal et al.</i> [1986]	83	136	9.0	9	63
	Flattening versus Besse and Courtilot Pole		Rotation Versus Besse and Courtilot Pole	Rotation Versus Issykkul Basin	
Issyk-Kul	16°±5°		-11°±9°	-	
Naryn	25°±8°		-8°±11°	-	
Fergana	26°±7°		-31°±10°	-20°±11°	
Chaktal	18°±10°		-22°±11°	-10°±12°	

Poles are taken from three apparent polar wander curves and directions calculated for a point located at 41°N 75°E (top part of table). Flattening and rotations are calculated according to *Beck* [1980] and *Demarest* [1983]. Symbol A95 is radius of circle of confidence at 95% probability level; other symbols as in Table 1.

Furthermore, no anisotropy was measurable, either in basalts, or in sediments from the Naryn and Fergana basins. We therefore conclude that neither compaction nor deformation can explain our regional inclination anomaly.

The studied rocks accumulated under continental conditions, many of them on alluvial fans. These may have primary tilts of 10° or more; but it is very unlikely that all tilts were in the same direction.

Finally, a large scatter of paleomagnetic directions was found at between-site level and, most important, at within-site level. A large dispersion of paleomagnetic data is known to lead to a somewhat shallower mean inclination [*Calderone and Butler*, 1991], but only by a few degrees.

Each of the factors discussed above could have modified the magnetic inclination for the entire collection by only a few degrees, compared with the reference data. To create the observed anomaly of about 20°, all factors should be additive, which is not a satisfactory explanation.

The mean inclination for Issyk-Kul, Naryn and Fergana basins indicates a paleolatitude of 24°N, whereas the expected paleolatitude is 45°N. The simplest interpretation is a northward displacement of Tien-Shan terranes by at least 2500 km. This is far larger than the 200-300 km estimated by *Molnar and Tapponnier* [1975] or the 200 km estimated by *Avouac* [1991], assuming a mechanism of crustal thickening alone. The only other possibility for accommodating the relative displacement is a strike-slip displacement of several thousand kilometers. So far there is no evidence for this. We therefore consider that a straightforward comparison of reference latitude and measured latitude is not valid here. As it happens, this is not the first sign of alarm for Paleogene paleomagnetic data from Eurasia. *Westphal et al.* [1986] found the same systematic shallowing of inclinations throughout a midlatitudinal band between Iberia and Central Asia and this was later confirmed by *Kissel et al.* [1987] and *Huang and Opdyke* [1992]. No adequate interpretation of this phenomenon has been proposed so far.

**Declination.** The above analysis of inclination data makes us cautious about the validity of a reference Eurasian declination. We therefore prefer to compare declinations from one basin to another.

The most suitable basin for a local reference appears to be Issyk Kul. No large faults are known to crosscut this basin [*Sadybakasov*, 1991]. Mean declinations are statistically identical for all localities and the fold and reversal tests show that the data are consistent. We therefore infer that Issyk-Kul behaved as a quasi-rigid block during the Cenozoic. Furthermore, Issyk-Kul is relatively near the undeformed foreland. Another area in a similar tectonic position is the Northern Chinese Tien Shan, where paleomagnetic results from Cretaceous and Tertiary rocks have revealed no rotations [*Chen et al.*, 1991]. In what follows, for ease of description, we will take as a regional reference direction the mean declination for Issyk-Kul (2°±9°).

Paleomagnetic data from the Naryn basin are rather scattered on all levels (Figure 12); nevertheless, all tests for the entire basin are positive. The mean direction for Naryn agrees with that for Issyk Kul, implying no relative rotation between the two basins. This conclusion can probably be extended to the entire area north-east of the Talas-Fergana fault. Nevertheless, the large observed scatter might be hiding some rotations at local scale. Indeed, the basin is known to be crosscut by faults [*Sadybakasov*, 1991]. Our structural studies have shown that many such faults have strike-slip displacements, especially within the Paleogene succession, and these could be associated with variable rotations. More paleomagnetic data are necessary for a definite conclusion.

The mean declinations for Issyk Kul and Naryn basins are slightly westward of the Eurasian reference declination for 40 Ma (Table 6), the difference being marginally significant for the former and insignificant for the latter. Considering the quality of our data as well as the questionable validity of the Eurasian reference data, we cannot attribute any tectonic significance to these differences.

For the Fergana basin, the tests point to uniformity of paleomagnetic data from the three localities. We infer that the basin rotated in a quasi-uniform manner during the Cenozoic. Several large faults are known to crosscut the basin [*Sadybakasov*, 1991] and so it may be that internal blocks underwent similar rotations, in domino style. With reference to Issyk-Kul, the Fergana basin has rotated on average 20°±11° counterclockwise. Chaktal data slightly differ from

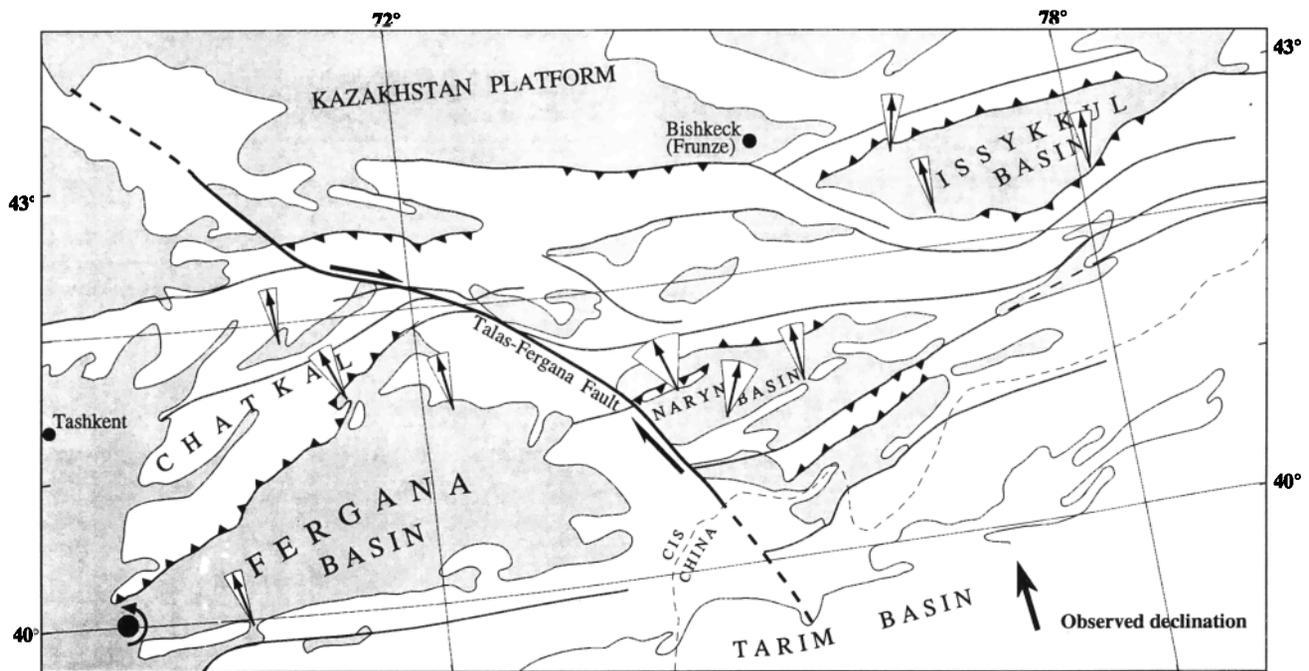


Fig. 12. Observed paleomagnetic declinations, superimposed on a simplified structural map of the Kirghiz Tien-Shan. Solid circle in the western Fergana basin indicates assumed pole of relative counterclockwise rotation between Fergana basin and Kazakhstan platform. Rotation of the Fergana basin relative to the Issyk-Kul basin is  $20^{\circ} \pm 11^{\circ}$  counterclockwise. The rotation mode implies a Cenozoic left-lateral displacement of  $110 \pm 60$  km on the Talas-Fergana fault. Symbols and conventions are as for Figure 1.

Fergana data. The apparently smaller angle of rotation for Chatkal (Table 6) is in agreement with predictions from structural data [Cobbold and Davy, 1988]. Unfortunately, the reliability of this conclusion is hindered by the scarcity of data from the Chatkal basin.

Our result for the Fergana basin is in good agreement with rotations inferred from the structure of the basin and adjacent areas. The Chatkal ranges form a triangular area on a map, with the apex in the SW (Figure 12). The altitude increases progressively northeastwards, as far as the Talas-Fergana fault. Our structural studies indicate that the direction of shortening across the ranges is NW-SE and that the amount of shortening increases toward the NE. This implies a counterclockwise rotation of the Fergana basin, with respect to the Kazakhstan platform [Cobbold and Davy, 1988]. Assume a pole at the apex of the ranges. For a rotation of  $20^{\circ} \pm 11^{\circ}$ , the amount of shortening across the Chatkal ranges then increases toward the NE, from zero to a value of  $110 \pm 60$  km. The corresponding strike-slip displacement along the Talas-Fergana fault is right-lateral, with a value of  $110 \pm 60$  km. If the pole of rotation were further to the SW, this value would be greater. Even the minimum value is compatible with the 200-km offset of Permian and older structures observed by Burtman [1980]. It suggests that much, if not all, of the total offset on the Talas-Fergana fault is Cenozoic.

A counterclockwise rotation of the Fergana basin has also been inferred from a recent paleomagnetic study of Cretaceous sediments [Bazhenov, 1993]. Out of a total of 15 localities, 14 secondary pre-folding directions were inferred to be Late Cretaceous. The mean directions for these localities show a counterclockwise rotation of  $25^{\circ} \pm 7^{\circ}$  compared with the Late Cretaceous reference direction. For seven localities, a bipolar pre-folding component, presumably primary and lower Cretaceous, was also isolated. A counterclockwise rotation of

$21^{\circ} \pm 10^{\circ}$  is inferred from this component. Such results are in very good agreement with our own Tertiary data.

In Mesozoic sediments of the eastern Tadjik depression (Figure 1), Bazhenov and Burtman [1981, 1986] and Pozzi and Feinberg [1991] determined counterclockwise rotations relative to stable Asia. These data and our results from the Fergana basin are in good agreement with the block rotations inferred by Cobbold and Davy [1988] from the Cenozoic fault pattern.

Thus the paleomagnetic results show that Cenozoic deformation has been heterogeneous at the scale of Kyrgyzia. The Talas-Fergana fault appears to be a major lithospheric discontinuity, separating domains with differing amounts of block rotation. Counterclockwise rotations to the west of the fault may be associated with indentation and emplacement of the Pamir thrust sheets.

## CONCLUSIONS

Our study of Cenozoic formations from the Tien-Shan shows that bipolar remanent magnetizations were acquired before folding and are probably of primary origin. From the paleomagnetic inclinations, we infer paleolatitudes between  $20^{\circ}N$  and  $30^{\circ}N$ . These are small in comparison with paleolatitudes predicted by APWPs of Eurasia. Our inferred paleolatitudes are also incompatible with the kinematics of Central Asia as we understand them today. We thus consider that the APWPs for Eurasia are not directly applicable to the Kyrgyz Tien-Shan and that the measured inclinations are affected by factors not yet well understood.

From our measured declinations, we infer that the Fergana basin has rotated  $20^{\circ} \pm 11^{\circ}$  counterclockwise relative to the Issyk-Kul basin since the Paleogene. This is compatible with the rotation inferred by Cobbold and Davy [1988] from the

Cenozoic fault pattern. It implies a right-lateral displacement of at least 110±60 km on the Talas-Fergana fault. This is compatible with the 200-km offset of Permian and older markers observed by Burtman [1980], suggesting that most, if not all, of the displacement on the fault is Cenozoic.

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