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THE OCCURRENCE AND FISSION-TRACK AGES OF LATE NEOGENE AND QUATERNARY VOLCANIC SEDIMENTS, SIWALIK GROUP, NORTHERN PAKISTAN

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ABSTRACT

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Volcanic sediments, now mostly bentonites and bentonitic mudstones, occur throughout the Late Neogene and Quaternary Siwalik Group of northern Pakistan. A number of these deposits have been dated by the fission-track method, utilizing zircon phenocrysts from these deposits, and provide the chronometric constraints upon which a paleomagnetic stratigraphy is developed for the Siwalik Group. Notable in the occurrence of these altered tuff horizons is an apparent mode in their stratigraphic development from approximately 3.0 to 1.5 m.y. B.P. which coincides with the period of activity of the Dacht-e-Nawar volcanic complex of east-central Afghanistan. Fission-track ages of certain tuffs for critical areas of northern Pakistan are reported herein.

INTRODUCTION

The region of northern Pakistan (Fig.1) known as the Potwar Plateau (Wadia, 1928; Cotter, 1933) is considered the stratotype for the Neogene and Quaternary Siwalik Group and for widely used Miocene and Pliocene faunal zones of South Asia (Fig.2).

Recently, an effort has been made to evaluate the remanent magnetic-polarity stratigraphy of the Siwalik Group of northern Pakistan (Keller et al., 1977; Visser and Johnson, 1978; Barndt et al., 1978; Opdyke et al., 1979; N. M. Johnson et al., 1982). Arising from these various paleomagnetic and stratigraphic studies of the Siwalik Group has been the recognition of volcanic-ash beds (many now bentonites) throughout much of the section. In general, these tuffs, tuffaceous mudstones and bentonites are found developed in three separate stratigraphic levels of the Siwalik Group (Fig.2): the

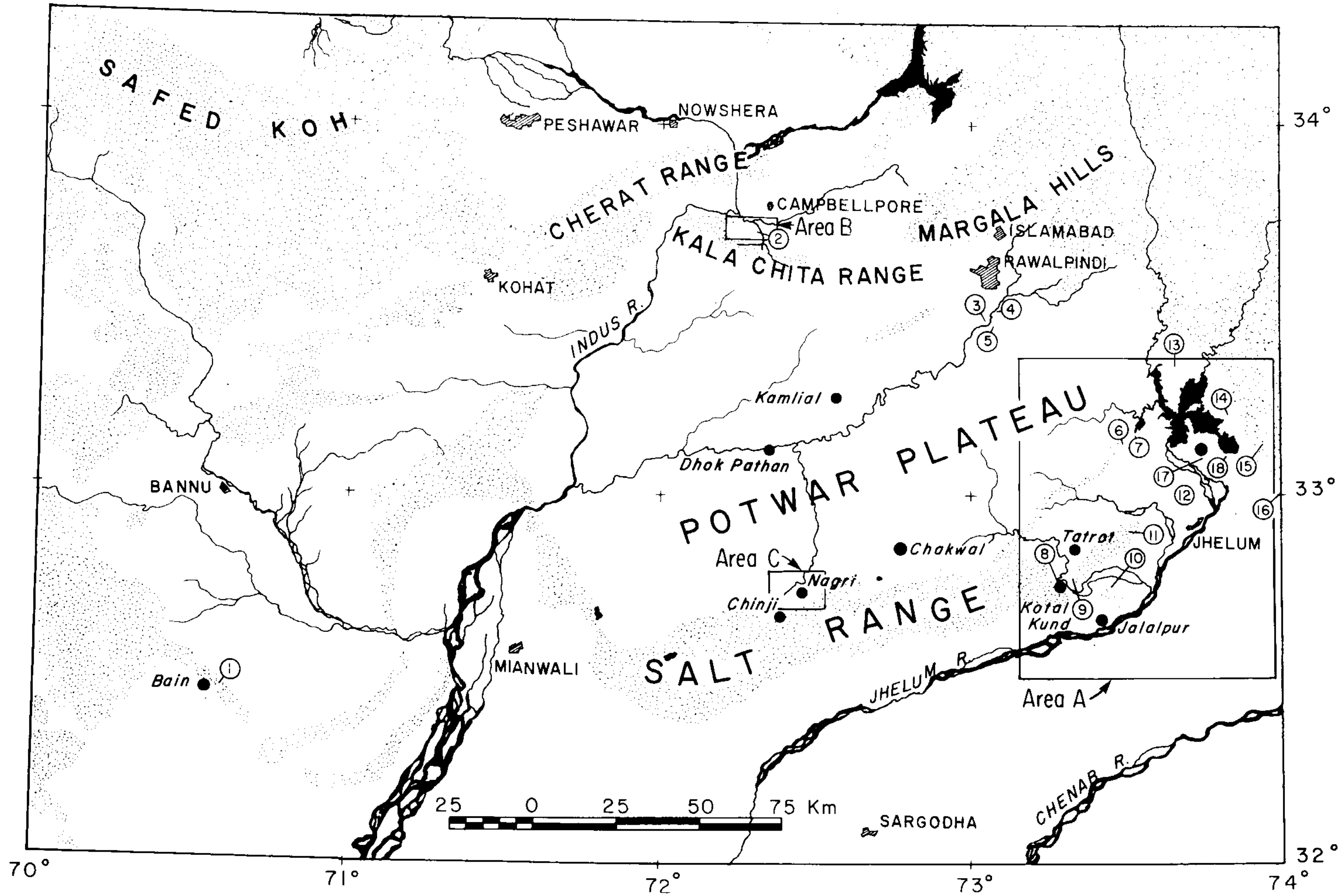


Fig.1. Localities in northern Pakistan which record evidence of Pliocene and Pleistocene volcanicity. Each of the eighteen (encircled) sites has been studied intensively and a paleomagnetic reversal stratigraphy has been constructed for each (see Fig.6). For Area A, see Fig.3, for Area B, see Fig.10, for Area C, see Fig.12.

middle portion of the Upper Siwalik Subgroup associated with rocks which yield faunas of the upper Tatrot faunal zone and the lower Pinjor faunal zone (see Opdyke et al., 1979, for a discussion of this faunal transition); the lower portion of the Nagri Formation at its stratotype associated with rocks which yield faunas of the early Nagri faunal zone (see Pilbeam et al., 1977a, 1979; N. M. Johnson et al., 1982, for a discussion of the faunal composition and paleomagnetic stratigraphy of this sequence); and the uppermost portion of the Kamlial Formation in the northern Salt Range. These tuff beds of the Kamlial and Nagri Formations lie in conformable sequence to strata of the Chinji Formation at its stratotype. The Chinji faunal zone is similarly defined from this area (see Pilbeam et al., 1977a, 1979; and N. M. Johnson et al., 1982, for a discussion of the faunal composition and paleomagnetic stratigraphy of this sequence).

The present paper describes the stratigraphic occurrence and presents fission-track ages of certain of the tuffs associated with the formations of the Siwalik Group in portions of northern Pakistan.

VOLCANIC SEDIMENTS IN THE UPPER SIWALIK FORMATIONS

Bentonites exposed in sediments of the upper portion of the Siwalik Group in the Pir Panjal foothills of Kashmir on the east bank of the Jhelum River were recognized as early as 1930 by C. S. Middlemiss (Middlemiss, 1930) and were described by K. L. Bhola of the Geological Survey of India in 1948 (Bhola, 1948). Work during the next twenty years by members of the Geological Survey of Pakistan led to the discovery of numerous bentonite deposits in southwestern Kashmir and the Salt Range which have been variously exploited (Ali and Shah, 1962; Akbar et al., 1964; Ali et al., 1965).

During the course of geological reconnaissance in the Potwar Plateau, eastern Salt Range and portions of southwestern Kashmir, we have located all of the outcrops of Siwalik bentonites discussed in the earlier literature together with a large number of additional localities (Figs.1 and 3). At several localities these tuffaceous sediments are associated with rocks which have yielded mammalian faunas typical of the Tatrot land mammal faunal zone. The bulk of these volcanic sediments, however, are associated with alluvial sediments containing typical Pinjor land mammal faunas.

At some localities, more than ten tuff layers can be observed in relatively thin (300—400 m) stratigraphic sections of Upper Siwalik rocks. Several of these tuffs are persistent making it possible to map large areas of the Siwalik fluvial terrane in the Jhelum area as isochron-bounded lithosomes (Visser and Johnson, 1978; Opdyke et al., 1979; Johnson et al., 1979; Ali et al., 1965; Summers, 1977; Raynolds, 1980). Facies variability within these lithosomes can thus be readily determined.

Where only a few prominent tuffs are in evidence in the Upper Siwalik section, the other tuff horizons are commonly represented by olive-gray

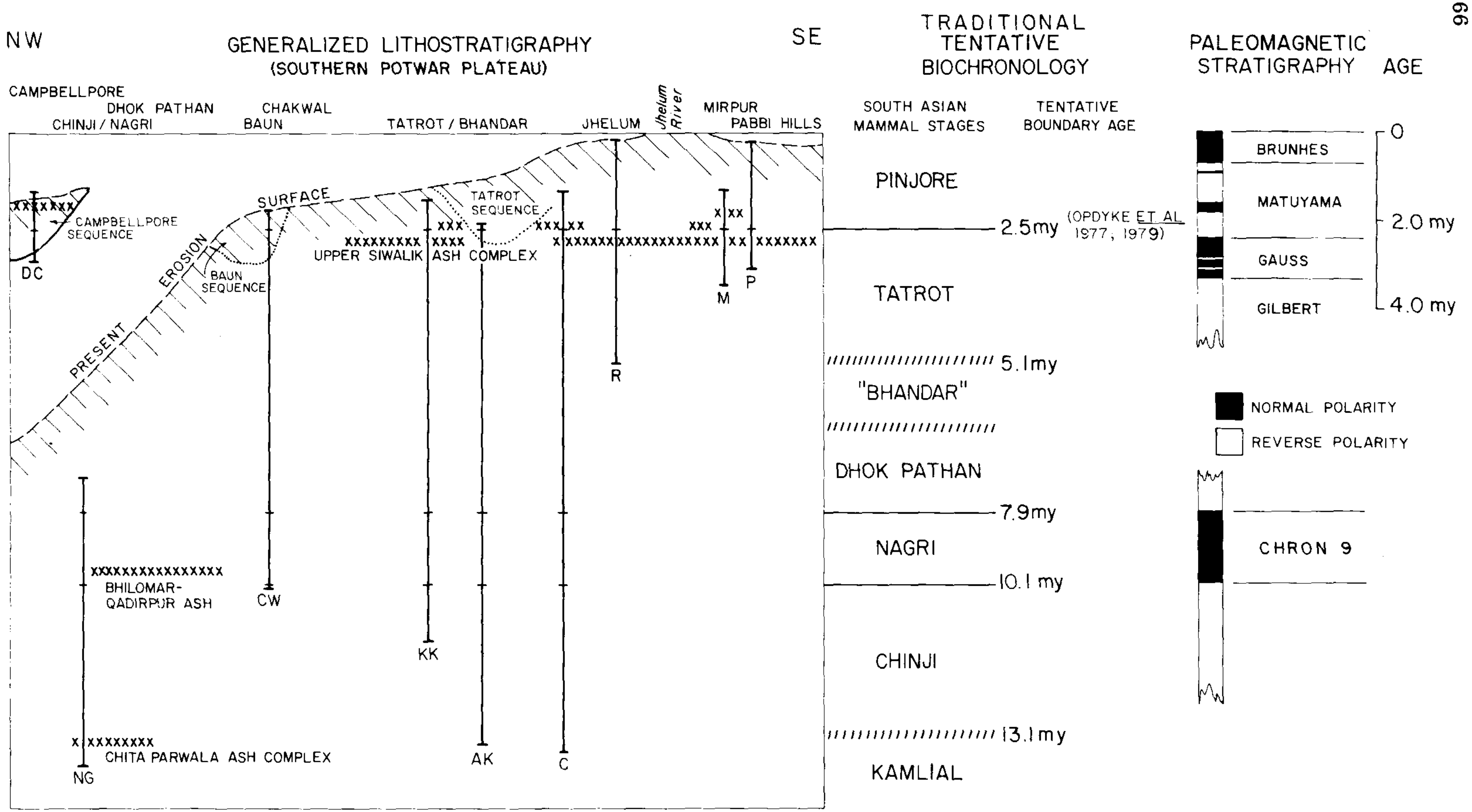


Fig.2. Explanation on p.67.

(Munsell color 5Y4/1) mudstones having abrupt basal contacts and a slightly bentonitic character (see, for example, the olive-gray mudstone horizons illustrated in Fig.5). These lithofacies variants are interpreted as representing very impure tuffaceous flood-basin sediments. Whereas most pure tuffs appear to represent primary airfall deposits into flood-basin pond environments, these olive-gray mudstones exhibit considerable reworking and contamination from enclosing overbank mudstone sediments.

STRATIGRAPHIC OCCURRENCE OF VOLCANIC SEDIMENTS

Tuff couplet (Jhelum area)

In the eastern Potwar and adjacent Kashmir, the tuffs, tuffaceous sediments and bentonites in the upper part of the Siwalik Group are in most cases easily distinguished from the surrounding rocks as well as from each other. For example, in the case of the two laterally persistent tuffs of the Jhelum area which occur in superposition in normally and reversely magnetized sediments, respectively (Fig.4), the lower tuff commonly consists of dark greenish-gray (5GY4/1) to olive-black (5Y2/1) biotitic claystone, with a thin but persistent pale-blue (5PB7/2) or pale-pink (5RP8/2) waxy, biotite-poor claystone layer or stringer at its base. Its lower contact is sharp; commonly there are distinct rip-ups of underlying mudstone in the basal few centimeters of the bentonite. The bentonite is up to 40 cm thick, but at most sites grades upward over tens of centimeters into the enclosing mudstones. At only one site was there any suggestion of bedding within the lower bentonite. At Mangla Anticline site *17* (Figs.3 and 5), a water-laid primary air-fall phase and four evidently reworked phases can be defined

Fig.2. Tentative chronostratigraphy of the Late Cenozoic clastic sedimentary succession observed in the southern Potwar Plateau, northern Pakistan. Remanent magnetic-polarity stratigraphy applicable to the Upper Siwalik Subgroup (Pinjor and Tatrot faunal zones) is illustrated. The approximate duration of various of the stratigraphic sections thus far studied in the current research program is illustrated in the general lithostratigraphy (left). These stratigraphic sections, several of which are discussed in text and in N. M. Johnson et al. (1982), are as follows: *NG* = type Nagri/Chinji locality, south-central Potwar Plateau; *CW* = Chakwal locality, section along the Sauj Kas, 20 km southwest of Chakwal, south-central Potwar Plateau; *KK* = Kotal Kund locality, section measured in the vicinity of Wadi Simli, eastern Salt Range; *AK* = Andhar Kas locality, section measured along the Andhar Kas, north flank of Jogi Tilla, eastern Salt Range; *C* = Chambal locality, section measured along the Jamarghal Kas, east flank of Chambal ridge, eastern Salt Range; *R* = Rhotas anticline locality, section measured along the Sanghoi and Basawa Kas, 12 km southwest of Rhotas Fort, eastern Salt Range; *M* = Mirpur locality, section measured along the Jhel Kas, 6 km south of New Mirpur, southwestern Kashmir; *P* = Pabbi Hills locality, section measured along the Grant Trunk Road, Kharian or Pabbi Hills anticline, 10 km southeast of Jhelum. The Upper Siwalik tuff complex and the Bhilomar/Qadirpur Ash are discussed in the present report. See Opdyke et al. (1979) and N. M. Johnson et al. (1982) for a complete discussion of these sites and the tentative boundary ages assigned to the various South Asian mammal stages.

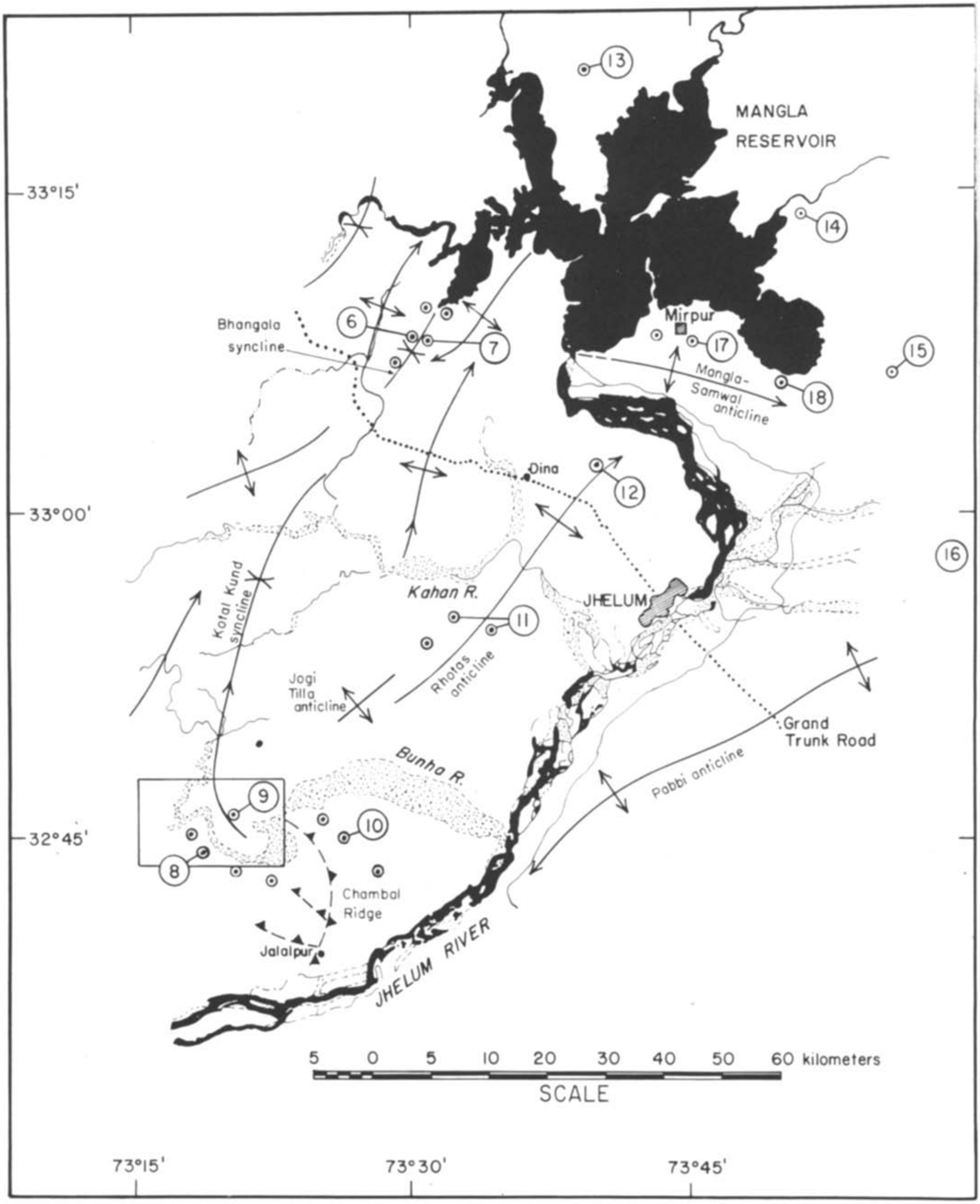


Fig.3. Location map of Upper Siwalik bentonitized tuff localities in the Jhelum area, southeastern Potwar Plateau and adjacent southwestern Kashmir, northern Pakistan. Localities discussed in text associated with the Mangla-Samwal (site *17*) anticline, Kas Guma (site *15*), Bhangala (sites *6* and *7*), Kotal Kund syncline (sites *8* and *9*) and Rhotas anticline (site *11*) are indicated. Area outlined is Fig. 7.

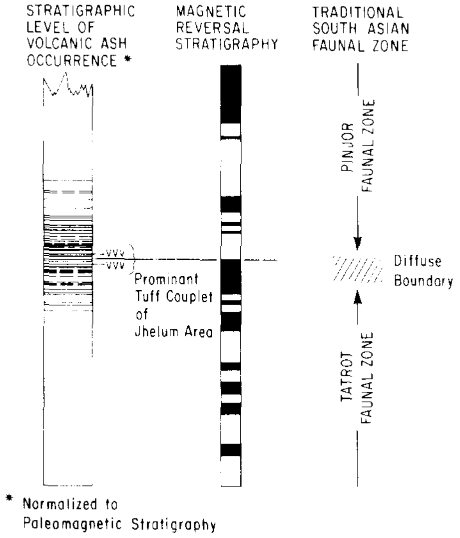
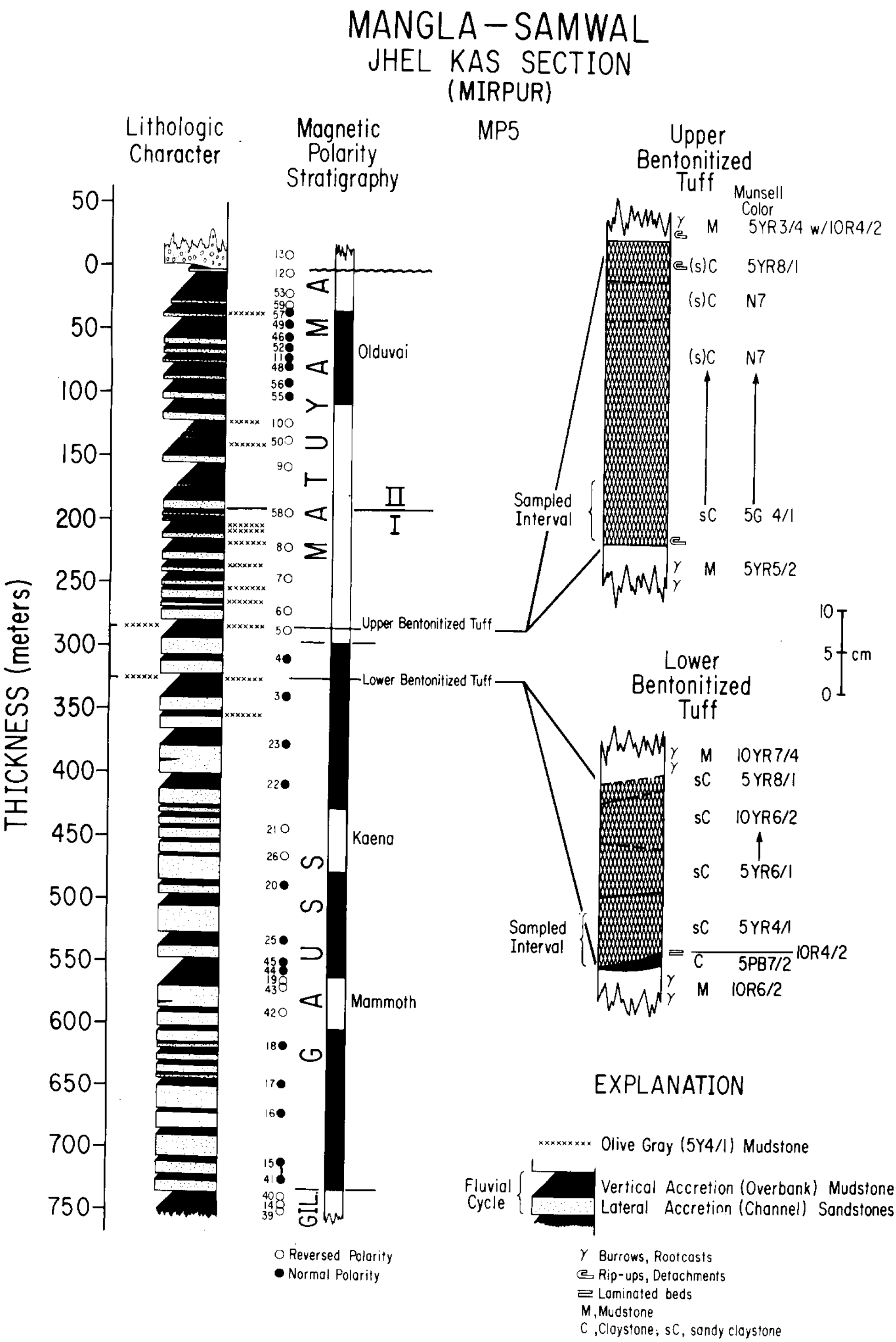


Fig.4. Stratigraphic occurrence of Upper Siwalik tuffs, tuffaceous sediments and bentonites associated with rocks of the Tatrot and Pinjor faunal zones in northern Pakistan. Each stratigraphic level has been normalized to a common paleomagnetic stratigraphy which has been erected for each locality yielding these volcanic sediments. Interpretation of the magnetic record of individual sites is presented in Fig.6.

within the dark greenish tuff by changes in color, texture and abundance of biotite. In places, the bentonite is quite impure, containing medium-grained quartz sand along with common reddish mudstone clasts.

In contrast to the lower tuff, the appearance of the upper laterally persistent tuff of the Jhelum area varies considerably. At most outcrops, however, it is easily distinguished from the lower tuff. It has abundant biotite, a feature characteristic of all of the tuffaceous sediments in Siwalik rocks which we have observed. The upper tuff may be up to 1.75 m thick, and varies in color from gray (N5-N8) to greenish-black (5G2/1) or olive-black (5Y2/1). Both upper and lower contacts are sharp and planar at most sites. As in the lower tuff, mudstone clasts are not uncommon; unlike the lower tuff, however, the upper tuff is, at most sites, divisible into two to five distinct units on the basis of size and abundance of biotite grains or color. Frequently the upper layers are harder, lighter in color, and less biotitic than the lower ones.

Though very little distinct glass was identifiable in thin section in the tuffs (possibly because of the very fine grain size), most would be termed an altered tuff, not a true bentonite. At site *11* (Rhotas Anticline) (Fig.3) the upper tuff also appeared to be partially altered; the most noteworthy feature here, however, is the striking lamination and small-scale cross-bedding displayed in its uppermost 20 cm. Thus the upper tuff, though easily distin-


MANGLA—SAMWAL
JHEL KAS SECTION
(MIRPUR)
Lithologic Character
Magnetic Polarity Stratigraphy
MP5
Upper Bentonitized Tuff
Munsell Color
THICKNESS (meters)
MATUYAMA
GAUSS
GIL.
Olduvai
Kaena
Mammoth
II
I
Upper Bentonitized Tuff
Lower Bentonitized Tuff
Sampled Interval
M 5YR3/4 w/10R4/2
(s)C 5YR8/1
(s)C N7
(s)C N7
sC 5G 4/1
M 5YR5/2
10
5 cm
0
Lower Bentonitized Tuff
M 10YR7/4
sC 5YR8/1
sC 10YR6/2
sC 5YR6/1
sC 5YR4/1
C 5PB7/2 10R4/2
M 10R6/2
EXPLANATION
Olive Gray (5Y4/1) Mudstone
Fluvial Cycle
Vertical Accretion (Overbank) Mudstones
Lateral Accretion (Channel) Sandstones
○ Reversed Polarity
● Normal Polarity
Burrows, Rootcasts
Rip-ups, Detachments
Laminated beds
M, Mudstone
C, Claystone; sC, sandy claystone

guished from the enclosing rocks and the lower bentonite, varies significantly in its mode of occurrence over the area.

Details on the mineralogy and field aspect of these two prominent tuffs in the Upper Siwalik formations can be found in D. M. Summers et al. (in prep.).

Other tuffs of the Potwar Plateau and adjacent areas

The numerous other localities of the Potwar and southwestern Kashmir which yield evidence of one or more tuffs in outcrops of Upper Siwalik rocks all share common sedimentologic features which we interpret to represent fluvial overbank or flood-basin lithofacies. In general, all tuffs and tuffaceous sediments thus far observed have color, textural and fabric properties which appear similar to those described above for the two laterally persistent horizons of the Jhelum area. Certain localities contain a much more complete stratigraphic record of volcanicity than others because of the greater frequency of tuff occurrence within a given stratigraphic interval.

The most important among these are sites located: near the villages of Pind Savikka and Kotal Kund in the eastern Salt Range (Figs.1 and 3, sites *8* and *9*); near the villages of Dheri Choan and Dheri Kot, south of Campbellpore, on the south flank of the Peshawar structural basin (Figs.1 and 6, site *2*); in the vicinity of the villages of Shahpur and Dhok Saiydan along the Soan River south of Rawalpindi (Figs.1 and 6, sites *3* and *5*) and along the Jhel Kas, south of New Mirpur, Kashmir (Figs.1 and 3, site *17*). Several other excellent exposures of Lower and Middle Siwalik rocks have been observed (Figs.1 and 3) and are discussed below, but those mentioned above represent critical localities which we feel may provide important tectonic, sedimentologic, and paleontologic information on the character of the Upper Siwalik fluvial environment and the nature and timing of the Potwar Plateau, Peshawar intermontane basin and Salt Range structural development.

Pind Savikka and Kotal Kund area. The doubly plunging syncline in which the Pind Savikka tuff horizons lie is located 42 km southwest of the town of Jhelum, Gujrat District, Punjab, Pakistan, at latitude 32° 43′, longitude 73° 22′. The syncline, known as the Bunha/Kotal Kund syncline after the

Fig.5. Magnetic-polarity stratigraphy of the Siwalik succession as exposed along the northern flank of the Mangla—Samwal anticline in the vicinity of New Mirpur, southwestern Kashmir. Schematic representation of lithologic character of the lower and upper bentonitized tuffs (discussed in text) is illustrated at right. From 3—5 oriented rock specimens were collected from each site in the measured section according to procedures outlined in 1975 by N. M. Johnson et al. (Geol. Soc. Am. Bull., 86: 5—12) and Opdyke et al. (1979). In the latter, statistical validity of the paleomagnetic character of the sampling program in this section is discussed.

Bunha River and the hamlet of Kotal Kund which lies within it, is in the eastern limit of the Salt Range (Figs.1 and 3).

The most complete stratigraphic development of any exposed Upper Siwalik tuff sequence is located on the northern limb of the Kotal Kund syncline along the footpath between the villages of Pind Savikka and Kotal Kund, where steeply dipping sandstone beds create a rugged topography of hogback ridges dissected by sandy ravines (Fig.7).

Thirteen bentonized volcanic tuff horizons are found at the Pind Savikka site, spanning a stratigraphic interval of 352 m. The ash horizons are distinguishable from the enclosing rocks on the basis of their light-gray color (Munsell Color N6 to N8), texture, fabric and the presence of biotite. The bentonitized tuffs are generally less competent than the enclosing rocks, and are thus subject to deformation: thickening, thinning and slumping are common among the Pind Savikka ashes, giving any particular tuff different aspects at different exposures (Frost, 1979).

Fluvial lateral-accretion (channel) facies at the Pind Savikka site are 4—10 m thick and display poorly developed cross-bedding. The two conglomeratic channel deposits (see Fig.8, lithologies 1 and 166) are most characteristic of gravel sheets associated with ephemeral braided streams. The horizontal laminations of other channel deposits (see Fig.8, lithologies 23 and 102) are also indicative of channel-bar deposits in ephemeral sand beds or braided streams. A number of thin sandy horizons, interpreted as levee or crevasse splay occur throughout the Pind Savikka interval (Fig.8). These thin sands fine upwards into vertical-accretion flood-plain deposits which usually evidence some degree of pedological maturation.

In stratigraphic section 1 (Fig.8) the presence of burrows, roots and some krotovina are evidence of subaerial exposure and homogenization of soil material, the first steps in soil "ripening" (Pons and Zonneveld, 1965). Kankars, suggestive of "B"-horizon calcium-carbonate accumulation, are developed in many of the vertical accretion deposits. When well-developed, kankars consolidate and form a continuous calcic horizon (caliche) as occurred in lithology 168 (Fig.8).

Stratigraphic section 2 (Fig.8) illustrates more intense soil ripening than section 1. Burrows, roots and kankars are almost ubiquitous throughout the vertical accretion deposits. Some of the levee or splay sands also show bioturbation and disruption of their original lamination. Red-brown claystones, common in section 1, are absent, and in their place are yellow-brown silts and claystones exhibiting black Mn and Fe mottling, an indication of poorly drained edaphic environments.

Although stratigraphic section 2 encloses the same 40-m stratigraphic interval as stratigraphic section 1, plus an additional 60 m, there are only two volcanic tuffs in section 2 (the stream proximal environment) and five ashes in section 1 (the backswamp environment). This confirms the hypothesis that section 1 was a stream-distal site where primary air-fall tuffs deposition could be preserved easily. Section 2 was a stream-proximal site.

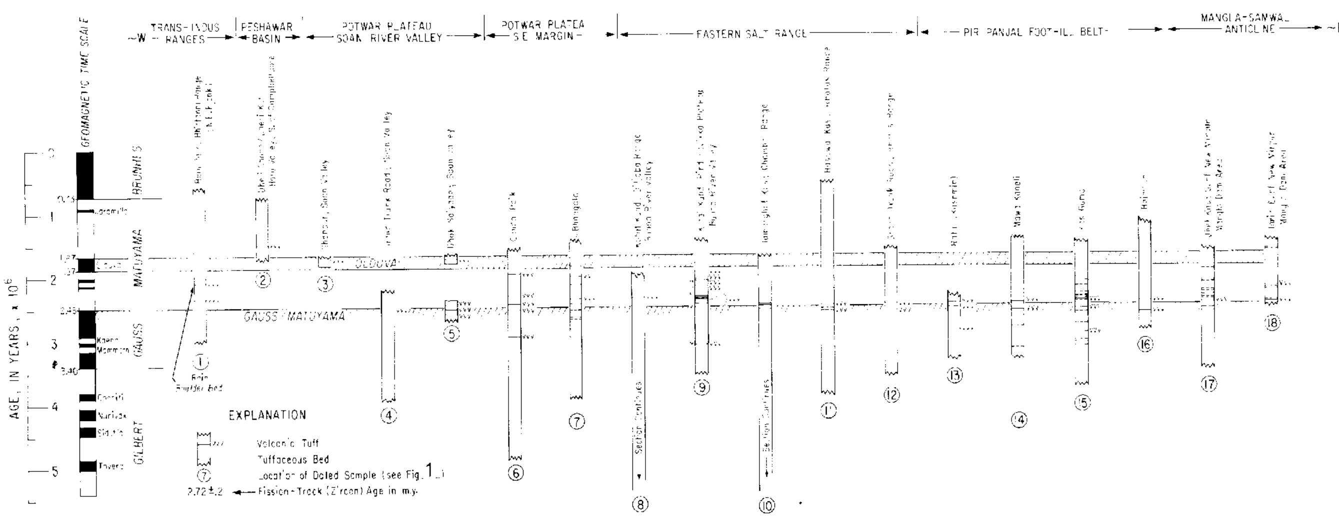


Fig. 6. Chronology of selected Siwalik Group localities in northern Pakistan which contain volcanic deposits. These tuffs have been used to constrain the paleomagnetic reversal stratigraphy which has been developed for the enclosing sediments. See Fig. 1 for locations. Data for sites *3–5* from J. Moragne (pers. comm.), for sites *6*, *7*, *12–15* from R. Raynolds (pers. comm.).

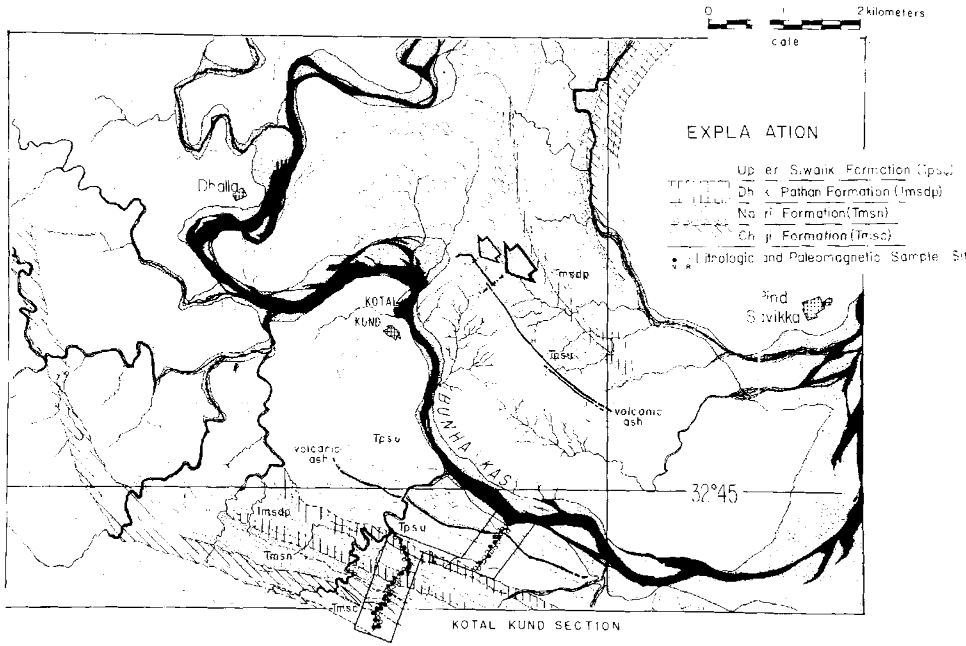


Fig.7. Schematic location map of Upper Siwalik tuff outcrops in the vicinity of Kotal Kund and Pind Savikka, District Gujarat, Punjab. Refer to Fig.8 for lithostratigraphy of Sections 1 and 2 and Fig.9 for a paleomagnetic interpretation.

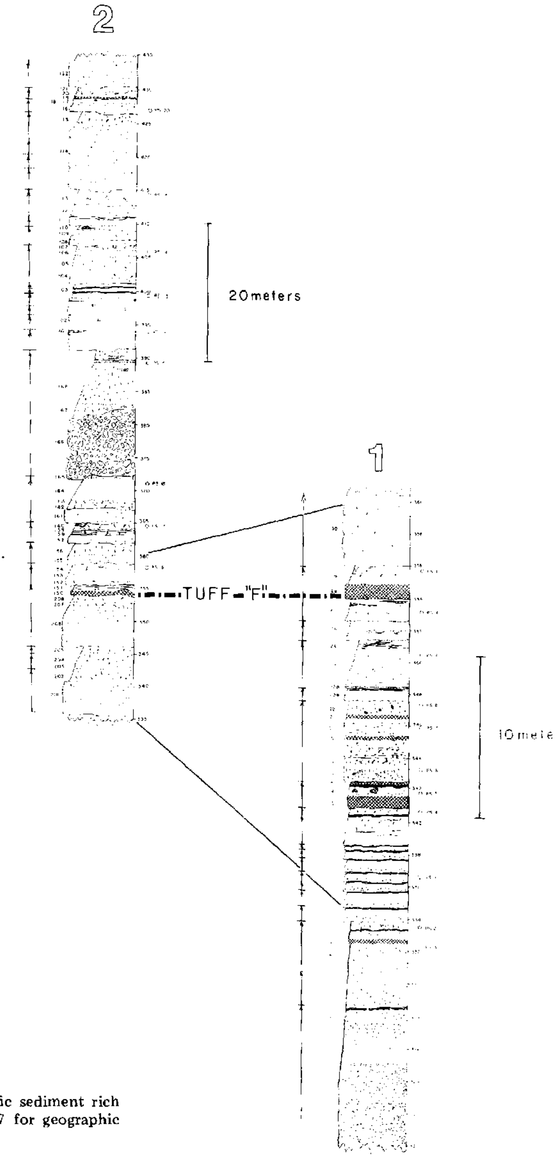


Fig.8. Lithostratigraphic detail of stratigraphic section through volcanic sediment rich interval of Upper Siwalik formations, Kotal Kund syncline. See Fig.7 for geographic detail and Fig.9 for a paleomagnetic interpretation.

In other areas of the Potwar Plateau, fewer tuff horizons are found than at Pind Savikka. Examination of the depositional environment at these locations may show that they were nearer to ancient stream channels than was the Pind Savikka area. Paleoenvironment rather than anomalously high sedimentation rate or other structural controls seems to be the major factor in determining tuff preservation.

The magnetic polarity zonation of the Pind Savikka section is shown in Fig.9. The Pind Savikka magnetic reversal zonations indicate that a reversed magnetozone overlies a normal magnetozone. The normal magnetozone contains two brief reversed subzones, and the reversed magnetozone contains one short normal subzone. This magnetic reversal pattern matches that established for the entire Gauss reversed magnetic chron and the lower

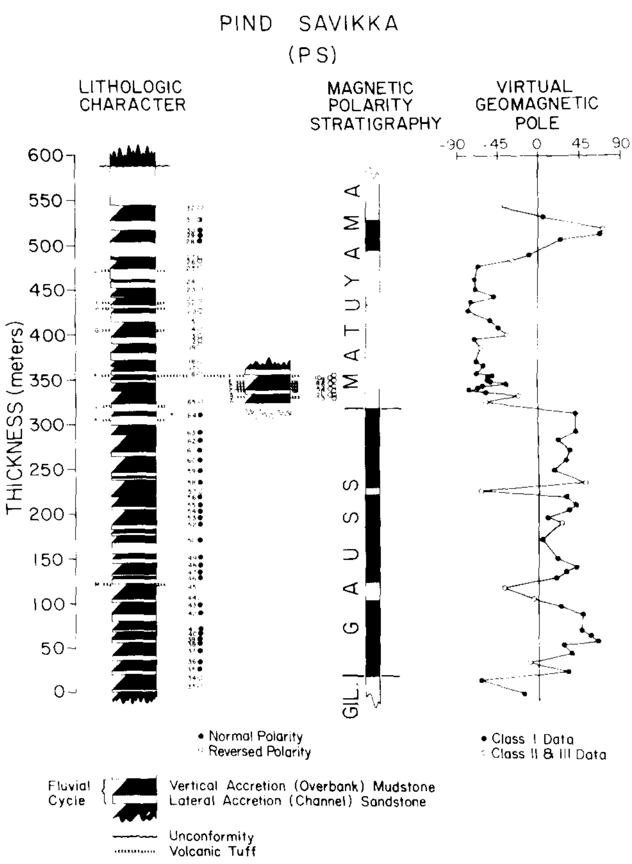


Fig.9. Magnetic polarity stratigraphy of the Pind Savikka area of the Kotal Kund syncline. See Opdyke et al. (1982) for similar treatment.

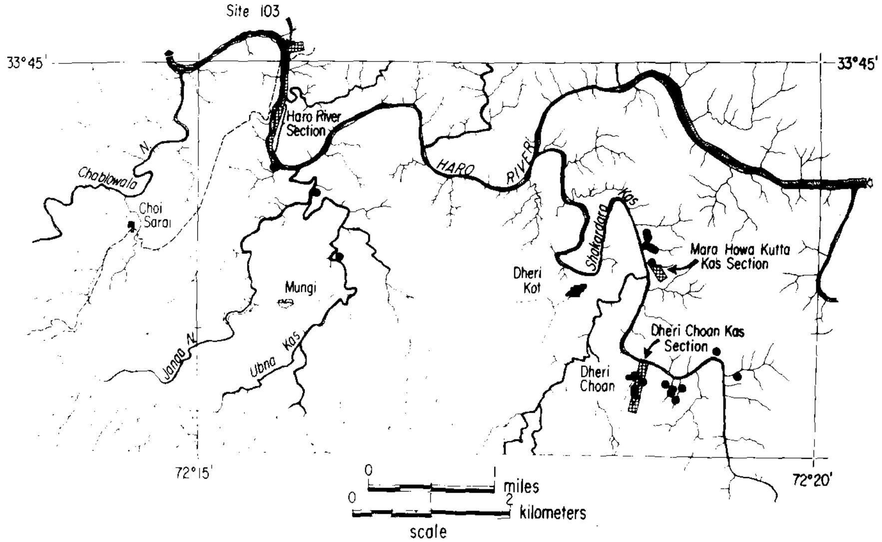


Fig.10. Outline map of the Campbellpore basin section (Fig.11) which has been studied in our preliminary attempts at developing a chronology for the Peshawar Basin sedimentary record. The Campbellpore area represents a geographically confined region on the south flank of the much larger Peshawar structural basin. Localities in Fig.11 are illustrated. See Fig.1, locality *2*, for regional setting. Tuff sites DK-2 and DK-3 are indicated along the right bank of the Shakardara Kas in the eastern part of the map area near the village of Dheri Kot. The three stratigraphic sections indicated on this figure are illustrated in Fig.11.

half of the Matuyama normal magnetic chron, spanning a time period from 3.40 to 1.67 m.y. (Fig.8).

Campbellpore area. One hundred and sixty-five kilometers to the northwest of Jhelum, isolated exposures of tuff occur to the south of the town of Campbellpore (renamed Attock in late 1979) (Allauddin et al., 1971; Jehan et al., 1975; Opdyke et al., 1979) (Fig. 1, site *2* and Fig.10). The Campbellpore tuff is more difficult to distinguish from its enclosing rocks and it is lithologically quite different from either bentonite of the couplet discussed above. The enclosing rocks are pink and tan banded claystones (De Terra and Teilhard de Chardin, 1936), whereas the tuff tends to be very light-gray (N8-N7), pinkish gray (5YR8/1), or yellowish gray (5Y8/1), and only sparingly biotitic (Fig.11). The tuff is 1—2 m thick and consists

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Fig.11. Paleomagnetic reversal stratigraphy of the Campbellpore area of the Peshawar Basin. This dominantly lacustrine sequence lies within the middle Matuyama Magnetic Chron with a zircon fission-track age of 1.6 ± 2 m.y. determined from the bentonitized tuff occurring just above the top of the Olduvai normal polarity site. See Fig.10 for details of the geographic context of sample sites.

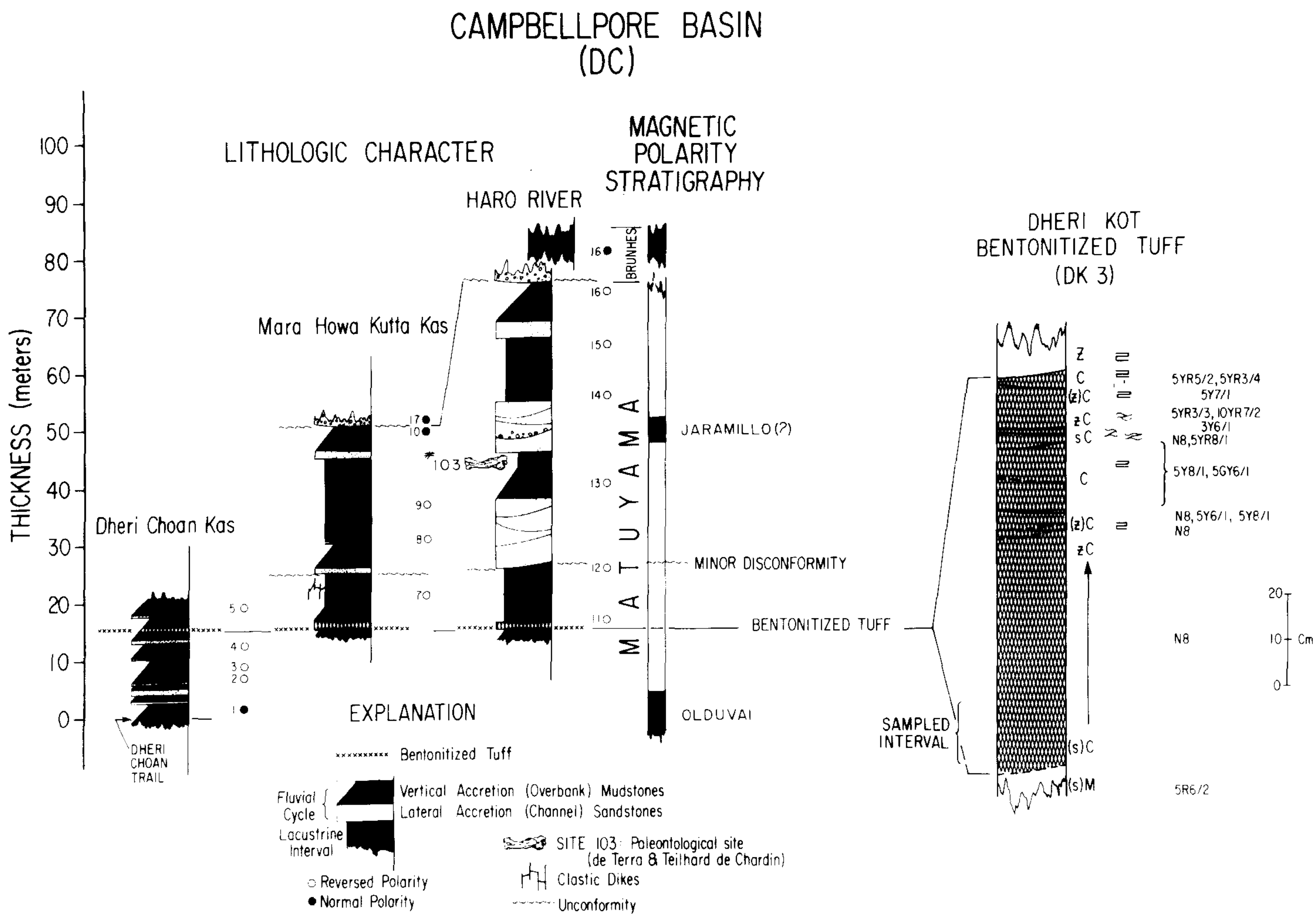

Fig.11. Explanation on p.78.

of as many as a dozen units distinguishable by subtle color changes and sometimes bounded by waxy brown clay or hard white (siliceous?) laminae. Lenticular bedding, small-scale normal faulting, and burrowing occur at various sites.

The site is important in that the tuff lies near the base of the Cenozoic basin-fill sediments which occupy the late orogenic Peshawar basin. Additionally, a rather prolific Pinjor-aged site along the banks of the Haro River (Fig.10, site *103*, after De Terra and Teilhard de Chardin, 1936) contains one of the more complete faunal assemblages available for this Late Pliocene—Early Pleistocene faunal zone.

Soan Valley, south of Rawalpindi. At the time of this writing, mapping of the Shahpur/Dhok Saiydan area has been completed and preliminary interpretations made of the implications of structural deformation in the area based on a magnetic-polarity stratigraphy (Raynolds, 1980) and the fission-track data reported below.

The tuff stratigraphy is complicated by the apparent involvement of the area in significant tectonic movement. Sediments carrying portions of the early Upper Siwalik volcanic record lie in angularly unconformable contact with flat-lying Siwalik Group rocks containing tuffs representative of the latest volcanic events. This apparent chronology is discussed below.

Jhel Kas area, New Mirpur, Kashmir. A magnetic polarity stratigraphy of the Siwalik section exposed along the Jhel Kas south of New Mirpur, Kashmir, has been reported earlier based on two preliminary fission-track ages determined on zircon from the two laterally persistent tuffs mentioned above (Visser and Johnson, 1978; Opdyke et al., 1979; Johnson et al., 1979). These preliminary dates have been now refined and additional localities in the Jhelum area have been studied, the results of which are reported below. The Jhel Kas area of the Mangla—Samwal anticline (Figs.3 and 5) has one of the best Late Pliocene and Early Pleistocene Siwalik stratigraphic sequences which we have had the opportunity to study.

Bhilomar and Qadirpur. One hundred and twenty kilometers southwest of Rawalpindi in the stratotype area of the Chinji and Nagri Formations a single bentonite bed crops out in the vicinity of the villages of Bhilomar and Qadirpur (Fig.12). This unit can be traced another 2 km to the northeast where it intersects the Gabhir Kas (River) (see Fig.12).

The Bhilomar/Qadirpur bentonite occurs in the middle of the Nagri Formation at its stratotype exposures (the Gabhir Kas) and is poorly exposed. We have detailed the magnetic reversal stratigraphy and ash stratigraphy of this sequence elsewhere (N. M. Johnson et al., 1982) and have constrained portions of that magnetic record by means of the fission-track age which is reported below.

The outcrop of the Bhilomar/Qadirpur bentonite is generally obscured by slump and recent agricultural activity in the area. One locality, a test

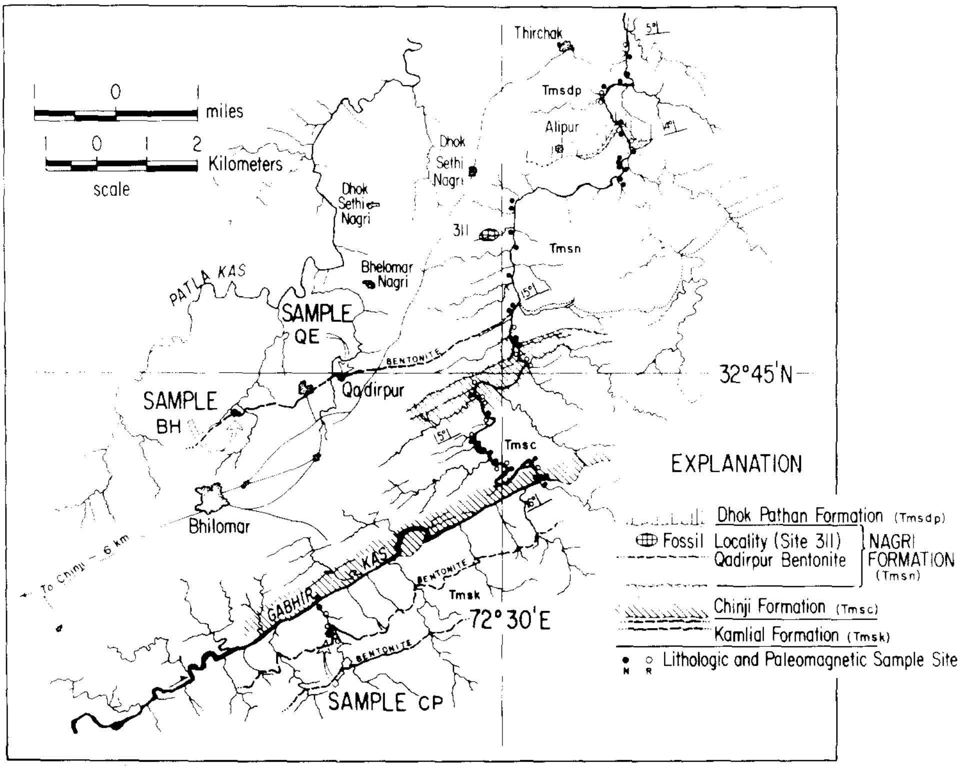

Fig.12. Schematic geologic and location map of the Siwalik Group exposed in the Chinji and Nagri Formation stratotype, southern Potwar Plateau (see Fig.1). Volcanic sediments of the Bhilomar/Qadirpur ash and the Chita Parwala ash complex are shown. The date reported on the B/Q ash came from site sample BH northeast of the village of Bhilomar.

pit constructed by a commercial operator at the site of an earlier excavation, was measured and sampled by us. The details of the ash stratigraphy of this site (sample QE, on Fig. 12, 0.5 km east of Qadirpur) are illustrated on the schematic stratigraphic column of the Chinji and Nagri Formations as exposed along the Baghir Kas (Fig.13).

The Bhilomar/Qadirpur bentonite may be equivalent to that found at Mankiala (Bhola, 1948) but at present we have no certainty that this is the case. No other occurrences of the Bhilomar/Qadirpur bentonite are presently known. The important fossil localities in the vicinity of Khaur 65 km to the north, although of equivalent age, do not seem to contain any volcanic sediments. At present the source of this volcanic deposit is unknown.

Other early Siwalik bentonites. We have located and sampled several other lower and middle Siwalik bentonite deposits. Among these are deposits from Mankiala (Bhola, 1947), Hatar (Akbar et al., 1964) and Phadrar (Bogue and Schmidt, 1961; Ali and Shah, 1962; Akbar et al., 1964). None of

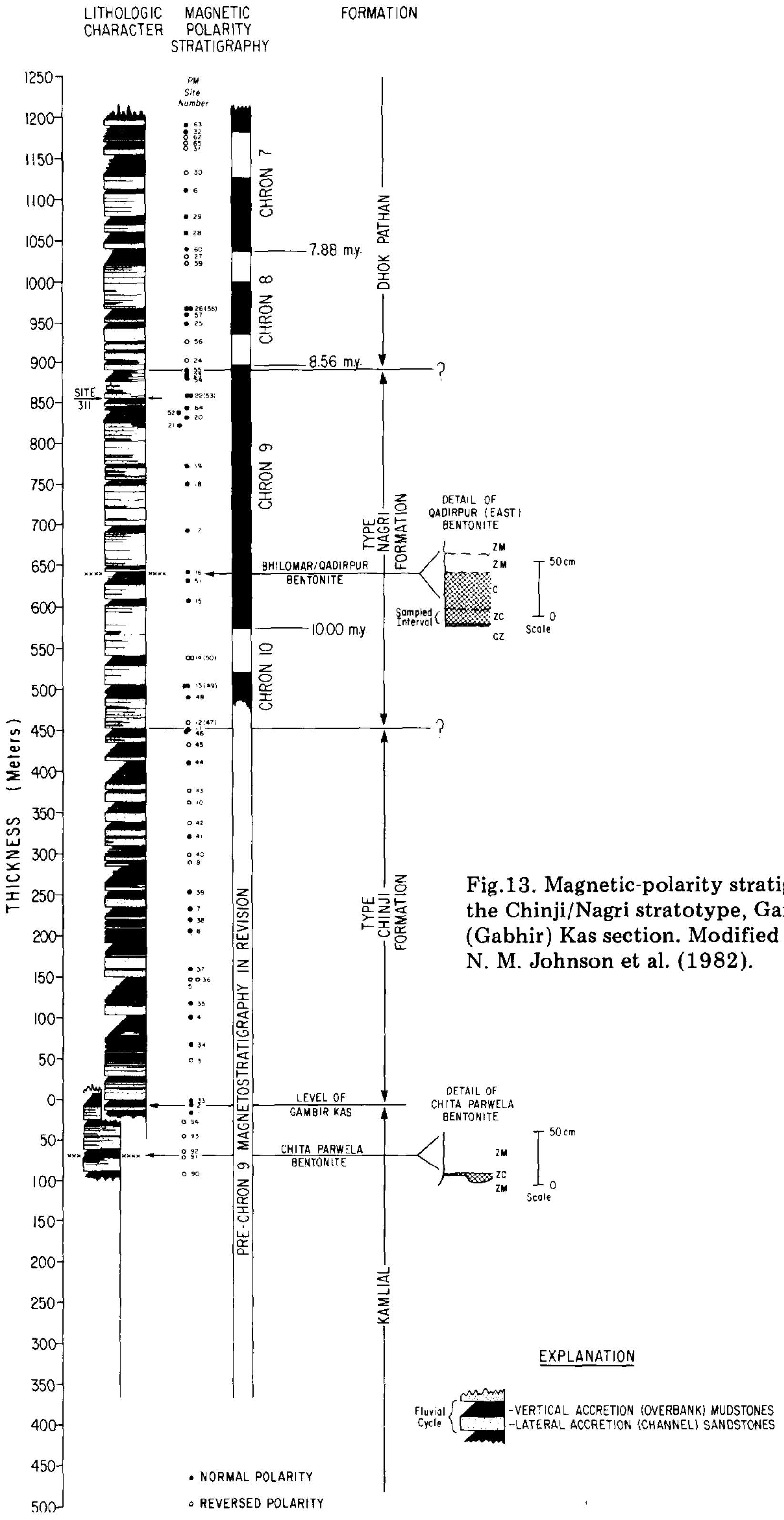

Fig.13. Magnetic-polarity stratigraphy of the Chinji/Nagri stratotype, Gambir (Gabhir) Kas section. Modified from N. M. Johnson et al. (1982).

these, however, have produced datable zircons or apatites at the present time, although our efforts in this regard are continuing.

FISSION-TRACK DATING TECHNIQUES

Zircon concentrates from tuffs were prepared from bulk samples of 5—10 kg which were dried, crushed and dispersed in water. Following wet sieving to remove clay minerals, the mineral concentrate was further sized to separate the 60—200-mesh fraction. Heavy-mineral fractions of the 60—200-mesh split were isolated with bromoform and methylene iodide. Final concentration was accomplished using a magnetic separator. About 0.3 g of generally euhedral zircons were recovered from about 10 kg of tuff.

Zircon microphenocrysts associated with the tuffs of the Upper Siwaliks are generally clear to slightly pink, doubly terminated and euhedral (Fig.14). Crystal lengths range from 0.1 to 0.3 mm. Numerous grains contain a variety of fluid- and crystal-phase inclusions. A few zircon grains are darker red than

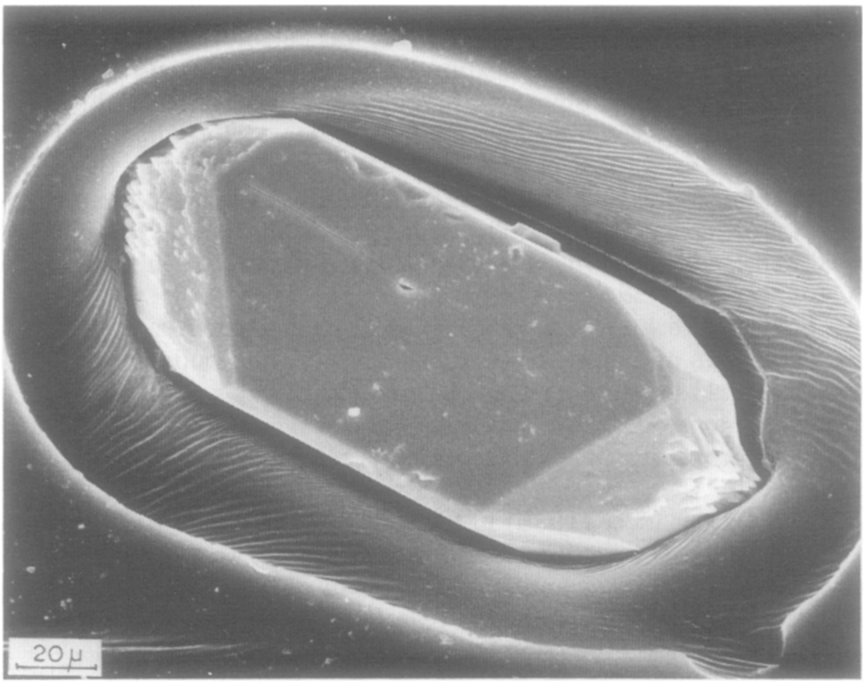

Fig.14. Scanning electron photomicrograph of euhedral zircon grain from the lower laterally extensive tuff from the Jhel Kas exposures south of New Mirpur, Kashmir (locality *17*, Figs.1 and 6; see detail of lower bentonitized tuff on Fig.5). Grain is partially embedded in teflon mounting medium. Etched grain features due to preparation procedures in which the grain mount is etched in a NaOH-KOH eutectic melt. (Original photomicrograph at 500 × by G. D. Johnson; Sample MP 3W.)

the common pink zircon grains and have a much higher density of spontaneous fission tracks. This suggests that these grains are old and detrital. They have, therefore, been excluded from the set under study. It seems probable that the light-pink and clear zircon grains are cogenetic with the ash falls responsible for the formation of the tuffs.

Zircon (as opposed to glass or apatite mineral phases) was chosen for fission-track dating of the Siwalik volcanic sediments for several reasons. Zircon is abundant in these tuffs and is consistently present. More importantly, zircon is fairly resistant to the process of thermal annealing (track fading). Present estimates (e.g., Briggs et al., 1979) place the long-term (about 10^6 years) annealing temperature of zircon at about 175—200°C. This value is higher for thermal events of lesser duration. Thus, the suites of zircons obtained, cogenetic as they appear to be with the ash falls, should date the eruption of the latter. Further, burial of these tuffs to much less than 1 km for times on the order of 10^6 years should have had no detectable effect on the spontaneous track densities of these zircons. They should record a primary age.

Zircons were prepared for dating using standard procedures (Naeser, 1978), and the grains were dated using the external detector method of recording induced tracks. In general, counting was performed with the aid of an optical microscope at a magnification of 1000 × using transmitted light and a 100 × oil-immersion objective. Samples were irradiated in the USGS TRIGA reactor at Denver, and the neutron doses (determined by C. W. Naeser) were monitored using N.B.S. Glass SRM 962, employing the N.B.S. copper foil calibration. Fossil fission tracks were etched in a eutectic melt of KOH and NaOH at 250°C for 2—3 h. Exceptions are sample BK-1, which was etched at 210°C for 27 h, and samples KK and CA, which were etched at 230°C for about 20 and 15 h, respectively.

Several points of technique peculiar to such young air-fall zircons should be noted. The zircon microphenocrysts recovered for this study are euhedral, and when mounted on a slide they lie on one of their four prism faces (parallel to the c-axis) (Fig.14). This guarantees attainment of the optimum orientation for proper track etching, which is required if true spontaneous track densities are to be revealed (Gleadow and Lovering, 1978). Further, as pointed out by Gleadow (1980) in his study of the KBS tuff, the dating of very young zircons is beset by a number of problems. The most significant of these are: (1) very slow etching rates as a result of low accumulated radiation damage leading to incompletely revealed tracks, and (2) few tracks present per etched surface (leading to counting bias in favor of higher track-density grains). Fortunately, in the case of these Siwalik zircons, uranium contents are high enough to allow thorough revealing of tracks using reasonable etching times (Fig.15). In addition, most etched surfaces contain at least several tracks (Fig.15), lessening the possibility of a too old age resulting from observer bias away from zero-track grains.

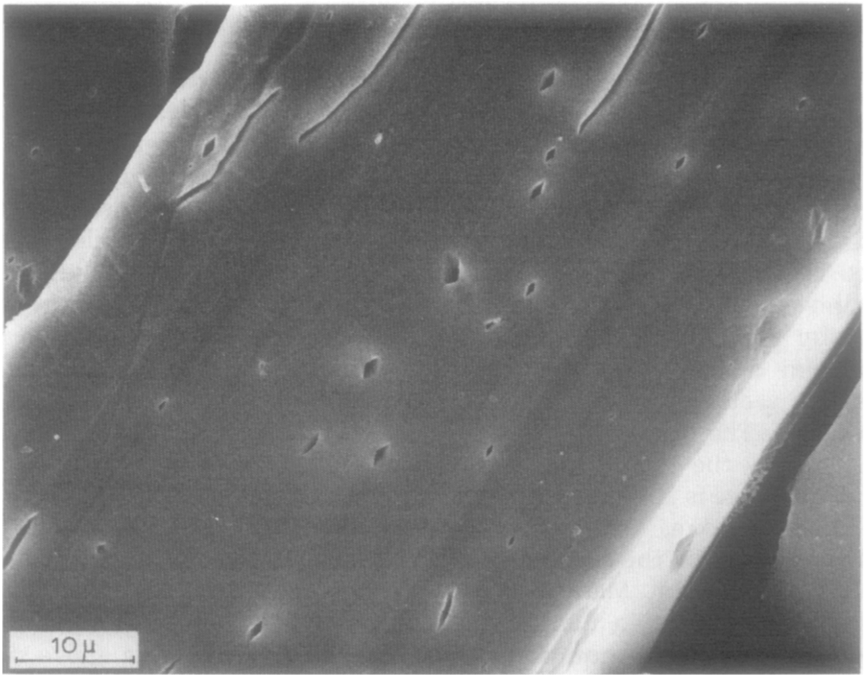

Fig.15. Scanning electron photomicrograph of NaOH—KOH etchant enhanced spontaneous fission tracks developed in euhedral zircon grain from the same locality as in Fig.14. Grain is mounted in teflon as in Fig.14 and contains etchant-enhanced inclusions (large curved features) in addition to abundant diamond-shaped fission tracks. Grain is slightly zoned as is evident by higher concentration of tracks in early phase portion of crystal. (Original photomicrograph at 1500 × by G. D. Johnson; Sample MP 3W.)

FISSION-TRACK AGES

Fig.6 summarizes the tuff stratigraphy observed in the eighteen stratigraphic sections of Upper Siwalik deposits thus far studied in the Potwar Plateau and adjacent areas. Those tuffs which have been dated herein (Table I) are indicated.

These fission-track ages, although representing only a portion of the datable pyroclastic record in the upper portion of the Siwalik Group, allow some chronometric constraints to be applied to the stratigraphic succession and places the magnetostratigraphy firmly in the polarity reversal time scale.

Pind Savikka and Kotal Kund area

The implications of the fission-track ages (2.52 ± 0.16 m.y.) on the paleomagnetic stratigraphy of the Kotal Kund syncline and its interpretation are discussed elsewhere (N. M. Johnson et al., 1982).

Campbellpore area

The stratigraphic sequence of Upper Siwalik rocks displayed in the Campbellpore area contains unequivocal Pinjor fauna (De Terra and Teilhard de Chardin, 1936; De Terra and Patterson, 1939; Opdyke et al., 1979). The only mammalian fauna thus far described from this area is that of De Terra and Teilhard de Chardin (1936) (their site # 103; see also Figs.10 and 11). This fauna is of typical Pleistocene affinity and has also been included along with a study of the magnetic stratigraphy in Opdyke et al. (1979); however, more recent data allow a more secure interpretation of the stratigraphy and magnetostratigraphy of the Campbellpore basin. De Terra and Teilhard de Chardin's site # 103 lies some 25 m higher in the local stratigraphic section than the bentonitized tuff from which we report the 1.61-m.y. age. The paleomagnetic transition from normal to reversed polarity lying below the tuff in all likelihood is the Upper Olduvai transition, whose inferred age is 1.67 m.y. (Mankinen and Dalrymple, 1979).

The short-duration, normal-magnetized magnetozone lying at the 50-m level (Fig.11) may be the Jaramillo subchron. The polarity of paleomagnetic site DC10 (see Fig.11, Mara Howa Kutta Kas section) is, beyond doubt, normally magnetized. No neighboring samples lying above or below site DC10 were found to be normally magnetized (site DC17, lying above site DC10, occurs in later Pleistocene terrace materials and is thus temporally more closely related to site DC16 in the Haro River section (Fig.11).) We feel that since site DC10 lies directly beneath the Brunhes-age disconformity in contiguous section and since a correlative normal polarity zone was not detected in the section along the Haro River which contains De Terra and Teilhard de Chardin's paleontological site 103, it is possible that this normal polarity zone represents Brunhes-aged remagnetization. Even if the Jaramillo event is not present in our section, however, site 103 nevertheless must be younger than the top of the Olduvai normal event (1.67 m.y.).

The maximum average sediment accumulation rate which we have thus far observed in the Pakistani Siwalik Group is 100 cm/1000 yr (Khan and Opdyke, 1981). We feel that there is insufficient sedimentologic evidence for sedimentation rates as high as even half of this value at the Cambellpore site. Given these circumstances and assuming that polarity of site DC10 is erroneous, the reversely polarized interval comprising the bulk of the Campbellpore section must be older than the Jaramillo normal event. Therefore, site 103 must be older than 0.97 m.y. and would fall into the 0.97—1.7 m.y. time interval and probably nearer the mid-point of this interval. This fauna thus lies in Matuyama-aged reversely magnetized sediment above what is probably the Olduvai subchron and above the tuff dated herein at 1.61 m.y. A probable date of 1.5 m.y. for this important faunal locality appears to be a reasonable estimate.

TABLE I

Fission-track ages of zircon microphenocrysts separated from bentonitic water-laid tuffs of the Upper Siwalik Subgroup, northern Pakistan (localities of these tuffs are described in text and illustrated on Figs.1 and 6)

Sample No.	Magnetic polarity of enclosing sediment	Trial No.	No. of grains	Spontaneous tracks		Induced tracks		Neutron flux ($\times 10^{15}$ n/cm^2)	Correlation coefficient (r)	Age[1] (m.y.) ± 2σ
				track count (N_s)	track density N_s (cm^{-2})	track count (N_i)	track density N_i (cm^{-2})			
Upper bentonitic tuff, Jhelum area										
MP-4 (DF878)	R	1	8	156	4.88×10^5	2293	1.44×10^7	1.18	0.827	2.40 ± 0.20
Lower bentonitic tuffs, Jhelum area										
D-1 (DF873)	N	1	8	163	5.22×10^5	2216	1.28×10^7	1.19	0.926	2.62 ± 0.18
		3	7	81	4.16×10^5	1121	5.76×10^6	1.19	0.931	2.57 ± 0.18
MP-3W (DF876)	N	1	8	259	7.77×10^5	3746	2.25×10^7	1.24	0.831	2.56 ± 0.21
B (DF880)	N	2	9	129	5.54×10^5	1577	6.78×10^6	1.16	0.902	2.84 ± 0.34
BK1 (DF709)	N	1	6	111	5.71×10^5	1498	7.70×10^6	1.29	0.985	2.86 ± 0.18
Bentonitic tuff, Campbellpore area (Peshawar Basin)										
DK-2	R	1	11	52	1.70×10^5	944	3.08×10^6	0.977	0.710	1.61 ± 0.10
Tuff, Shahpur area, south of Rawalpindi (Soan Syncline)										
Cap Ash (CA)	N	1	11	158	1.83×10^6	608	7.05×10^6	0.206	0.669	1.60 ± 0.18
Bentonitic tuff, Bain Pass area (Bhitanni Range, Trans-Indus)										
BP-2	R	1	7	109	2.26×10^6	1145	2.37×10^7	0.981	0.994	2.79 ± 0.24
Bentonitic tuff, Kotal Kund and Pind Savikka area (Kotal Kund Syncline, eastern Salt Range)										
PS-H1	R	1	7	85	1.27×10^6	1217	1.81×10^7	1.01	0.579	2.11 ± 0.30
KK	R	1	6	137	6.9×10^5	1341	1.35×10^7	0.826	0.766	2.52 ± 0.16

[1]Precision estimate calculated according to procedures outlined by McGee and Johnson (1979).
$\lambda_F = 7.03 \times 10^{-17}$ yr^{-1}; $\lambda_D = 1.551 \times 10^{-10}$ yr^{-1}; $\sigma = 580 \times 10^{-24}$ cm^2; $I = 7.252 \times 10^{-3}$

Soan valley

The age of the tuff of the Lei Conglomerate south of Rawalpindi (1.60 ± 0.18 m.y.), in the vicinity of Shahpur, seems to make it nearly contemporary with those of the Campbellpore area some 75 km to the west and probably equivalent to the Jari tuff which is found in the Mangla—Samwal anticline near New Mirpur (see uppermost olive-gray mudstone, a tuffaceous sediment, in Fig.5 at the 40-m interval from the top of the section).

Jhel Kas Area, New Mirpur, Kashmir

Fig.5 represents the magnetic-polarity zonation of the Siwalik section as exposed in the Mangla—Samwal anticline south of New Mirpur, southwestern Kashmir. The magnetic-polarity transition located at the 295-m level must represent the Gauss and Matuyama transition, the present best estimate of which is 2.48 m.y. (Mankinen and Dalrymple, 1979). Faunas from the Mirpur area confirm a Late Pliocene or Early Pleistocene age for the sequence.

Nagri stratotype

A fission-track age of 9.46 m.y. ± 0.59 (Table II) is determined on zircon phenocrysts from the Bhilomar site of the Bhilomar/Qadirpur bentonite (Fig.12). The bentonite lies within a long normal magnetozone which extends below the tuff for some 80 m and overlies it for an additional 250 m or more. The long normal polarity event recorded in the Nagri Formation and encompassing the Bhilomar/Qadirpur bentonite is correlated to magnetic chron 9 (Fig.13). The rationale for this interpretation and its significance for the development of a magnetic stratigraphy for the Nagri Formation and younger Siwalik formations is discussed in N. M. Johnson et al. (1982).

VOLCANIC STRATIGRAPHY AND SOURCE

To date, eighteen stratigraphic sections of Upper Siwalik strata containing tuffs, tuffaceous sediments and bentonites have been analyzed (Figs.1 and 6). In several of these there is an excellent record of tuff (or bentonitized tuff) and olive-gray bentonitic mudstone development. The newly erected biochronology of the Upper Siwaliks given by Opdyke et al. (1979) suggests that the lower limit of the Pinjor faunal zone may be approximated by the Gauss and Matuyama polarity transition and, as evidenced in this paper, corresponds to the apparent mode of the record of volcanicity that we have recognized in this analysis of Upper Siwalik volcanic sediments.

The development of tuffs in the upper part of the Siwalik Group represent the in situ alteration of volcanic primary air-fall and reworked material.

TABLE II

Fission-track ages of zircon microphenocrysts separated from the water-laid Bhilomar—Qadirpur bentonite of the Nagri Formation stratotype, south Potwar Plateau, Pakistan (localities of this tuff sequence are described in text and illustrated on Fig.15)

Sample No.	Magnetic polarity of enclosing sediments	Trial no.	No. of grains	Spontaneous tracks		Induced tracks		Neutron flux ($\times 10^{15}$ n/cm^2)	Correlation coefficient (r)	Age[1] (m.y.) $\pm 2\sigma$
				track count (N_s)	track density N_s (cm^{-2})	track count (N_i)	track density N_i (cm^{-2})			
Bhilomar—Qadirpur bentonite										
BH	N	1	7	118	8.75×10^5	399	2.95×10^6	1.07	0.816	9.46 ± 0.59
BH	N	2	9	156	7.51×10^5	643	3.09×10^6	1.13	0.655	8.20 ± 0.71

[1]Precision estimate calculated according to procedures outlined by McGee and Johnson (1979).
$\lambda_F = 7.03 \times 10^{-17}$ yr^{-1}; $\lambda_D = 1.551 \times 10^{-10}$ yr^{-1}; $\sigma = 580 \times 10^{-24}$ cm^2; $I = 7.252 \times 10^{-3}$.

Syn- and late orogenic volcanism is unknown in the Himalayas and no Pliocene to Quaternary volcanic rocks have been observed in any of the Himalayan terrane. A number of Pliocene and Quaternary volcanic centers are known in Afghanistan (Vikhter et al., 1978; Bordet, 1972a, b, 1975) and in Baluchistan to the west (G. D. Johnson, 1982). However, the distance of greater than 1000 km of most of these volcanic areas from the Potwar area of Pakistan makes them improbable sources for the upper Siwalik tuffs.

One of these volcanic centers, however, lies only 600 km west of the Jhelum area. The Dacht-e-Nawar volcanic complex occurs associated with a large N—S trending graben in the Hazardadjat spur of the Kindu Kush of Afghanistan (Bordet, 1975). This area, some 175 km southwest of Kabul and 60 km west of Gazni, represents the largest known Pliocene to Quaternary center of volcanism on the margins of the Indian lithospheric plate.

The rocks of the Dacht-e-Nawar, associated with several large stratovolcanoes, explosion craters with associated welded tuffs, and explosion breccias and domes, are primarily andesites to rhyodacites. Although some 50 independent volcanoes have been recognized in the Dacht-e-Nawar (Bordet, 1975), only a few have been dated.

The age disposition of bentonites and olive-gray bentonitic mudstones from upper Siwalik beds of the Potwar area of Pakistan and the available age determinations on several dacites and andacites from the Dacht-e-Nawar area (Bordet, 1975) are illustrated in Fig.16. The volcanic sediments of the Siwalik Group provide a distal record of inferred explosive volcanic activity

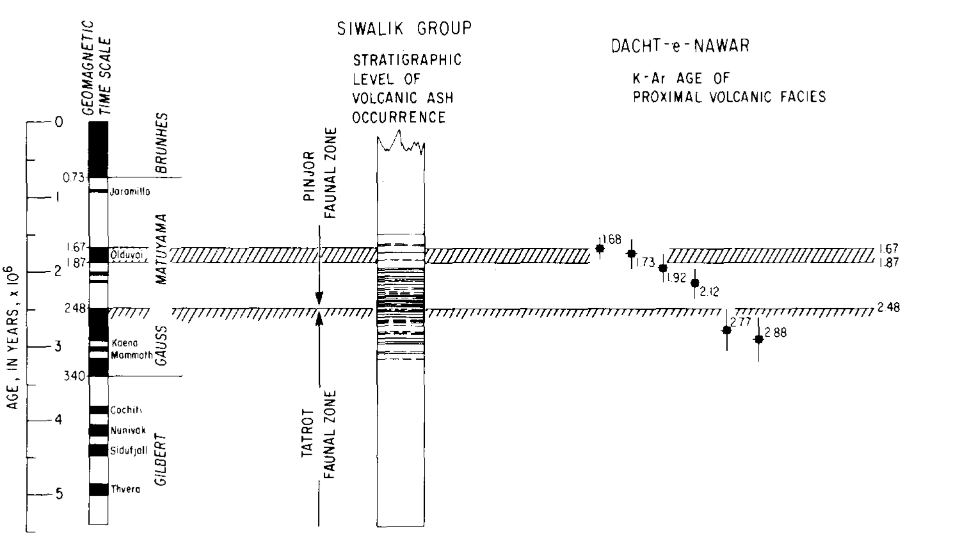

Fig.16. Comparison of radiometric ages determined from southern Dacht-e-Nawar area of Afghanistan (data from Bordet, 1975), the fission-track ages determined on the lower and upper bentonitized tuffs of northern Pakistan, and the interpolated ages of all volcaniclastic sediments recognized in the Upper Siwaliks discussed in the text.

of some source which, in considering paleowind patterns, in all probability lies to the west of the Potwar. The striking correlation seen between the apparent age of tuff development in the upper part of the Siwalik Group and the recorded periods of activity of the Dacht-e-Nawar suggests a cause-and-effect relationship. That is, the Dacht-e-Nawar volcanic center seems a plausible source for the tuff deposits of the Upper Siwalik Subgroup in the Potwar Plateau.

SUMMARY

(1) A number of datable volcanic tuff horizons occur within the Siwalik Group of northern Pakistan. These tuffs are for the most part completely altered to bentonites, but accessory micro-phenocrysts of zircon permit dating of these deposits by the fission-track method.

(2) Two laterally persistent bentonitized tuffs from the Jhelum area, one from the Campbellpore area of the Punjab and several others have been dated: Jhelum area, 2.40 ± 0.20 m.y. and 2.58 ± 0.06 m.y.; Campbellpore area, 1.61 ± 0.10 m.y.

(3) The two prominent tuffs of the Jhelum area lie astride the Gauss and Matuyama magnetic-polarity reversal transition. The tuff of the Campbellpore area lies in the upper Matuyama reversed-polarity interval above the Olduvai normal-polarity event.

(4) The historically important Lower Pleistocene fauna of De Terra and Teilhard de Chardin (1936) from a site along the Haro River south of Campbellpore is assigned a probable age of 1.5 m.y.

(5) The bentonitized tuffs and bentonitic rocks of the upper portion of the Siwalik Group of northern Pakistan seem derived from the Dacht-e-Nawar volcanic complex in Afghanistan some 600 km to the west. The chronostratigraphy established for the Siwalik tuffs is contemporary with the known period of activity of this andesitic-rhyodacitic terrane.

(6) A tuff from mid-way through the Nagri Formation is dated at 9.46 m.y. ± 0.59. This tuff appears to lie within magnetic Chron 9.

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