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Notes

Did the Kohistan-Ladakh island arc collide first with India?

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ABSTRACT

The Kohistan-Ladakh block occupies the northwestern corner of the Himalayan mountains and has long been recognized to represent an island arc constructed on ocean floor during Jurassic and Cretaceous times. Because the Kohistan-Ladakh block now lies within the Asian continent, it is important to know how and when it became sandwiched between India and the rest of Asia. We have found from analysis of paleomagnetic data that in Late Cretaceous–early Paleocene times, the Kohistan-Ladakh island arc could not have been far from the equator. India was close to the equator, but the southern margin of Asia was more than 3000 km to the north. Our new U-Pb zircon age results from rocks of the Kohistan-Ladakh block show that calc-alkaline volcanic arc igneous activity ended in the Kohistan-Ladakh arc by 61 Ma. We interpret that cessation to date the collision of Kohistan with India. This new timing is confirmed by evidence that a Southern Hemisphere enriched DUPAL mantle source was involved in the generation of the latest Cretaceous Teru Volcanic Formation rocks of the Kohistan-Ladakh arc. Further confirmation of the collision of the Kohistan arc with India in early Paleocene times comes from evidence of the timing of obduction of ophiolites and from the unconformity of postcollisional sedimentary rocks onto the

Indian continental margin in northwestern and western Pakistan. Final incorporation of India, now carrying the Kohistan-Ladakh block in its NW corner, into Asia took place at the Shyok suture. The best evidence for the timing of that suturing ca. 50 Ma comes from two postcollisional granites (ages 47 Ma and 41 Ma) in northern Kohistan, which show in their zircon isotopic compositions evidence of the involvement of ancient Asian continental crust that did not exist under Kohistan before the suture formed. The 50 Ma age for Shyok suturing against the then-active Karakoram Andean arc fits well with the extension of the suture beyond the eastern end of the Kohistan-Ladakh block to join the precisely dated ca. 51 Ma Yarlung–Tsang Po suture between India and the southern (Lhasa block) margin of Tibet, which at that time was also occupied by an Andean arc, the Gangdese arc.

Keywords: Himalayas, Kohistan, Indian plate, remote sensing, geochronology, geochemistry.

INTRODUCTION

The closing of the Neotethys ocean and the collision of India with Eurasia are considered to have had important consequences for such diverse phenomena as global climate change, changes in oceanic circulation, the initiation of the Asian monsoon, changes in seawater chemistry, and such tectonic phenomena as the rise of the Tibetan Plateau, the building of the Himalayan mountains, the establishment of the Indus-

Gangetic foreland basin, and the initiation of intra-Asian deformation from Indonesia to Lake Baikal and the Altai. Knowing the exact timing of this major collision is imperative if the collision's effect on all these phenomena is to be fully understood, but the timing is still not everywhere well constrained, having been assigned ages in various places between ca. 65 Ma and ca. 34 Ma (see, for example, Patriat and Achache, 1984; Dewey et al., 1989; Klootwijk et al., 1991; Le Pichon et al., 1992; Rowley, 1996; Yin and Harrison, 2000; Najman et al., 2001, 2003; Zhu et al., 2005; Ding et al., 2005; Aitchison et al., 2007). Timing of the India-Asia collision has proven particularly difficult to resolve in the western Himalaya because of the presence of the Kohistan-Ladakh island-arc block between the two continents. Suture zones between the Kohistan-Ladakh arc block and both India and Asia have been identified and interpreted to have formed sequentially, although which collision happened first has remained unclear. Helping to clarify that issue is the purpose of this paper.

GEOLOGICAL BACKGROUND

Distribution of Rocks

The Kohistan-Ladakh block exposes rocks that represent a geochemical progression through pre-, syn-, and postcollisional arc magmatism, and it provides a window into the deep thermal and compositional structure of the India-Asian collision zone. The block is bounded by the Indus suture to the south and by the Shyok suture to the north (Fig. 1). The

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Figure 1. Landsat satellite image showing a regional tectonic sketch map. Faults and sutures are drawn from Yin (2006), Tapponnier et al. (1981), Lawrence et al. (1981), and Gaetani et al., (2004). BO—Bela ophiolite; MBO—Muslim Bagh ophiolite; ZO—Zhub ophiolite; WO—Waziristan ophiolite; KO—Khost ophiolite; DO—Dargai ophiolite; GF—Ghazband fault; CF—Chaman fault; PF—Panjao shear; HF—Heart fault; MFT—Main Frontal thrust; MBT—Main Boundary thrust, MMT—Main Mantle thrust; MK—Main Karakoram thrust.

southern area of the block exposes Cretaceous, probably older than 95 Ma (Schaltegger et al., 2002), mafic and ultramafic rocks of the Jijal complex, the Kamila amphibolites, and the Chilas complex (Jan and Howie 1981; Coward et al., 1982; Bard, 1983; Treloar et al., 1989; Jan and Windley, 1990). The northern part of Kohistan consists mainly of the Kohistan batholith, which has yielded isotopic ages between 150 and 27 Ma (Heuberger et al., 2007). Remnants of arc volcanic and sedimentary rocks are exposed in both southern and northern regions of Kohistan (Tahirkeili et al., 1979; Dietrich et al., 1983). Two sets of volcanic rocks have been distinguished in northern Kohistan, where the research reported in this paper is concentrated. The older Chalt volcanics have been dated to the Albian to Cenomanian (ca. 108–97 Ma) from the presence of *Orbitolina* in intercalated sedimentary rocks (Pudsey, 1986). Younger volcanic rocks form the Teru Volcanic Formation, which was called the Shamran volcanics by Sullivan et al. (1993) and which was correlated with the Utror and Drosh volcanic rocks in southern and western Kohistan by Treloar et al. (1996). No modern isotopic ages are available for the Utror volcanic rocks, and a whole rock K/Ar age of 55 ± 2 Ma (Treloar et al., 1989) is not now regarded as dating the time of eruption. The Teru Volcanic Formation and associated plutonic rocks of the Kohistan batholith are the focus of this study. The Teru Volcanic Formation consists of mafic to felsic lavas and associated pyroclastic rocks that have been largely removed from the area by erosion, so that outcrops are only exposed on the tops of ridges at ~3000 m elevation and higher (see Figs. 2A and 2B). Teru Volcanic Formation rocks, which form a typical arc igneous rock association (Danishwar et al., 2001; Khan et al., 2004), unconformably overlie the older rocks of the Kohistan batholith and in places are intruded by younger plutonic rocks of the batholith. Near Handrap, Teru Volcanic Formation rocks are overthrust by Chalt volcanic rocks carried on the south-verging, north-dipping, postbatholithic Ghizer thrust (Fig. 2B). Details and maps of the field relations of the Teru Volcanic Formation are published in Matsushita and Huzita (1965), Danishwar et al. (2001), and Khan et al. (2004).

Timing of the Collisions of the Kohistan-Ladakh Island-Arc Block with India and with Asia

Collision of the Arc Block First with India?

Several authors have reported evidence of collision between India and the Kohistan-Ladakh island arc during the later Cretaceous (ca. 95–65 Ma) before the terminal collision of India with Asia (e.g., Reuber, 1986; Corfield

et al., 1999, 2001; Ziabrev et al., 2004; Rowley, 1996; Yin and Harrison, 2000; Yin 2006). Tahirkeili et al. (1979), mainly using stratigraphic information, were among the first to suggest collision of the Kohistan-Ladakh island-arc block with India before the final India-Asia collision, and their hypothesis was supported by Andrews-Speed and Brookfield (1982). Bard (1983), using paleomagnetic data, suggested the welding of Kohistan onto the northern edge of India by not later than 85 Ma. Schärer et al. (1984) argued that the Kohistan-Ladakh arc became attached to India before India collided with Eurasia from U-Pb zircon ages of 101.2 Ma and 60.7 Ma for “Transhimalayan” plutons near Leh, which is close to the southern margin of Ladakh. Aitchison et al. (2007) suggested that an island arc collided with India at 55 Ma but did not include Kohistan-Ladakh within that arc. Another suggestion has been that Late Cretaceous–Paleocene events in the Indus suture zone and on the Indian continent do not reflect India-Kohistan collision, but rather the obduction of ophiolites onto the Indian continent shortly before that collision (Searle et al., 1997; Robertson, 2002; DiPietro and Lawrence, 1991; DiPietro et al., 2000; Corfield et al., 2001).

Collision of the Arc Block First with Asia?

Other authors have suggested that an intra-oceanic arc system, which included the Kohistan-Ladakh arc, collided with Asia along the Shyok suture (Fig. 1) at sometime between 95 and 75 Ma and before the Kohistan-Ladakh arc collided with India (Treloar et al., 1989, 1996, 2003; Petterson and Windley, 1985; Treloar, 1997; Hanson 1989; Clift et al., 2002). Some of these authors have further suggested that the Kohistan-Ladakh arc was a western oceanic extension of the continental Gangdese arc. According to that interpretation, the southern margin of Asia, which included both the Gangdese arc and the Kohistan-Ladakh arc, became an Andean-type convergent margin that survived for a further 20–40 m.y., until India collided with the combined Asia-Kohistan-Ladakh assemblage at ca. 55 Ma (Treloar et al., 1989). All these studies have placed the timing of collision between the Kohistan and the Karakoram margin of Asia between 100 and 75 Ma.

Present Research on the Timing of the Shyok Suture Zone Collision

To constrain these options, we undertook field, remote-sensing, geochronological, geochemical, and isotopic work in northern Kohistan and carried out geochemical analyses and isotopic age determinations on the Teru Volcanic Formation and some of the associated plutons that make up the Kohistan batholith (Figs. 1 and 2). We also

reassessed published paleomagnetic data on rocks with ages of ca. 65 Ma (Cretaceous-Tertiary [K/T] boundary) to obtain a value for their paleolatitude at that time. Our results, reported in this paper, provide evidence that is consistent with the idea that Kohistan-Ladakh collided with India before the terminal collision of India with Eurasia on the Shyok suture.

RESULTS

Remote Sensing and Field Investigation

Elevation and great relief render much of the study area inaccessible. Remote sensing therefore provides a useful tool in lithological and structural mapping, although interpretation of remote-sensing data in this area is hampered by snow, clouds, vegetation, and shadows from the high relief. Landsat Enhanced Thematic Mapper Plus (ETM+) and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) data were used for mapping the Teru Volcanic Formation. Although cloud-free Landsat ETM+ images were listed in U.S. Geological Survey (USGS) catalogs, there were no cloud-free ASTER images. A 2006 ASTER image with minimum snow and little cloud cover was acquired that covers part of the study area. ASTER offers relatively high spatial and spectral resolutions. It provides three bands in the visible to near-infrared (VNIR) spectrum at 15 m resolution, six bands in the short-wave infrared (SWIR) spectrum at 30 m resolution, and five bands in the thermal-infrared (TIR) spectrum at 90 m resolution. The ASTER data have 60-km-wide swaths. All bands of the ASTER data were investigated for use in this work. Specifically, the SWIR provided spectral information about the lithology and structure. Previous studies, including Ninomiya et al. (2005), Rowan et al. (2005), and research in this area by Khan and Glenn (2006), used ASTER data for lithologic mapping. In the current study, the ASTER data were transformed using principal components analysis (PCA). PCA for SWIR bands 1, 2, and 3 was most effective in delineating Teru Volcanic Formation, Kohistan batholith, and sedimentary rocks. Figure 2A is an ASTER PCA image covering part of the study area on which the geological interpretation has been plotted. The Landsat ETM+ 7-4-3 combination was most effective in determining the extent of regions of granitic rocks identified in the field (Fig. 2B). The remote-sensing study has established the extent of batholithic rocks, enabling individual plutons to be mapped, and it has served to distinguish plutonic from volcanic rock outcrops.



Figure 2. (A) Principal component analysis applied to Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) short-wave infrared (SWIR) data discriminates Teru Volcanic Formation (TVF), Kohistan batholith (KB), and limestone. Shyok suture zone contains clasts of ultramafic, volcanic, and sedimentary rocks; it forms an “S”-shaped, 2-km-wide zone running from NE to SW corners of the image. This image shows part of the study area (B) Landsat ETM+ bands 7, 4, and 2 displayed as red, green, and blue false-color composite image showing the Teru Volcanic Formation (TVF) and Kohistan batholith and major structures in northern Kohistan. Lithological and structural interpretation is based on satellite images (Landsat ETM+ and ASTER data). Photograph of contact between Teru Volcanic Formation and Shunji pluton is shown in lower left corner; xenoliths of Teru Volcanic Formation can be seen in Pingal pluton, photograph at top center. (Continued on following page.)

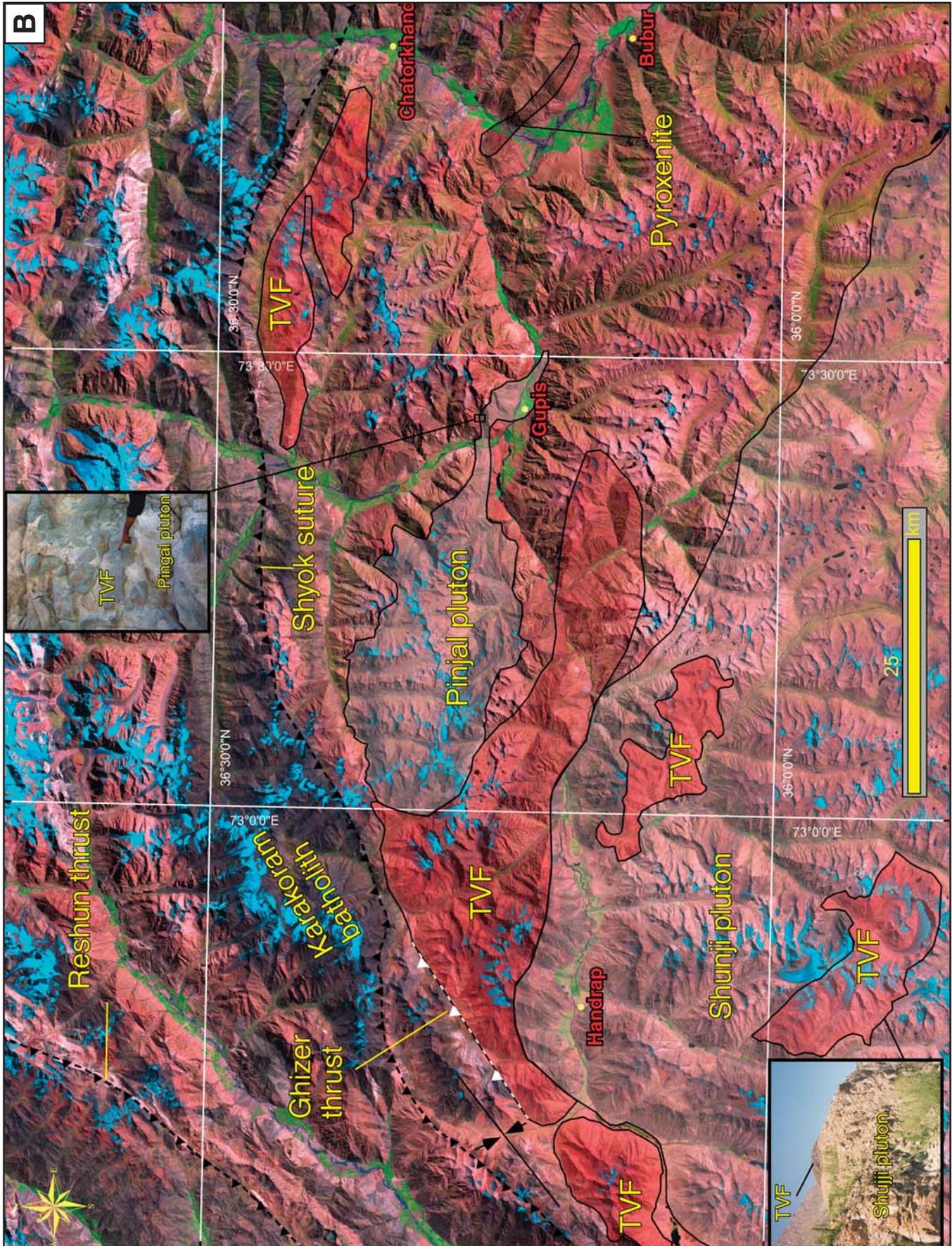


Figure 2. (continued).

Petrography

Mafic and intermediate lavas of the Teru Volcanic Formation display porphyritic textures with abundant phenocrysts (10%–40%) embedded in a fine-grained groundmass. The groundmass consists of microcrystalline feldspar, amphibole, pyroxene, and spinel. Plagioclase, clinopyroxene, and amphibole are ubiquitous phenocryst phases, along with minor spinel. Olivine and orthopyroxene are absent from most of the lavas. Clinopyroxene occurs alone as well as in polyminerally glomeroporphyritic clots. It is mostly unzoned and contains inclusions of titanomagnetite with or without plagioclase in their cores. Felsic lavas contain quartz phenocrysts and sanidine in addition to andesine and locally biotite. Their groundmass consists essentially of alkali feldspar and quartz.

Plutonic rocks of the study area include pyroxenite, gabbro, diorite, monzonite, and granite. A coarse-grained gabbro with dominant plagioclase (labradorite) and two pyroxenes also contains small amounts of olivine, hornblende, and opaque oxides. A diorite has a mineral assemblage that includes plagioclase (An_{52-19}), hornblende, biotite, sphene, ilmenite, and apatite. Some rare relicts of highly corroded augite crystals are present in the cores of the amphiboles of the diorite samples. Quartz monzonite is composed of quartz, K-feldspar, plagioclase (An_{21-15}), and hornblende. Sphene and titanomagnetite are accessories. Granites are abundant. An unusual rock from a locality near Babur (Fig. 2B) is a medium-grained and generally fresh pyroxenite composed dominantly of clinopyroxene, with spinel as an accessory mineral.

Major- and Trace-Element Geochemistry

Seventeen volcanic samples from the Teru Volcanic Formation and 12 plutonic rocks from Kohistan batholith were analyzed for major elements, and seven samples from the Teru Volcanic Formation and eight from Kohistan batholith were analyzed for rare earth and trace elements. Major elements were analyzed by inductively coupled plasma–atomic emission spectroscopy (ICP-AES). Methods are described in Casey (1997) and Smith (1994). Rare earth element (REE) and trace element concentrations were determined by inductively-coupled-plasma mass spectrometry (ICP-MS). Uncertainties based on repeated analysis of the internal standards (BIR-1 and BHVO-2) were >10% for Cs, Be, Zn, Pb, and Th, and <10% for rest of the trace elements analyzed.

Table 1 shows the major and trace element and isotopic compositions for the analyzed sam-

ples. When the data are recalculated to 100% on an anhydrous basis, five of the Teru Volcanic Formation rocks plot in a total alkalis versus silica (TAS) diagram as basalt, one as trachybasalt, five as basaltic andesite, one as basaltic trachyandesite, three as andesite, and two as rhyolite (Fig. 3A). Two samples can be classified as hawaiite and mugearite (using the formula $Na_2O\% - 2 > K_2O\%$). The SiO_2 versus K_2O diagram (Fig. 3B) shows that the volcanic rocks analyzed are calc-alkaline and belong mainly to the low- and medium-K series. Three samples plot in the high-K series, and two samples plot in the shoshonite series.

The Teru Volcanic Formation volcanic rocks have a typical subduction-related trace-element pattern (Fig. 4A), which is slightly enriched in light rare earth elements ($[La/Yb]_n = 3-15$), and most samples show a slight negative Eu anomaly, indicating plagioclase-controlled magmatic differentiation. Only one sample shows a positive Eu anomaly, which may indicate pyroxene fractionation or plagioclase accumulation. The pyroxenite samples are similar in their trace-element compositions to the volcanic rocks (Fig. 4B). The sole gabbro analyzed shows low REE concentrations and a relatively flat linear REE pattern. Monzonite and granite show relatively higher REE concentrations, and one granite sample had a sharp negative Eu anomaly. The normal mid-ocean-ridge basalt (MORB)–normalized variation diagrams (Figs. 4C and 4D) are characterized by significant negative anomalies for most of the samples in Nb, P, Zr, and Ti and positive Th, K, and Pb anomalies. Small but significant Ce anomalies are ubiquitous.

Geochronology

All geochronologic and isotopic analyses were conducted at the University of Kansas (KU). Results of U–Pb age dating of zircons are shown in Figure 5 and are given in Table 2. Zircon fractions used for isotope-dilution analyses were air-abraded, and individual grains were carefully selected by hand prior to dissolution. Most zircon fractions consisted of one to three grains. Zircons were dissolved, and Pb and U were separated using procedures modified after Krogh (1973) and Parrish (1987). All samples were total-spiked with a mixed ^{205}Pb – ^{235}U tracer. The U–Pb isotopic analyses were carried out in single-collector ion-counting mode. Because of the young ages of the samples and the relatively low U and Pb concentrations, results are presented as weighted averages of the $^{206}Pb/^{238}U$ age. Although blank levels averaged 2–4 pg during these analyses, the $^{206}Pb/^{204}Pb$ ratios of many runs were less than 100 because of small sample size and low amounts of radiogenic Pb. This

made other types of age determination for these samples (e.g., $^{207}Pb/^{235}U$) sensitive to common Pb corrections and essentially uninterpretable.

Three samples of Teru Volcanic Formation rocks yielded error-weighted $^{206}Pb/^{238}U$ ages of 64.8 ± 1.0 Ma, 63.1 ± 2.5 Ma, and 64.9 ± 0.9 Ma (Figs. 5A, 5B, and 5C). The age of 64.8 ± 1.0 Ma is the average of three of the four fractions analyzed; the fourth fraction gave an anomalously old Proterozoic age. Ages on the sample that yielded an age of 63.1 ± 2.5 Ma show a relatively large scatter, but none of the fractions was eliminated from the analysis. The 64.9 ± 0.9 Ma is the best-defined individual age among the Teru Volcanic Formation samples. One plutonic sample from the dioritic Shunji pluton of the Kohistan batholith gave an age of 64.5 ± 0.5 Ma (Fig. 5D). Again, all fractions were used in the final age determination. The late-stage Pingal pluton of the Kohistan batholith exhibits complex zircon behavior. In all, 12 fractions were analyzed, and ages ranged from early Paleozoic to Cenozoic (Table 1). Cenozoic ages (plotted in Fig. 5E) show broad scatter. Because these grains contain generally low U concentrations, and the pluton is structurally uncomplicated, we interpret the scatter to result from inheritance of variably aged zircons rather than Pb loss. For that reason, we averaged the $^{206}Pb/^{238}U$ ages for the three youngest fractions (Fig. 5F). That gave an age of 41.0 ± 0.5 Ma with a reasonable probability of fit (0.32), and so it is interpreted to be the emplacement age of this pluton.

Sr–Nd–Pb Isotopes

Sr, Nd, and Pb age-corrected isotopic analyses are presented in Table 3. Initial $^{87}Sr/^{86}Sr$ ratios varied from 0.703806 to 0.704881 in the volcanic rocks and from 0.70407 to 0.70517 in the plutonic rocks. Teru Volcanic Formation volcanic rock $^{143}Nd/^{144}Nd$ ratios ranged from 0.512826 to 0.512959, and Kohistan batholith plutonic rock ratios ranged from 0.512654 to 0.512932. Pb isotopic ratios gave the following values: $^{206}Pb/^{204}Pb$, 18.15–18.70 for Teru Volcanic Formation and 18.52–18.72 for Kohistan batholith; $^{207}Pb/^{204}Pb$, 15.50–15.87 for Teru Volcanic Formation and 15.53–15.64 for Kohistan batholith; $^{208}Pb/^{204}Pb$, 37.99–38.75 for Teru Volcanic Formation and 38.48–38.95 for Kohistan batholith. When plotted in an $^{87}Sr/^{86}Sr$ versus $^{143}Nd/^{144}Nd$ diagram, all samples plot close to the present-day Indian Ocean MORB trend and fall along the mantle array (Fig. 6A). In a $^{143}Nd/^{144}Nd$ versus $^{206}Pb/^{204}Pb$ plot, the samples fall in and close to the Indian Ocean MORB region and make a trend extending toward Enriched Mantle II (EMII) (Fig. 6B). That trend is more pronounced in the $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$

TABLE 1. MAJOR- AND TRACE-ELEMENT DATA AND Sr, Nd, AND Pb ISOTOPE DATA FROM THE TERU VOLCANIC FORMATION (TVF) AND KOHISTAN BATHOLITH (KB) FROM NORTHERN KOHISTAN

Sample no.:	1	2	9	16	17	18	33	34	41	47	59
Lat. (°E):	36.18	36.19	36.18	36.18	36.18	36.17	36.15	36.15	36.18	36.19	36.25
Long. (°N):	72.73	72.73	72.8	73.05	73.05	73.07	73.09	73.10	73.18	73.25	73.34
SiO ₂	60.62	70.31	57.34	49.38	53.06	46.77	51.85	53.00	51.33	48.67	52.03
TiO ₂	1.01	0.23	0.94	0.51	0.53	0.52	1.21	1.20	1.38	0.61	0.68
Al ₂ O ₃	16.55	14.95	16.88	12.14	12.69	13.98	17.81	17.78	17.73	19.71	17.43
Fe ₂ O ₃	7.94	2.62	8.35	11.41	9.31	11.81	11.69	10.37	10.10	9.77	8.42
MnO	0.14	0.09	0.13	0.2	0.28	0.17	0.24	0.28	0.20	0.20	0.22
MgO	2.68	0.74	3.56	9.52	6.97	9.79	4.90	4.55	6.51	5.61	4.21
CaO	4.3	3.65	6.93	11.34	12.95	12.18	6.15	7.66	8.67	11.11	13.07
Na ₂ O	4.17	5.48	4.56	2.72	3.66	2.05	3.71	3.65	3.13	3.07	3.11
K ₂ O	2.35	1.85	1.11	2.47	0.19	2.38	2.18	1.24	0.73	1.12	0.66
P ₂ O ₅	0.25	0.07	0.2	0.32	0.37	0.35	0.27	0.25	0.22	0.12	0.15
Total	100	100	100	100	100	100	100	100	100	100	100
Sr	717.61	184.25	1671.79			282.31	306.88		2542.70		
Ba	298.07	239.99	1116.59			75.80	166.69		722.90		
Li	40.66	29.71	23.77			32.10	26.08		117.02		
Be	1.36	1.70	6.07			0.88	1.68		8.69		
Rb	62.72	30.03	89.33			73.40	78.44		92.75		
Y	38.82	22.83	155.58			14.60	24.97		123.57		
Zr	200.72	146.61	300.28			32.57	54.59		259.06		
Nb	6.82	5.39	23.35			1.37	3.89		50.25		
Mo		0.05	0.09			0.13	0.13		0.64		
Sn	1.89	1.57	6.40			2.35	2.67		13.53		
Sb	0.31	0.53	0.68			0.17	0.41		1.56		
Cs	1.77	1.32	3.84			6.06	5.59		7.98		
La	14.68	16.04	62.48			16.52	10.66		74.18		
Ce	38.36	33.72	154.23			30.48	24.42		165.53		
Pr	4.66	3.85	19.53			4.02	3.47		21.92		
Nd	19.46	14.09	81.38			16.78	15.12		89.39		
Sm	5.19	3.17	22.36			3.83	3.92		21.64		
Eu	1.41	0.90	6.41			1.10	1.14		7.31		
Gd	5.71	3.21	24.08			3.35	4.36		22.96		
Tb	0.93	0.52	3.84			0.45	0.70		3.70		
Dy	6.16	3.32	25.27			2.56	4.34		22.33		
Ho	1.25	0.70	5.09			0.50	0.89		4.39		
Er	3.55	2.11	14.66			1.40	2.44		11.44		
Tm											
Yb	3.65	2.41	14.99			1.33	2.20		9.94		
Lu	0.58	0.40	2.29			0.21	0.32		1.52		
Hf	4.47	3.39	8.70			0.95	1.53		6.84		
Ta	0.46	0.39	1.55			0.09	0.25		3.43		
Tl											
Pb	8.03	9.37	19.96			2.78	8.32		20.14		
Th	6.32	10.08	24.22			6.25	2.88		17.48		
U	1.32	1.47	2.51								

Sample no.:	61	69	70	72	76	103	8	20	38	52	63
Lat. (°E):	36.25	36.35	36.35	36.25	36.18	36.16	36.13	36.21	36.24	36.31	36.39
Long. (°N):	73.42	73.34	73.34	73.69	72.76	73.08	73.16	73.28	73.43	73.38	73.32
SiO ₂	48.25	59.23	72.26	55.17	52.29	50.82	63.40	74.62	71.00	41.67	56.23
TiO ₂	1.11	0.57	0.26	0.64	0.57	0.42	0.78	0.18	0.41	1.05	0.73
Al ₂ O ₃	19.06	18.41	15.03	16.24	15.90	11.95	17.09	14.11	14.92	18.82	21.38
Fe ₂ O ₃	11.41	6.43	2.2	9.29	9.14	9.63	4.96	1.52	2.68	15.75	4.93
MnO	0.18	0.21	0.05	0.18	0.26	0.28	0.06	0.07	0.08	0.16	0.08
MgO	5.48	5.11	0.72	5.48	7.95	10.22	1.94	0.40	0.78	7.23	1.6
CaO	9.67	5.99	3.66	8.62	9.46	14.22	3.81	1.28	2.47	14.09	8.57
Na ₂ O	3.22	3.36	4.89	3.73	4.03	1.79	4.40	4.45	4.46	0.92	4.22
K ₂ O	1.41	0.5	0.81	0.52	0.27	0.39	3.17	3.30	3.09	0.27	1.97
P ₂ O ₅	0.21	0.19	0.1	0.13	0.13	0.27	0.40	0.06	0.12	0.04	0.29
Total	100	100	100	100	100	100	100	100	100	100	100
Sr					1716.62		3596.30	676.36	216.62	477.39	
Ba					477.11		2950.86	2461.67	377.96	85.93	
Li					28.24		141.53	73.50	20.07	3.10	
Be					2.68		10.41	8.34	1.78	0.22	
Rb					12.50		259.55	261.28	66.38	2.16	
Y					67.95		53.57	90.72	22.35	9.22	
Zr					141.14		939.22	551.32	78.10	16.15	
Nb					4.44		90.28	37.63	6.64	0.60	
Mo					0.20		0.21	0.18	0.06	0.04	
Sn					10.67		6.67	2.47	1.02	0.84	
Sb					0.66		0.30	0.32	0.12	0.01	
Cs					1.94		8.27	5.84	3.44	0.20	
La					16.18		189.47	113.35	15.37	2.36	
Ce					36.30		393.74	212.98	30.30	5.78	
Pr					5.37		43.23	22.76	3.34	0.90	
Nd					24.89		149.77	75.29	11.68	4.36	
Sm					7.74		26.44	14.37	2.64	1.44	
Eu					3.38		6.66	3.22	0.79	0.54	

(continued)

TABLE 1. MAJOR- AND TRACE-ELEMENT DATA AND Sr, Nd, AND Pb ISOTOPE DATA FROM THE TERU VOLCANIC FORMATION (TVF) AND KOHISTAN BATHOLITH (KB) FROM NORTHERN KOHISTAN (*continued*)

Sample no.:	61	69	70	72	76	103	8	20	38	52	63
Lat. (°E):	36.25	36.35	36.35	36.25	36.18	36.16	36.13	36.21	36.24	36.31	36.39
Long. (°N):	73.42	73.34	73.34	73.69	72.76	73.08	73.16	73.28	73.43	73.38	73.32
Gd					9.76		19.38	13.10	2.85	1.69	
Tb					1.68		2.33	2.05	0.47	0.26	
Dy					11.26		11.31	12.74	3.09	1.73	
Ho					2.36		1.79	2.64	0.68	0.34	
Er					6.81		4.45	8.27	2.13	0.93	
Tm											
Yb					6.61		3.70	10.14	2.52	0.83	
Lu					1.03		0.54	1.65	0.40	0.13	
Hf					3.69		19.88	13.44	2.10	0.52	
Ta					0.30		4.96	2.89	0.59	0.04	
Tl											
Pb					13.72		64.24	56.78	7.11	1.66	
Th					4.14		55.55	66.83	9.10	0.44	
U							7.07	7.02	1.64	0.08	
Sample no.:	67	96	99	104	106	108	111				
Lat. (°E):	36.23	36.25	36.26	36.25	36.10						
Long. (°N):	73.54	73.73	73.74	73.74	73.57						
SiO ₂	70.31	71.15	63.22	46.60	46.63	46.59	74.70				
TiO ₂	0.26	0.38	0.69	0.63	0.46	0.64	0.10				
Al ₂ O ₃	15.29	14.64	17.67	7.18	5.53	7.35	14.00				
Fe ₂ O ₃	3.07	3.06	4.61	15.53	14.99	16.32	1.69				
MnO	0.07	0.07	0.10	0.21	0.21	0.24	0.05				
MgO	0.86	0.97	1.60	11.56	13.43	11.66	0.44				
CaO	2.69	2.69	4.54	15.84	17.61	15.59	2.99				
Na ₂ O	3.82	3.37	3.89	1.34	0.66	0.96	3.82				
K ₂ O	3.49	3.56	3.45	0.96	0.36	0.51	2.17				
P ₂ O ₅	0.13	0.11	0.22	0.15	0.11	0.12	0.04				
Total	100	100	100	100	100	100	100				
Sr	1439.74			368.02		399.92	253.99				
Ba	1670.89			53.06		45.26	954.14				
Li	83.98			15.67		6.74	8.16				
Be	8.98			0.35		0.35	1.73				
Rb	382.95			22.00		9.17	22.28				
Y	94.43			11.88		12.23	30.56				
Zr	506.22			16.49		15.31	71.47				
Nb	39.73			0.62		0.51	9.43				
Mo				0.14		0.14					
Sn	4.60			0.86		0.78	0.76				
Sb	0.46			0.10		0.21	0.26				
Cs	20.49			0.56		0.33	1.72				
La	115.24			8.15		6.86	11.75				
Ce	223.02			17.41		15.56	26.75				
Pr	23.94			2.51		2.41	3.11				
Nd	83.27			11.17		11.42	10.85				
Sm	17.50			3.18		3.26	2.98				
Eu	3.80			0.92		0.91	0.33				
Gd	15.62			2.91		3.04	3.18				
Tb	2.34			0.39		0.41	0.59				
Dy	13.92			2.23		2.32	4.07				
Ho	2.89			0.43		0.44	0.90				
Er	8.60			1.21		1.23	2.84				
Tm											
Yb	9.74			1.10		1.09	3.41				
Lu	1.61			0.16		0.16	0.55				
Hf	12.71			0.69		0.69	2.72				
Ta	4.29			0.05		0.04	0.93				
Tl											
Pb	32.62			2.05		2.99	9.43				
Th	78.61			2.85		2.31	21.26				
U	13.88						5.16				

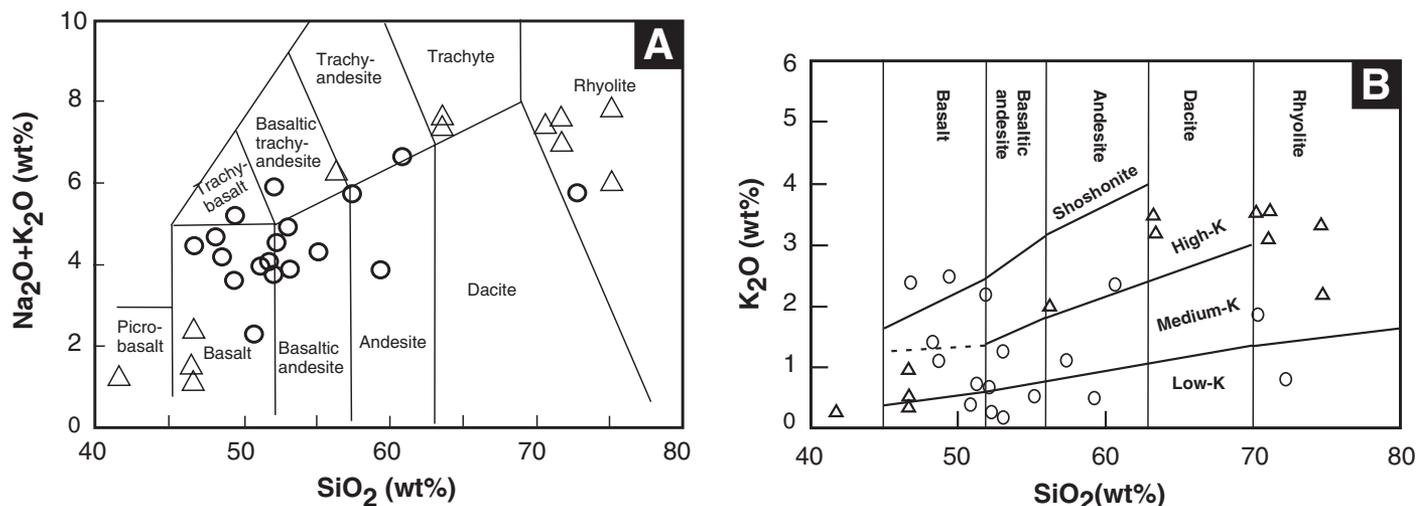


Figure 3. Classification of volcanic rocks. (A) Total alkalis versus silica (TAS) diagram for Teru Volcanic Formation (TVF) and Kohistan batholith (KB) (boundaries after LeBas et al., 1986; LeMaitre et al., 1989). (B) K_2O versus SiO_2 diagram for Teru Volcanic Formation and Kohistan batholith (boundaries after LeMaitre et al., 1989; Rickwood, 1989). Circles and triangles represent Teru Volcanic Formation and Kohistan batholith, respectively.

plot (Fig. 6C). The $^{208}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ ratios are both high with respect to the Northern Hemisphere reference line (NHRL) and thus demonstrate DUPAL isotopic characteristics (Hart, 1984; see also Khan et al. [1997] for DUPAL-character Kohistan rocks) (Figs. 6C and 6D). DUPAL is an EMII-enriched component that Hart (1984) named for Dupré and Allègre (1983), who first described mid-ocean-ridge lavas attributable to this source. DUPAL mantle generates lavas with distinctive isotopic characteristics, including relatively low $^{143}Nd/^{144}Nd$ and $^{206}Pb/^{204}Pb$ ratios and relatively high $^{87}Sr/^{86}Sr$, $^{208}Pb/^{204}Pb$, and $^{207}Pb/^{204}Pb$ ratios. Our Pb isotopic data show close similarity to those of the gabbroic rocks of the Jijal complex, suggesting a common source. The Jijal complex is considered to represent the basement of Kohistan island arc that had formed before 95 Ma (Schaltegger et al., 2002). Garrido et al. (2007) suggested that the Jijal complex rocks formed from an EMII-enriched end member, although Bignold and Treloar (2003) argued that high concentrations of Pb isotopes could have been caused by dehydration of seafloor sediments.

Paleomagnetism

Although many paleomagnetic studies have been carried out across the northwestern Himalayas (e.g., McRae, 1990; Badgley and Tauxe, 1990; Johnson et al., 1985; Klootwijk, 2005; Klootwijk et al., 1994; Klootwijk and Conaghan, 1979), paleomagnetic studies of rocks from the Kohistan arc block are quite

limited (viz. Zaman and Torri, 1999; Ahmed et al., 2000, 2001). Zaman and Torri (1999) and Ahmed et al. (2001) both focused on rock units close to the arc's northern boundary with the Karakoram block. Ahmed et al. (2000), on the other hand, examined rock units associated with Kohistan's southern boundary.

In their detailed study of Utror volcanics (correlated with the Teru Volcanic Formation) near Kalam, Ahmed et al. (2000) identified a high-temperature (530–680 °C) characteristic remanence (ChRM) with low negative in situ inclinations ($\sim -30^\circ$) oriented generally to the southeast. The study area is structurally complex, and samples were obtained from sites with a wide range of strikes and dips. Restoration of these units to the horizontal by unfolding significantly increases the scatter in magnetic directions and clearly indicates that the ChRM was acquired after deformation had begun. Site-to-site variations of in situ ChRM inclinations are small, suggesting that deformation was almost complete when the ChRM was acquired. However, corresponding in situ ChRM declinations span a much greater range (Ahmed et al., 2000), which reflects, but does not exactly match, a similarly large range of strike directions. In contrast to the inclinations, the declinations imply that significant rotations about vertical axes occurred after ChRM acquisition. From this, we conclude that the ChRM of the Utror volcanics was acquired during the later stages of deformation but before the deformation was complete.

Using results from seven Utror sites, Ahmed et al. (2000) obtained a mean in situ ChRM

inclination of -24.3° based on the inclination-only method of Enkin and Watson (1996). This direction indicates that the Utror volcanics acquired their ChRM during a period of reverse field polarity when they were located at $12.8^\circ \pm 4.5^\circ N$. Because small amounts of unfolding produce lower inclinations at all seven sites without significantly increasing the scatter in declinations, we suggest that it is likely that the ChRM was acquired at a latitude slightly less than the $12^\circ N$ obtained using in situ directions.

Paleomagnetic samples from 64 Ma Teru Volcanic Formation rocks (called the Shamran volcanics in Ahmed et al., 2001) on Kohistan's northern margin near Gupis display NNW directions with positive in situ magnetic inclinations. Dips and strikes for these sites are such that even small amounts of unfolding produce significantly larger scatter in magnetic directions. Further, in situ magnetic declinations are much less variable (viz. $N335^\circ$ to $N8^\circ$) than for the Utror sites, suggesting little or no local vertical-axis rotation after magnetization. These results are consistent with remanence acquisition after deformation was complete. The mean in situ inclination for these sites (viz. $+46.2^\circ$) yields a paleolatitude of $27.5^\circ \pm 6^\circ N$ (Ahmed et al., 2001), which is significantly further north than the inclination obtained for the Utror volcanics at Kalam.

Zaman and Torri (1999) identified a pre-deformation stable ChRM in Cretaceous-age red beds near Drosht that yielded paleolatitudes of $2.2^\circ S$ to $1.1^\circ N$ for the northern margin of Kohistan prior to collision.

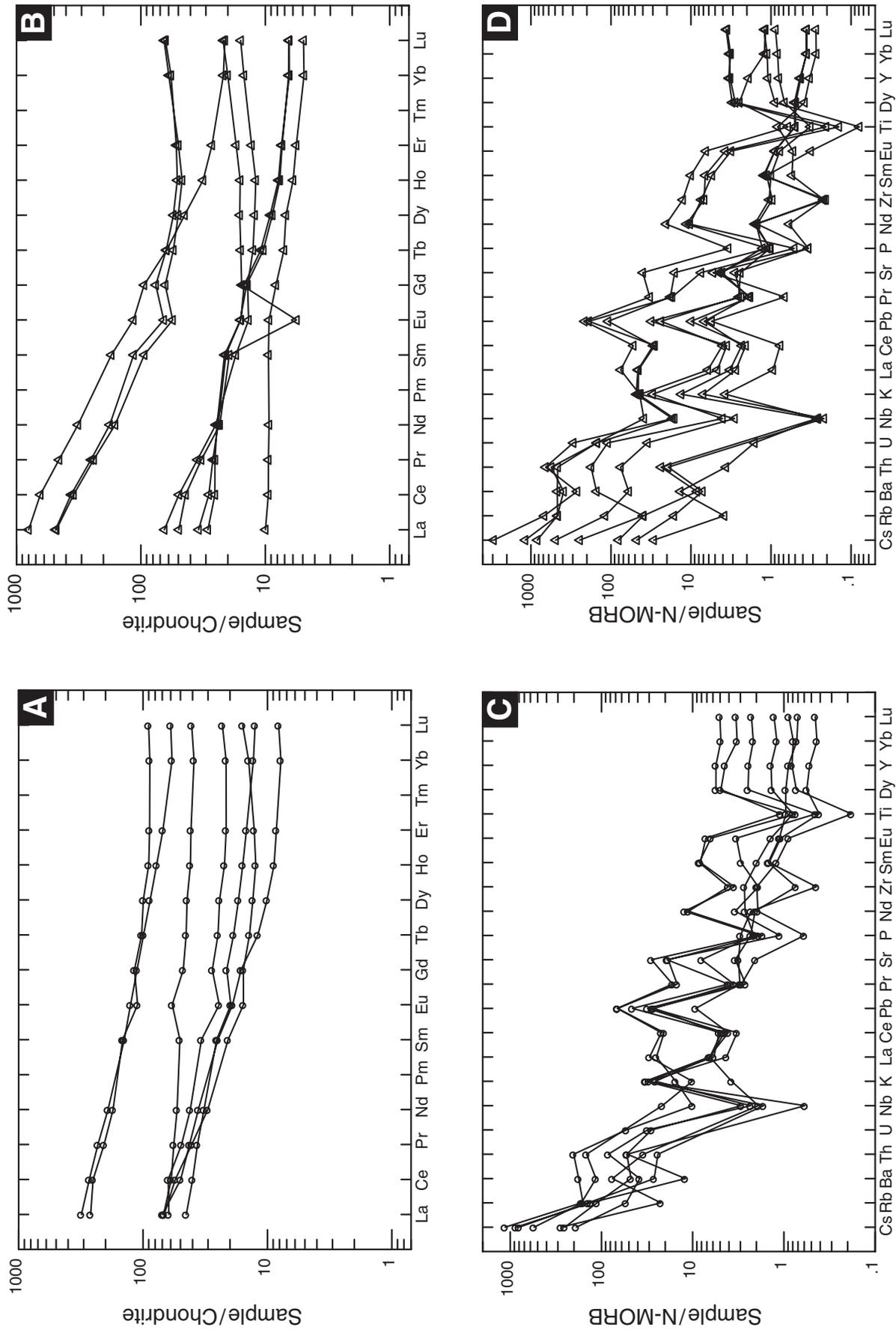


Figure 4. Chondrite-normalized (Sun and McDonough, 1989) and primitive normal mid-ocean-ridge basalt (N-MORB)-normalized (Sun and McDonough, 1989) trace-element variation diagrams for (A) Teru Volcanic Formation rare earth elements (REEs), (B) Kohistan batholith REEs, (C) Teru Volcanic Formation, N-MORB normalized, and (D) Kohistan batholith, N-MORB normalized.

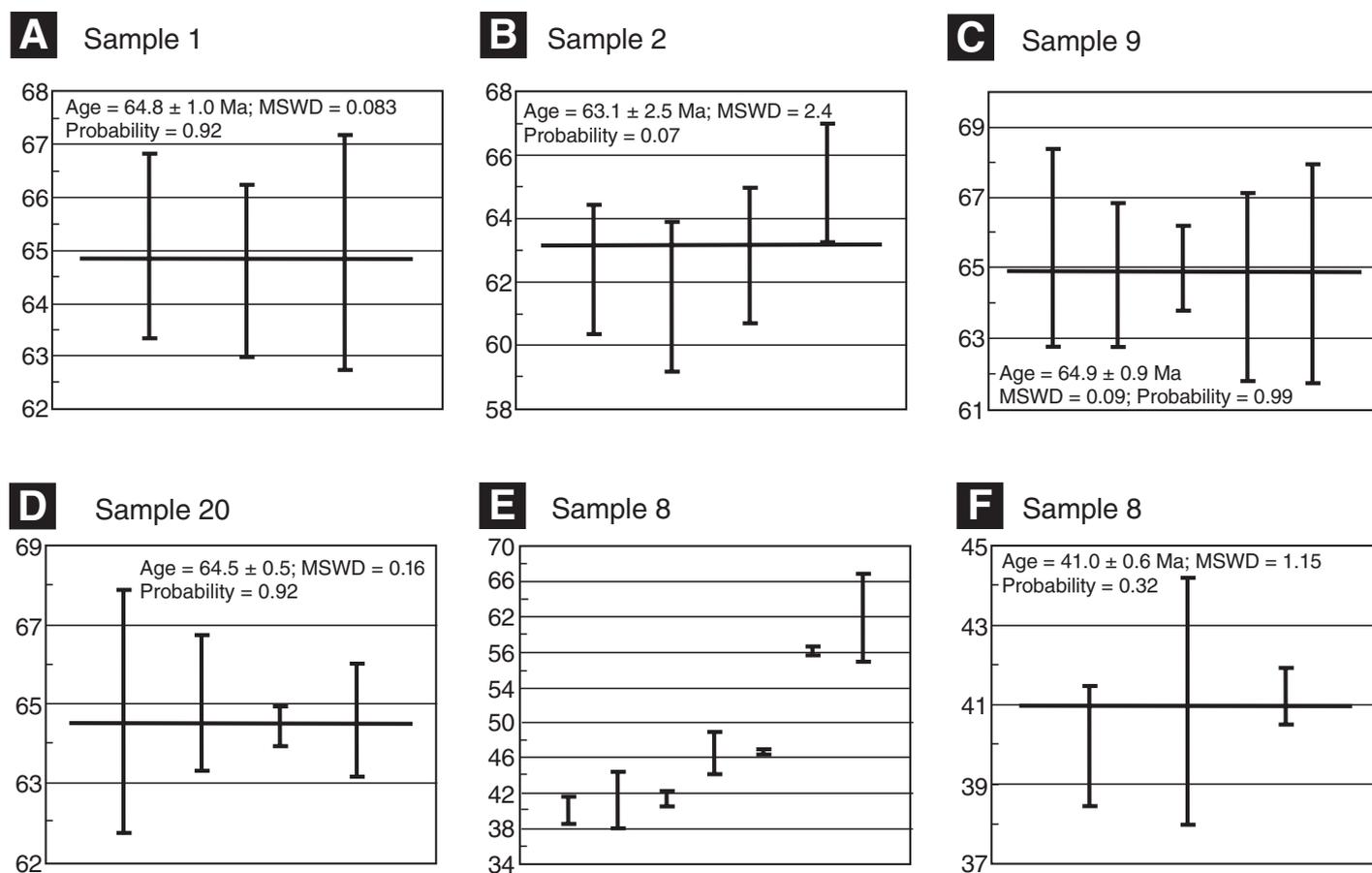


Figure 5. $^{206}\text{Pb}/^{238}\text{U}$ weighted average plots for Teru Volcanic Formation (TVF) and Kohistan batholith (KB). (A) Sample 1, Teru Volcanic Formation; (B) sample 2, Teru Volcanic Formation; (C) sample 9, Teru Volcanic Formation; (D) sample 20, Shunji pluton, Kohistan batholith; and (E–F) sample 8, Pingal pluton, Kohistan batholith. Data was reduced using the Isoplot program. MSWD—mean square of weighted deviates.

DISCUSSION

Field Geology and Remote Sensing

Field work confirmed the results of earlier studies that had demonstrated the occurrence of outcrops of volcanic rocks ranging from basaltic to rhyolitic among intrusions of plutonic rocks. Three newly mapped plutonic bodies had a range of compositions from gabbroic to granitic. Kohistan-Ladakh was found to be, as the earlier studies had shown, a region that exposed parts of a volcanic arc and its plutonic roots. Remote sensing extended field mapping and helped in the discrimination of individual igneous bodies. Mapping of the Pingal pluton (Fig. 2A) proved to be particularly important because isotopic results from that body indicated it to be post-collisional, a result that is consistent with its location abutting the Shyok suture zone. Background information for the application of a variety of methods of study aimed at characterizing

the structure of Kohistan and the nature and ages of the arc rocks was obtained in these studies.

Petrology and Trace-Element and Isotope Geochemistry

Petrography and major- and minor-element geochemistry confirmed that a full range of calc-alkaline volcanic arc rocks is exposed in Kohistan and that rocks of the low-K series predominate. Trace-element analyses undertaken in this study showed that the volcanic and plutonic rocks of northern Kohistan have broadly similar petrogenetic characteristics and that the depletion of Nb, P, and Zr and enrichment in Th, K, and Pb indicate the operation of subduction-related processes in their formation. The ternary diagram of Wood et al. (1981), which involves the three immobile trace elements Th-Hf-Ta, and which has been widely used to discriminate volcanic arc magmas from other types of magma, especially from the MORB source, was

used to plot results. The diagram shows that the analyzed rocks of northern Kohistan represent volcanic arc magmas enriched in Th without the accompanying enrichment in Zr-Hf and Nb-Ta that characterizes within-plate basalts and alkaline MORB. The concentration of Th relative to Hf and Ta places Teru Volcanic Formation and Kohistan batholith rocks close to the Th apex of the Wood diagram and emphasizes their volcanic arc affinities (Fig. 7).

There is a general consensus that the major source of arc magmas lies in the mantle wedge (Perfit et al., 1980; Gill, 1981; Plank and Langmuir, 1998; Davies and Bickle, 1991) and that the subducting slab provides the components that trigger the melting process. Components from the subducting slab that can contribute to the subarc mantle are thought to be dominated by hydrous fluids but may also include silicate melts from altered oceanic basalt and sediment. Subducted basalt and sediment have different isotopic and incompatible trace-element

TABLE 2. ZIRCON DATA—ANALYTICAL DATA FOR SAMPLES FROM THE KOHISTAN ARC

Fractions	Weight (mg)	U (ppm)	Pb [†] (ppm)	²⁰⁶ Pb [‡] / ²⁰⁴ Pb	²⁰⁶ Pb*/ ²³⁸ U	% err	²⁰⁷ Pb*/ ²³⁵ U	Radiogenic ratios % err	²⁰⁷ Pb*/ ²⁰⁶ Pb*	% err	²⁰⁶ Pb/ ²³⁸ U	²⁰⁷ Pb/ ²³⁵ U	Age corr. coef.	Pbc [§] (pg)
Sample 1														
1-1	11.8	87.52	1.29	148	0.01014	-2.7	0.06662	-5.2	0.04764	-4.3	65.1	65.5	0.55	5.1
1-2	10.2	108.4	1.63	154	0.01007	-2.5	0.06356	-3.7	0.04578	-2.6	64.6	62.6	0.73	5.1
1-3	3.7	128	28.9	1043	0.215	-0.62	2.512	-0.76	0.8477	-0.4	1255	1275	0.84	6
1-4	6.3	128.3	1.8	154	0.01012	-3.4	0.06273	-4.3	0.045	-2.5	64.9	61.8	0.82	3.7
Sample 2														
2-1	10.9	93.9	1.14	290	0.01015	-2.9	0.06475	-3.2	0.04626	-1.3	65.1	63.7	0.91	2.3
2-2	14.3	82.6	2.11	55	0.009719	-3.3	0.0621	-21	0.04634	-20	62.3	61.2	0.46	20
2-3	9.5	95.3	2.06	65	0.00989	-3.4	0.06269	-16	0.04644	-15	62.8	61.8	0.43	12
2-4	10.9	91.7	2.6	48.4	0.009582	-3.8	0.06324	-19	0.04786	-18	61.5	62.3	0.42	20
Sample 8														
8-1	2.8	105.5	6.01	30.7	0.009628	-7.9	0.05892	-22	0.04438	-19	61.8	58.1	0.6	15
8-2	2.2	96.9	2.62	36	0.006389	-7.6	0.03803	-26	0.04317	-23	41.1	37.9	0.46	4.8
8-3	5.2	263.8	3	145.8	0.006409	-1.7	0.04137	-4.2	0.04681	-3.6	41.2	41.2	0.52	4.3
8-4	4	243.5	5.9	45.8	0.006214	-3.7	0.04031	-8.6	0.04705	-6.8	39.9	40.1	0.63	14
8-5	6.2	121	3.22	42	0.007226	-5	0.04645	-17	0.04662	-15	46.4	46.1	0.49	15
8-6	31.7	702.2	5.32	1815	0.00725	-0.51	0.04716	-0.53	0.04718	-0.14	46.6	46.8	0.97	5.6
8-7	22.7	227.9	2.6	302.8	0.009048	-0.81	0.0591	-1.1	0.04737	-0.61	58.1	58.3	0.82	10
8-8	24	354.6	9.96	501	0.02464	-0.56	0.2324	-0.77	0.06841	-0.5	156	212	0.76	27
8-9	15.2	169.7	6.13	818	0.03212	-0.58	0.321	-0.61	0.07249	-0.18	204	283	0.95	6.5
8-10	15.5	151.9	23.5	43.5	0.04302	-3.9	0.4762	-5	0.08029	-3.6	271	395	0.69	250
8-11	13.7	179.2	13.6	866	0.07081	-0.51	0.7241	-0.53	0.07416	-0.13	441	553	0.97	13
8-12	8	161.7	13.7	232	0.0645	-0.72	0.6328	-0.92	0.07115	-0.57	403	498	0.79	24
Sample 9														
9-1	12.9	45.1	1.25	51.1	0.01022	-4.3	0.04966	-17	0.03524	-15	65.5	49.2	0.44	11
9-2	18.3	87.3	1.09	282	0.01013	-1.8	0.06517	-2.7	0.04667	-1.9	65	64.1	0.72	3.8
9-3	12.3	53	0.8	116	0.01004	-4.2	0.06553	-8	0.04732	-6.4	64.4	64.4	0.6	4.2
9-4	12.3	41	0.86	65	0.01011	-4.8	0.06578	-9.9	0.04721	-8.2	64.8	64.7	0.57	6.9
9-5	23	40.9	0.51	216	0.0101	-3.2	0.06133	-9.9	0.04405	-8.9	64.8	60.5	0.44	3
Sample 20														
20-1	12	111.2	1.29	263	0.01007	-2.2	0.06466	-2.7	0.04658	-1.4	64.6	63.6	0.85	3.4
20-2	39	116.3	1.57	301	0.01004	-0.82	0.06297	-1.6	0.04549	-1.3	64.4	62	0.61	2.8
20-3	13.8	75.9	1.13	141	0.01013	-2.6	0.06312	-4.1	0.04518	-2.9	65	62.1	0.7	5.4
20-4	18.1	32.3	0.43	133	0.0101	-4.8	0.05792	-8.1	0.0416	-6.2	64.8	57.2	0.64	3.2

Note: Zircon dissolution followed the methods of Krogh (1973) and Parrish (1987). Elemental separation was done with a HCl column chemistry for Pb and U. Decay constants used were $^{238}\text{U} = 0.15513 \times 10^{-9} \text{ yr}^{-1}$ and $^{235}\text{U} = 0.98485 \times 10^{-9} \text{ yr}^{-1}$ (Steiger and Jäger, 1977). Isotopic analyses were determined on a VG Sector multicollector thermal ionization mass spectrometer. A mass fractionation correction of $0.18\% \pm 0.05\%/\text{amu}$, as determined by standard runs on NBS 981 (common Pb) and NBS 982 (equal atom Pb), was applied to the Pb data. Samples were spiked with a mixed $^{209}\text{Pb}/^{235}\text{U}$ spike. Errors on $^{206}\text{Pb}/^{238}\text{U}$ were minimized by use of a Daly multiplier and are typically on the order of 1% or less. Common Pb corrections were made using values determined from Stacey and Kramers (1975) for the interpreted crystallization age. % err are analytical errors in percent. For measured and radiogenic ratios this is the 2-sigma. Errors were computed using data algorithm of Ludwig (1989). Corr. coef. is the correlation of $^{206}\text{Pb}/^{238}\text{U}$ and $^{207}\text{Pb}/^{235}\text{U}$ errors as determined by Ludwig (1989).

[†]Common and radiogenic component with blank and spike subtracted.

[‡]Measured ratios.

[§]Total amount of common Pb in analysis.

compositions, so that by considering these differences, it is possible to identify contributions from different components. The Teru Volcanic Formation shows a large range of chemical compositions, from basalt to rhyolite, which can be explained by fractional crystallization, assimilation, wall-rock reaction, and magma mixing. Little variation is seen in the isotopic compositions, and isotopic variations do not correlate with composition. Instead, the correlation between isotopes and trace elements in this data set, as in other island-arc data sets, appears to be related to variable contributions of sediments and fluids to the mantle wedge.

The source characteristics of Teru Volcanic Formation and Kohistan batholith rocks are amenable to being modeled through the use of mixing calculations because the Nd, Sr, and Pb isotopic compositions of the analyzed rocks

form a trend between Indian Ocean MORB and EMII mantle reservoir end members. Modeling calculations were performed using N-MORB taken from Lehnert et al. (2000) as end members values, and EMII data from Hart (1988) and Workman et al. (2004). The calculations indicate that mixing of 15% and 40% of N-MORB and 60%–85% EMII can generate the Sr and Nd isotopic ratios, and mixing between 5%–15% of N-MORB and 95% and 85% of EMII can generate the Pb isotopic ratios of the mantle wedge composition from the Teru Volcanic Formation and Kohistan batholith (Figs. 8A and 8B). Both sets of models indicate a dominant role for an enriched DUPAL-type mantle source in the generation of the volcanic and plutonic rocks of the Kohistan-Ladakh arc. DUPAL mantle has been mapped close to and south of the equator, indicating that the Kohistan arc, which grew during

Cretaceous times, formed far to the south of its present position. In an earlier study, Khan et al. (1997) had already identified a DUPAL signature in three other Kohistan rock groups: the Chalt volcanic rocks, the Kamila amphibolite, and rocks of the Chilas complex.

Isotopic Ages in the Kohistan-Ladakh Block

Published modern U-Pb zircon isotopic ages for volcanic igneous and plutonic rocks of the Kohistan-Ladakh block extend back to ca. 154 Ma (Schaltegger et al., 2002). Heuberger et al. (2007) reported ages close to 107 Ma for three rocks (a quartz-diorite, a basaltic sill, and a granite dike) of the arc block in western Kohistan near Drosch as well as an age for a diorite of close to 112 Ma in the same area. U-Pb ages older than ca. 95 Ma have been reported (Schaltegger

TABLE 3. Sr, Nd, AND Pb ISOTOPE DATA FROM THE TERU VOLCANIC FORMATION (TVF) AND KOHISTAN BATHOLITH (KB)

Sample no.	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$	$^{87}\text{Sr}/^{86}\text{Sr}$	$^{143}\text{Nd}/^{144}\text{Nd}$	ϵ_{Nd}
1	18.503	15.587	38.64	0.704135	0.51283	4.16
2	18.445	15.563	38.67	0.704785	0.512831	4.32
9	18.466	15.587	38.67	0.704147	0.51284	4.34
16	18.658	15.565	38.748	0.704478	0.512901	5.64
17	18.512	15.554	38.579	0.704459	0.512884	5.4
18	18.588	15.558	38.712	0.704881	0.512892	5.5
33	18.432	15.582	38.421	0.704693	0.512826	4.02
34	18.429	15.587	38.433	0.704347	0.512827	4.05
41	18.43	15.573	38.399	0.703806	0.512883	5.24
47	18.284	15.512	38.109	0.703942		
59	18.432	15.533	38.286	0.704331	0.512908	5.84
61	18.471	15.548	38.318	0.704342	0.512791	3.22
69	18.356	15.547	38.232	0.704233	0.512895	5.3
70	18.28	15.529	38.162	0.704355	0.512942	6.38
72	18.351	15.541	38.226	0.704192	0.512938	6.07
76	18.189	15.5	37.993	0.704085	0.512959	6.42
103	18.613	15.547	38.672	0.704278	0.512911	5.83
8	18.634	15.642	38.906	0.704615	0.51271	1.92
20	18.523	15.58	38.652	0.705172	0.512821	4.32
38	18.602	15.599	38.753	0.705156	0.512819	4.18
52	18.668	15.612	38.816	0.704538	0.512821	3.15
63	18.62	15.58	38.725	0.70407	0.512864	4.91
67	18.654	15.547	38.672	0.704865	0.512781	3.45
96	18.714	15.581	38.878	0.704921	0.512806	3.89
99	18.726	15.637	38.958	0.705109	0.512654	1.07
104	18.601	15.532	38.561	0.704236	0.51291	5.66
106	18.563	15.532	38.509	0.704105	0.512929	5.91
108	18.551	15.528	38.483	0.704115	0.512932	6.29
111	18.626	15.528	38.676	0.704811	0.512841	4.32

et al., 2002), and an age of ca. 101 Ma came from a granite near Leh in Ladakh (Schärer et al., 1984). An Albian stratigraphic age for fossils in sedimentary rocks intercalated within the Chalt volcanic rocks (Pudsey, 1986) and Aptian-Albian fossiliferous limestones from the Shyok suture zone reported by Heuberger et al. (2007) as interlayered with basalts and andesites of the Kohistan-Ladakh block indicate depositional ages for sedimentary rocks of the island arc some time between ca. 125 Ma and ca. 100 Ma. Kohistan-Ladakh arc activity extending from Late Jurassic to mid-Cretaceous times is established by these isotopic and stratigraphic ages. Three U-Pb zircon ages close to 65 Ma obtained on Teru Volcanic Formation rocks and the ca. 65 Ma age on a diorite all reported here are younger than the 154 Ma to ca. 100 Ma arc activity ages and close to the youngest published zircon age of ca. 61 Ma (for a granite near Leh, in Ladakh; Schärer et al. 1984) from within the Kohistan-Ladakh block. The five ages in the 65–61 Ma range form a group that is younger than all other calc-alkaline volcanic arc igneous rock zircon ages from the block. We interpret them to mark the end of igneous activity in the Kohistan-Ladakh calc-alkaline volcanic island arc and, for that reason, the time of arc collision with India on the Indus suture.

In great contrast, the Pingal pluton of the Kohistan batholith near the northern margin of the Kohistan-Ladakh block (Fig. 2) yielded a U-Pb zircon age of ca. 41 Ma, which was based

on the three youngest of several fractions. Results for material from other zircon fractions of that rock showed ages as old as Paleozoic, and these are regarded as having involved underlying continental material of the Karakorum basement. For that reason, and because of the close proximity of the pluton to the Shyok suture (Fig. 2), as well as its young age, the Pingal pluton eruption is considered to postdate formation of the Shyok suture and the collision of India (including the Kohistan-Ladakh block) with Asia. Heuberger et al. (2007, p. 85) working in the Drosh area of western Kohistan, found, as has been found in this study, that the “.....magmatic and tectonic history of the Karakoram-Kohistan [Shyok in this paper] Suture Zone continued to Eocene times.” They reported two rocks with Cenozoic zircon U-Pb ages: a metagabbro with an age of 50 Ma, and a granite dike with an age of 47 Ma (which resembled our samples from the Pingal pluton in containing Proterozoic zircon cores) from within the suture zone. They also reported a crosscutting granite dike from ~20 km inside the Kohistan-Ladakh block with an age of ca. 39 Ma. A leucogranite with an age of ca. 30 Ma had earlier been reported from farther to the northeast at the Indus confluence (Schaltegger et al. 2002). Fraser et al. (2001) reported U-Pb zircon isotopic ages from the eastern Karakoram close to the Shyok suture in the Hunza valley and in the Baltoro region that included ages for a Karakoram Andean arc and its metamorphosed accretionary prism active in

Jurassic and Cretaceous times, as well as granitic ages that extend to as young as 8 Ma. Monazites in a Proterozoic orthogneiss with ages close to 5.4 Ma were interpreted as evidence of “.... partial melting during sillimanite grade metamorphism of a Proterozoic gneiss during the Pliocene” (Fraser et al. 2001, p. 1451).

Taken together, zircon isotopic ages on igneous and metamorphic rocks that yield Cenozoic ages in Karakorum and Kohistan-Ladakh rocks from either side of, but close to, and from within the Shyok suture zone in the Hunza valley and Baltoro regions (Fraser et al., 2001, their Fig. 8), near Drosh in the western Karakoram (Heuberger et al., 2007), and in the Pingal pluton in this study include a total of 16 ages that between them span much of the Cenozoic. The timing of the Shyok suturing event within that period is constrained, on isotopic data, by results from intrusions within the Kohistan-Ladakh block that show evidence of involvement of continental basement because the Kohistan-Ladakh block had no continental basement until after it collided with Asia. The Pingal intrusion with an age of ca. 40 Ma (this study) and a granite dike with an age of ca. 47 Ma (Heuberger et al., 2007) are the only two rocks in which evidence of continental contamination has been discerned. On that basis, we place the time of suturing in the Shyok suture zone between Kohistan and the Karakorum margin of Asia at ca. 50 Ma, recognizing that evidence of postcollisional metamorphic and igneous activity close to the Shyok suture zone reaches into the late Cenozoic in the Hunza valley and Baltoro areas, as it does farther east in Nanga Parbat (Krol and Zeitler, 1996). Farther east still, in the Zaskar mountains of western Ladakh, strong evidence has been found of suturing at ca. 50 Ma (e.g., Garzanti et al., 1996). That suturing has in the past been considered (for example, in Rolland et al., 2002) to have been on the Main Mantle thrust (which is a name applied in the Western Himalaya to the Indus suture of Kohistan and Ladakh), which is here, because of its late age, considered to have been on the Shyok suture.

Our work and that of Heuberger et al. (2007) both emphasize that tectonic activity persisted in the Kohistan-Ladakh block after the Shyok suturing was complete at ca. 50 Ma. Earthquakes show activity persisting to present day, and Heuberger et al. (2007, p. 87) emphasized a late “strong sinistral strike-slip overprint” in the Shyok suture zone near Drosh. Isotopic ages of ca. 46 Ma on coesite-bearing eclogites from the Kaghan valley (Fig. 2) in the Indus suture zone on the southern side of the Kohistan-Ladakh block (Sachan et al., 2004) are here interpreted as indicating a time coincident with, or soon after, the time of suturing in the Shyok suture

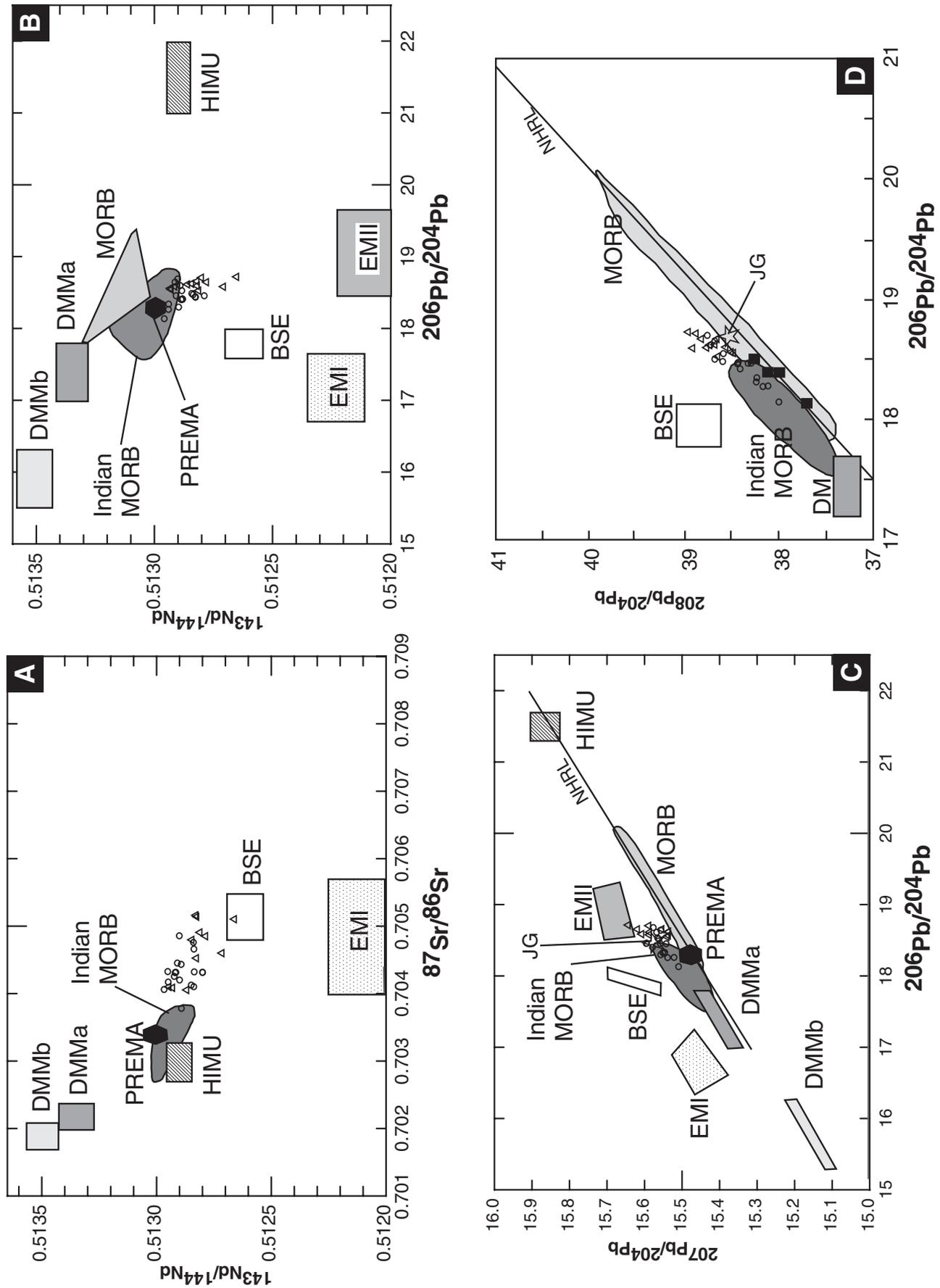


Figure 6. Isotope plots for Teru Volcanic Formation (TVF) and Kohistan batholith (KB). Teru Volcanic Formation is represented by circles, and Kohistan batholith is represented by triangles. The mantle sources of mid-ocean-ridge basalt (MORB) and the mantle end members Depleted Mantle (DM), PREvalent Mantle (PREMA), and Bulk Silicate Earth (BSE) are from Zindler and Hart (1986); the Indian ocean MORB is from Simonetti et al. (1998). JG represents gabbroic rocks from Jijal complex, Kohistan (after Garrido et al., 2007). EMII represents Enriched Mantle II, HIMU represents Mantle with high U/Pb ratio, and NHRL represents Northern Hemisphere Reference Line.

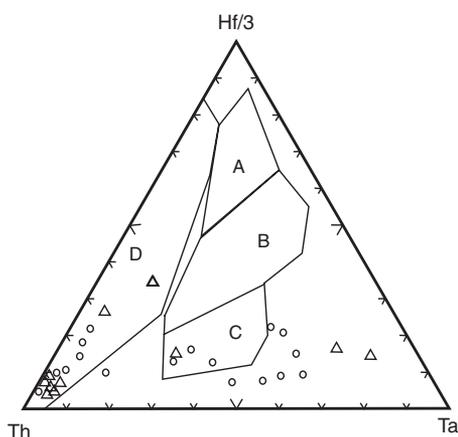


Figure 7. Tectonic discrimination diagram after Wood et al. (1981). The concentration of Th relative to Hf and Ta places Teru Volcanic Formation and Kohistan batholith rocks close to the Th apex, which emphasizes their volcanic arc affinities.

zone, ~100 km north of the Kaghan valley on the northern side of the Kohistan-Ladakh block, when deformation associated with that northern collision was sufficiently intense in the southern suture zone to begin to raise coesite-bearing eclogites from the depth of ~90 km, at which they had equilibrated at some earlier time. The coesite-bearing eclogites of Tso Morari on the Indus suture zone boundary of the Kohistan-Ladakh block in eastern Ladakh (Kaneko et al., 2003) had also achieved isotopic equilibrium at a depth of ~90 km by ca. 53 Ma (Leech et al., 2005). The beginning of the elevation of those rocks is here similarly attributed to far-field

effects of the Shyok suture zone collision, which was then in progress ~50 km away to the northeast. Our interpretation of the ages of eclogites south of the Kohistan-Ladakh as a manifestation of suturing between India and the Kohistan-Ladakh batholith may require a reappraisal.

Paleomagnetic Results

Apparent polar wander paths (Besse and Courtillot, 2002; Schettino and Scotese, 2005) show the southern margin of Asia between 80 and 40 Ma to have been located at about ~30°–35°N and to have experienced very little latitudinal motion since 55 Ma. In contrast, paleomagnetic measurements and seafloor magnetic anomalies show that India has moved rapidly northward during the past 80 m.y., with its northern margin crossing the equator at ca. 60 Ma and reaching 10°N before 50 Ma. The Utror ChRM from Kalam, which records the paleolatitude of the Kohistan-Ladakh arc's southern margin, was acquired at a location somewhat south of 12°N during the later stages of Utror volcanic rock deformation. That ChRM constrains the collision of India with the Kohistan-Ladakh arc to have occurred before 50 Ma at a latitude close to the equator. The Utror volcanic rock ChRM is totally inconsistent with collision of the Kohistan-Ladakh arc with Asia at a time before it collided with India.

The mean in situ inclination for the Teru Volcanic Formation volcanic rock sites (viz. +46.2°) indicates a paleolatitude of $27.5^\circ \pm 6^\circ$ N (Ahmed et al., 2001), and apparent polar wander paths (Besse and Courtillot, 2002; Schettino and Scotese, 2005) place India's northern margin near 27°N at ca. 30 Ma. The Teru Volcanic Formation ChRM records the latitudinal position of those volcanic rocks after their deformation was com-

plete. Sampled Teru Volcanic Formation localities now lie at ~36°N. The collision of India and the Kohistan-Ladakh block with Asia recorded in the Teru Volcanic Formation deformation therefore occurred before ca. 30 Ma. Since that collision, the Teru Volcanic Formation rocks on the collided Kohistan-Ladakh block have traveled about another 10° northward.

The age of the Cretaceous red beds of Drosh and the time of their ChRM acquisition are not well determined. Their equatorial paleolatitude does not match that predicted for the southern Asia margin during the Cretaceous (Besse and Courtillot, 2002; Schettino and Scotese, 2005) but agrees well with other data cited here showing a Cretaceous equatorial position for Kohistan.

In summary, all three of the detailed paleomagnetic studies of rocks from the Kohistan-Ladakh arc block are consistent with a model, built here on other types of data, in which the Kohistan-Ladakh arc collided first with India at around the end of Cretaceous times (65–61 Ma) at equatorial or low northerly latitudes, followed by a later collision at ca. 50 Ma with Asia some 15° to 20° further north.

Relationship of the Two Collisions of the Kohistan-Ladakh Block to the Indian-Asian Collision Zone in Western Pakistan

Recent work on the Muslim Bagh ophiolite in western Pakistan (Figs. 1 and 9) found tholeiitic to calc-alkaline chemistry, boninitic magmas, high-temperature hydrothermal deposits, and serpentinite diapirs that indicated a forearc setting (Khan et al., 2007; Khan and Mahmood, 2008). The forearc is here suggested to represent an along-strike extension of the Kohistan-Ladakh forearc. The age of thrusting onto the

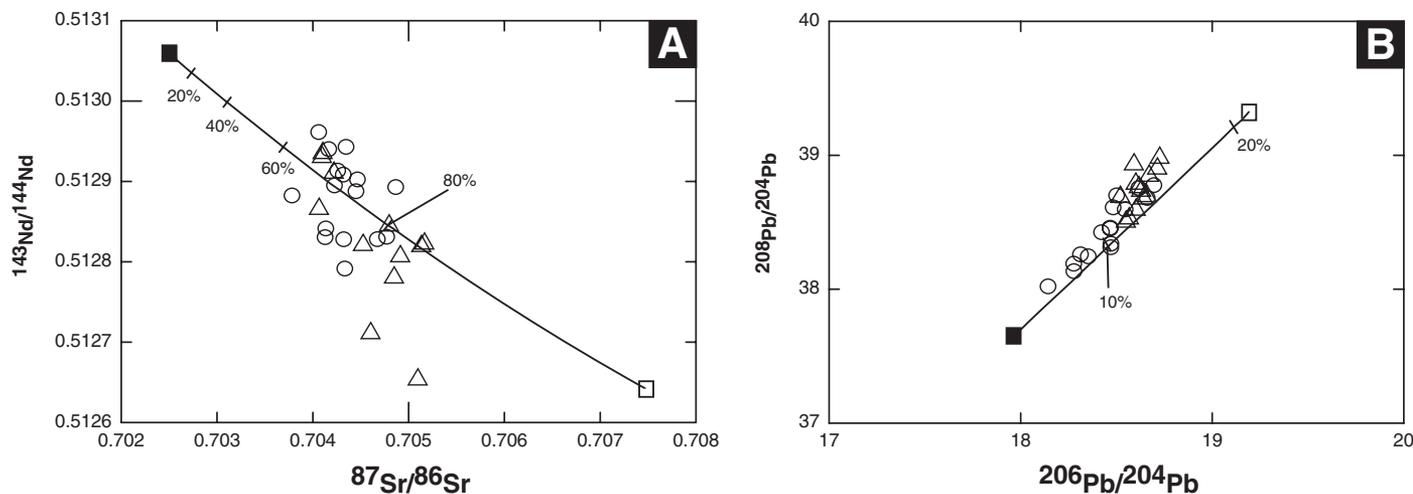


Figure 8. (A) $^{143}\text{Nd}/^{144}\text{Nd}$ vs $^{87}\text{Sr}/^{86}\text{Sr}$ variation diagram for the Teru Volcanic Formation showing the calculated two mixing lines, between Indian mid-ocean-ridge basalt (MORB) and enriched mantle (EMII) source. (B) Kohistan batholith.

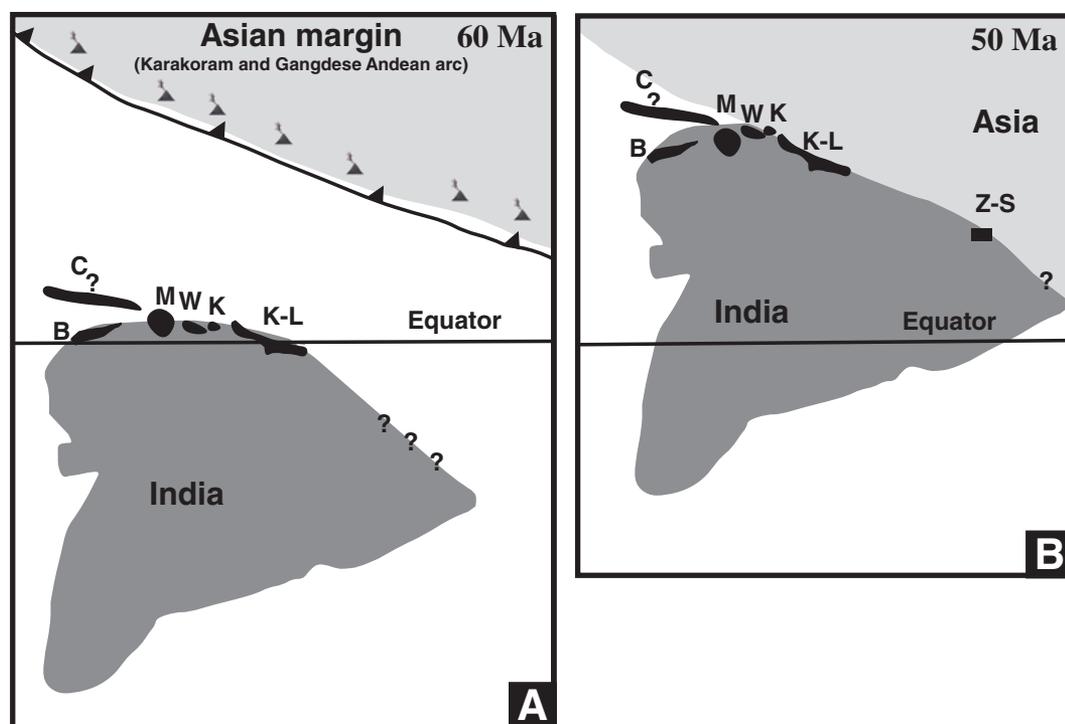


Figure 9. (A) Sketch showing India just after its collision with Kohistan and related arcs at 60 Ma. (B) Collision of India-Kohistan with Asia at 50 Ma. B—Bela ophiolite; C—Chagi arc; K—Khost ophiolite; K-L—Kohistan-Ladakh; M—Muslim Bagh ophiolite; W—Waziristan ophiolite; Z-S—Zepure Shan Range. Z-S is the site for which Zhu et al. (2005) reported collision of India and Asia at 50.6 ± 0.2 Ma. Location of India and Asian margin is after Scotese (2001).

Indian continent of the Muslim Bagh ophiolite is bracketed between the age of the youngest sediments beneath the ophiolites, which are late Maastrichtian (ca. 67 Ma) in age, and the ages of the oldest limestones unconformably overlying the Muslim Bagh ophiolite, which are early Eocene (54–47 Ma) in age (Allemann, 1979). The $^{39}\text{Ar}/^{40}\text{Ar}$ ages from metamorphic sole thrusts of 70.7 ± 5 Ma and 65.1 ± 4 Ma may date the beginning of obduction of the Muslim Bagh ophiolite onto the Indian continent. Figures 1 and 9 show the other ophiolite bodies now lying within the Indian-Asian collision zone in western Pakistan: the Bela, Zhob, Waziristan, Khost, and Dargai ophiolites. Like the Muslim Bagh ophiolite, the Bela ophiolite is unconformably overlain by Eocene to Oligocene transgressive shallow-marine sediments (Allemann, 1979), and it is underlain by Early Paleocene sediments (Hunting Survey Corporation, 1960). The Zhob ophiolite is also overlain by early to middle Eocene shallow-water foraminiferal limestone (Allemann, 1979). Further north, the Khost and Waziristan ophiolites are considered to be along-strike continuations of the Muslim Bagh and Zhob ophiolites (Treloar and Izatt, 1993), where obduction of the Khost ophiolite is interpreted to have occurred during the Paleocene (Cassaigneau, 1979). The age of the Dargai ophiolite is not well constrained.

A biostratigraphic analysis in the Waziristan and Kurram areas of northwestern Pakistan (Beck et al., 1995, p. 55) established evidence

of collision “after 66 Ma but before 55.5 Ma” and evidence of later overlapping by upper Lower Eocene marine strata “demonstrating that suturing was complete by 49 Ma.” In the light of the tectonic complexity of the area to the east of Waziristan (Tapponnier et al., 1981), we suggest that evidence of suturing on both the Indus suture (at ca. 60 Ma) and Shyok suture (at ca. 50 Ma) is conflated in this record.

In summary, obduction onto the Indian continental margin in western Pakistan is bracketed, stratigraphically, between late Maastrichtian and early Eocene times (between ca. 67 Ma and ca. 50 Ma). Sole thrust ages of ca. 65 Ma date the beginning of obduction, when the arc was attempting to subduct the continent, and are necessarily older than the time when the ophiolites came to rest on continental crust. They can be several million years older. Ages of 65 Ma for obduction of ophiolites onto the Indian continent (e.g., Searle et al., 1997; Gnos et al., 1997; DiPietro and Lawrence, 1991) may be more compatible with sole-thrust ages than with final arc-continent collision. As yet, in contrast to Kohistan, from which we report arc-collisional ages of 65 Ma to 61 Ma on the basis of the ages of the youngest calc-alkaline igneous rocks of the Kohistan-Ladakh block, ages for final arc igneous activity are not yet available from western Pakistan. That information will be needed before the full history of western Pakistan ophiolite obduction and subsequent arc collision can be established.

Relationship of the Two Collisions of the Kohistan-Ladakh Block to the Indian-Asian Collision Zone Farther East

About 200 km east of the stretch of the Indus suture immediately north of Tso Moriri, the Shyok and Indus sutures bounding Ladakh are mapped on the regional scale as coming together in the Indus–Yarlung–Tsang Po suture zone. That suture zone has itself been mapped eastward for more than 700 km as far as the Eastern Himalayan syntaxis. Its collisional age is presently best bracketed by observations in the Zepure Shan area (Zhu et al., 2005) that assign the “initiation” of collision to the time of P-8 foraminiferal assemblages and thus close to 51 Ma. The appearance of arc-ophiolite detritus in the strata along the Indian margin may reflect obduction rather than terminal collision.

At the time of the final collision between India and Asia, the Indus–Yarlung–Tsang Po suture zone could only have continued along strike to the east into the Shyok suture zone because the arc collision on the south side of the Kohistan-Ladakh block had, on the evidence presented in this paper, already happened. The ages of the Shyok suture reported in this paper and Indus–Yarlung–Tsang Po sutures are identical at close to ca. 50 Ma within resolution, which is consistent with that conclusion. A confusing feature of nomenclature emerges from the age of the Indus–Yarlung–Tsang Po collision. Sutures cannot end within continental crust. They must

either join other sutures, or intracontinental transform fault complexes within a continent, or they can emerge to join active plate boundaries in oceanic lithosphere. The Indus–Yarlung–Tsang Po suture zone joins, and is contemporary with, the Shyok suture zone. Both have an age of ca. 50 Ma. By contrast, the Indus suture on the southern side of the Kohistan–Ladakh block is ~10 m.y. older than, and has no such simple relationship with, the Indus–Yarlung–Tsang Po suture zone. What is called the Indus suture south of the Kohistan–Ladakh block marks the site of the collision of the Kohistan–Ladakh island arc with India at ca. 61 Ma. After that collision had happened, the active convergent plate boundary merged along strike, perhaps through arc to arc transform systems, with the then-active convergent plate boundary on the southern margin of Asia adjacent to the Gangdese and Karakoram active Andean volcanic arcs. Westward of the Kohistan–Ladakh block, the then-convergent boundary of Asia continued to the southern margin of the Central Afghan block (Tapponnier *et al.*, 1981), which had grown throughout the Cenozoic in the Makran. There is evidence that processes similar to those invoked by our work may also have occurred along strike to the east before terminal collision (Ding *et al.*, 2005; Aitchison *et al.*, 2007).

CONCLUSIONS

(1) The Kohistan–Ladakh block in the western Himalaya is a preserved fragment exposing rocks from several crustal levels of a calc-alkaline island arc that had been constructed on ocean floor during Late Jurassic and Cretaceous times. The arc developed above a northward-dipping subduction zone, and arc igneous rocks yield DUPAL source (i.e., Southern Hemisphere) isotopic signatures.

(2) A cluster of isotopic ages between 65 and 61 Ma on volcanic and plutonic rocks of the Kohistan–Ladakh arc marks the end of calc-alkaline igneous activity in the arc and, we conclude, the time when the arc collided with a continent.

(3) Paleomagnetic evidence from India and evidence from seafloor magnetic anomalies show that India was traveling northward through much of the Cretaceous and that its northern margin was close to the equator at 65 Ma. Volcanic rocks of the Kohistan–Ladakh arc with ages close to 65 Ma acquired a ChRM during later stages of their deformation at a latitude close to the equator. These results show that the continent with which the Kohistan–Ladakh arc collided had to have been close to the equator at 65 Ma, the time of arc collision. India was that continent.

(4) Confirmation of that conclusion comes from evidence of collision, and related obduction, in western Pakistan, where the youngest sedimentary rocks below overthrust ophiolites are late Maastrichtian (ca. 67 Ma) in age, and the oldest sedimentary rocks unconformably overlying the ophiolites are early Eocene in age. Well-studied sedimentary rocks in Waziristan and Kurram are here interpreted as showing evidence of both the Indus and Shyok suturing events.

(5) After India and the Kohistan–Ladakh arc collided, they lay far to the south of the margin of the Asian continent, but India continued to travel northward, and the newly acquired Kohistan–Ladakh block occupying its northern margin eventually collided with Asia in the Karakoram. Establishing the time of that collision is difficult because the Karakoram has been active, first as an Andean arc, and (after the Kohistan–Ladakh block collision) as a region of postcollisional convergent igneous activity throughout the Cenozoic. Critical information comes from two granites in northern Kohistan close to and within the Shyok suture, which have yielded zircon ages as old as Paleozoic and Proterozoic within a population of zircons that yielded Eocene ages. These rocks show the involvement of underlying old continental material. That kind of material did not exist beneath the Kohistan–Ladakh block, which had been constructed on ocean floor, until the time of the collision with the Karakoram. The two granites, with ages of 41 Ma and 47 Ma, are therefore postcollisional and permit an estimate of the time of the Shyok collision at ca. 50 Ma.

(6) Confirmation of that age comes from the ca. 50 Ma time of collision in the Yarlung–Tsang Po suture zone to the east. Suture zone continuity requires that the Yarlung–Tsang Po suture continues to the west. The suture zone south of the Kohistan–Ladakh block was already closed by 50 Ma, so that the continuation of the ca. 50 Ma Yarlung–Tsang Po suturing event has to have been in the Shyok suture zone.

(7) In this paper, we have not pursued the commonly published suggestion that the Kohistan–Ladakh arc collided with Asia during the later Cretaceous (e.g., Petterson and Windley, 1985). That idea goes back for more than 20 yr and has been used in many interpretations of the history of the western Himalaya, but reconsideration of that interpretation in this study was forced by the finding, from paleomagnetic evidence, that the Kohistan–Ladakh arc lay close to the equator at 65 Ma at a time when the southern margin of Asia lay almost 3000 km farther north. That evidence was soon found compatible with evidence of the end of Kohistan–Ladakh arc calc-alkaline igneous activity at 65–61 Ma and with the timing of obduction of ophiolites and the deposi-

tion of postcollision sedimentary rocks south of the Kohistan–Ladakh block and onto the Indian continent. Until now, the history of igneous activity in the Karakoram, which extends continuously without an obvious break from that of an Andean margin to postcollision, has made it difficult to resolve the timing of suturing on the Shyok suture. The ability to distinguish two granites with mid-Eocene isotopic ages within and close to the Shyok suture zone as postcollisional allows a new time for the Shyok suture to be suggested here.

We have narrowed the times of collision in the Indus suture (65–61 Ma) and the Shyok suture (ca. 50 Ma) on either side of the Kohistan–Ladakh block, but we recognize the limited amount of evidence that we have been able to use in addressing this important question for the understanding of the evolution of the India–Asian collision. Additional field, remote-sensing, petrological, geochemical, isotopic, thermochronological, and paleomagnetic work in carefully selected areas is needed to test the model that we have erected. In particular, the role of late tectonism that we suspect may have involved substantial amounts of strike-slip motion may prove to have been critical, although it is as yet hardly known.

The zircon ages of the Teru Volcanic Formation and Kohistan batholith, their island-arc character, their isotopic affinity with enriched mantle sources from the sub–Southern Hemisphere mantle, and the paleomagnetic evidence are indicative of the collision of Kohistan with India around 65–61 Ma at a latitude far south of its present position (Fig. 9). We conclude that the India–Kohistan collision predates the accretion of Kohistan–India to the Asian continent.

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