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Magnetic polarity maps and time maps in the eastern Potwar Plateau; Applications of magnetic polarity stratigraphy

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Abstract

The use of magnetic polarity stratigraphy has allowed Upper Miocene and Plio-Pleistocene Siwalik sediments in the eastern Potwar Plateau to be dated precisely by direct correlation to the world-wide magnetic polarity time scale. Three examples are illustrated where measured sections calibrated by paleomagnetics allow geologic time to be extrapolated across broad areas to create new time maps based on the ability to see stratigraphic strike line patterns on Google Earth imagery. These maps allow precise dating of fossils as well as robust interpretations of the influence of growing folds and faults on the evolving fluvial geomorphology and depositional patterns of the region.

Keywords: Siwaliks, Paleomagnetism, stratigraphy, Potwar Plateau, Pabbi, Mangla

1. Introduction

The purpose of this paper is to synthesize earlier research in rock dating of the Siwalik sediments of the eastern Potwar Plateau using paleomagnetic stratigraphy. We provide revised and more detailed maps of dated sedimentary layers on several significant vertebrate fossil-rich folded and faulted anticlinal structures.

The Himalayan foreland basin contains one of the most extensively studied sedimentary records of mountain building Karunakaran and Rao (1976); Burbank et al. (1996). This record is preserved in the fluvial sediments represented by the Siwalik Group Parkash et al. (1980) and their equivalents. These strata are Miocene to Recent in age, and in the Potwar Plateau and Salt Range area (Figure 1), they lie with profound unconformity on Eocene and older shelf carbonate sediments that accumulated on the northern margin of the sub-continent prior to the closure of the Tethys Sea. The processes of mountain building (orogeny) and deposition of synorogenic sediments continue to the present day. The petrology of the sandstone beds within these fluvial sediments reveals the history of genesis, uplift, and erosion of the Himalayan Mountain chain Krynine (1937); Chaudhri (1972); Graham et al. (1975); Abid et al. (1983); Cerveny et al. (1988); Critelli and Ingersoll (1994); Zeitler et al. (2001); Najman et al. (2003). Modern river systems (including the Indus, the Jhelum, the Sutlej, the Ravi and the tributaries to the Ganges) continue to transport and deposit fluvial sediments today. At their distal ends, the Indus and the Ganges rivers supply sediment to the Indus and Ganges submarine fans Mallik (1978); Ingersoll and Suczek (1979); Suczek and Ingersoll (1985); Clift et al. (2019).

The most extensive and well-exposed outcrops of Siwalik rocks occur in Pakistan in the folded structures adjacent to, and north of, the Salt Range on the Potwar Plateau (Figure 2). To the west, across the Indus River, equivalent rocks are well exposed in the Kohat Basin and surrounding ranges Khan (1983); Pivnik and Khan, (1996); to the east the equivalent rocks are exposed, but often obscured by vegetation, in the Himalayan foothills of India and Nepal

Johnson and Vondra (1972); Meigs et al. (1995); Najman et al. (2004); Chirouze et al. (2012).

2. International Collaboration

In 1972, Dartmouth College's Department of Earth Sciences began a long-term collaboration with the Department of Geology, University of Peshawar. Professor Gary D. Johnson, who had previously worked in India for several years during the field research phase of his PhD dissertation, initiated this collaborative project with Dr. Rashid A. K. Tahirkheli who later rose to become Vice Chancellor of Peshawar University. Over the next nearly three decades, additional faculty members from Dartmouth, as well as over thirty Dartmouth undergraduate and graduate students became involved in this multi-disciplinary research collaboration, while graduate students and faculty from Peshawar University pursued studies in the US as well.

In parallel with the Dartmouth/Peshawar efforts, a collaboration was established between Yale University and the Geological Survey of Pakistan focusing mostly on the Lower and Middle Siwaliks. The American portion of this collaboration later moved to Harvard University and was active for many decades Pilbeam et al. (1977, 1980).

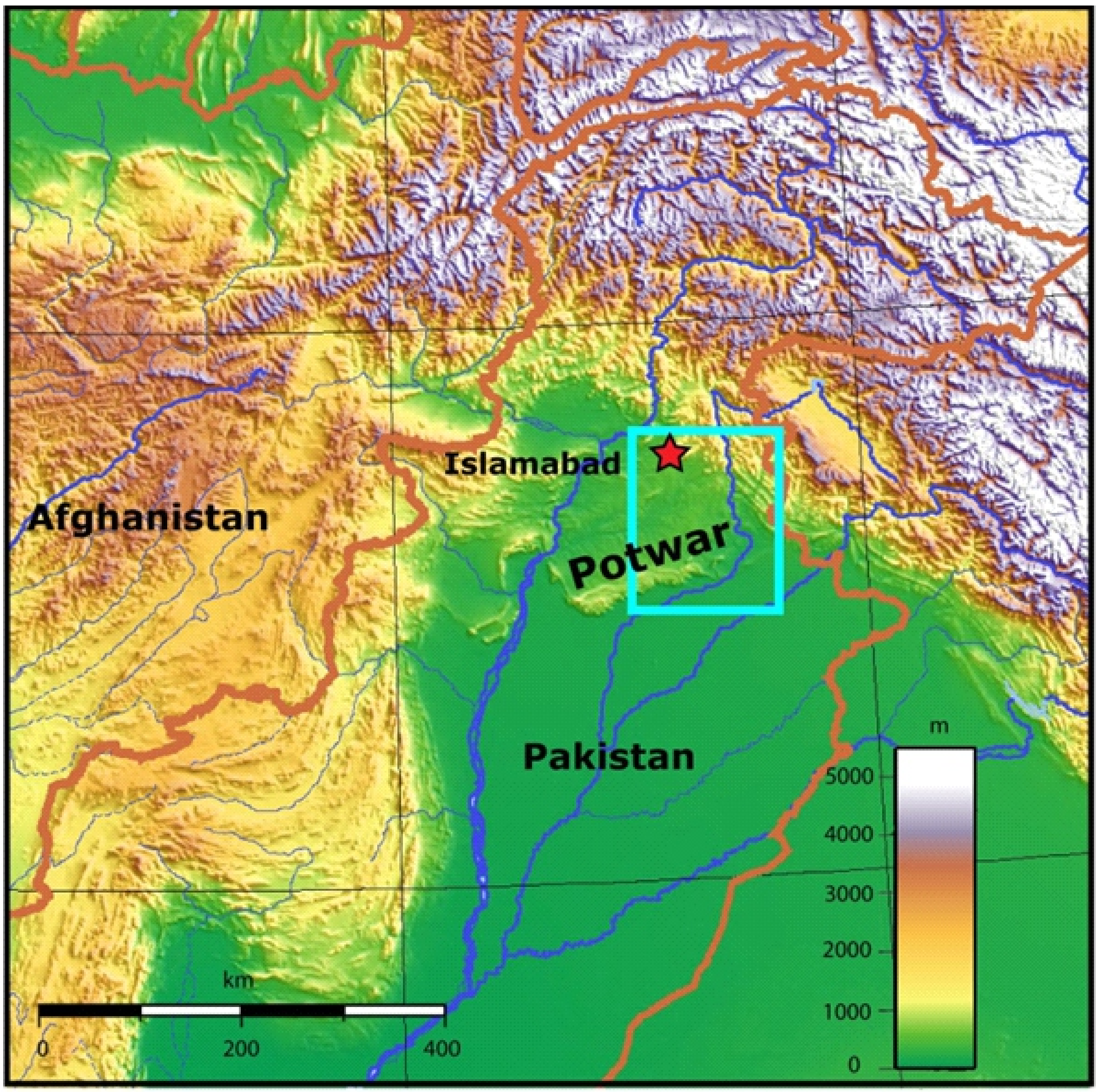

Fig. 1. Index map, blue box highlights the area of interest on the eastern Potwar Plateau.

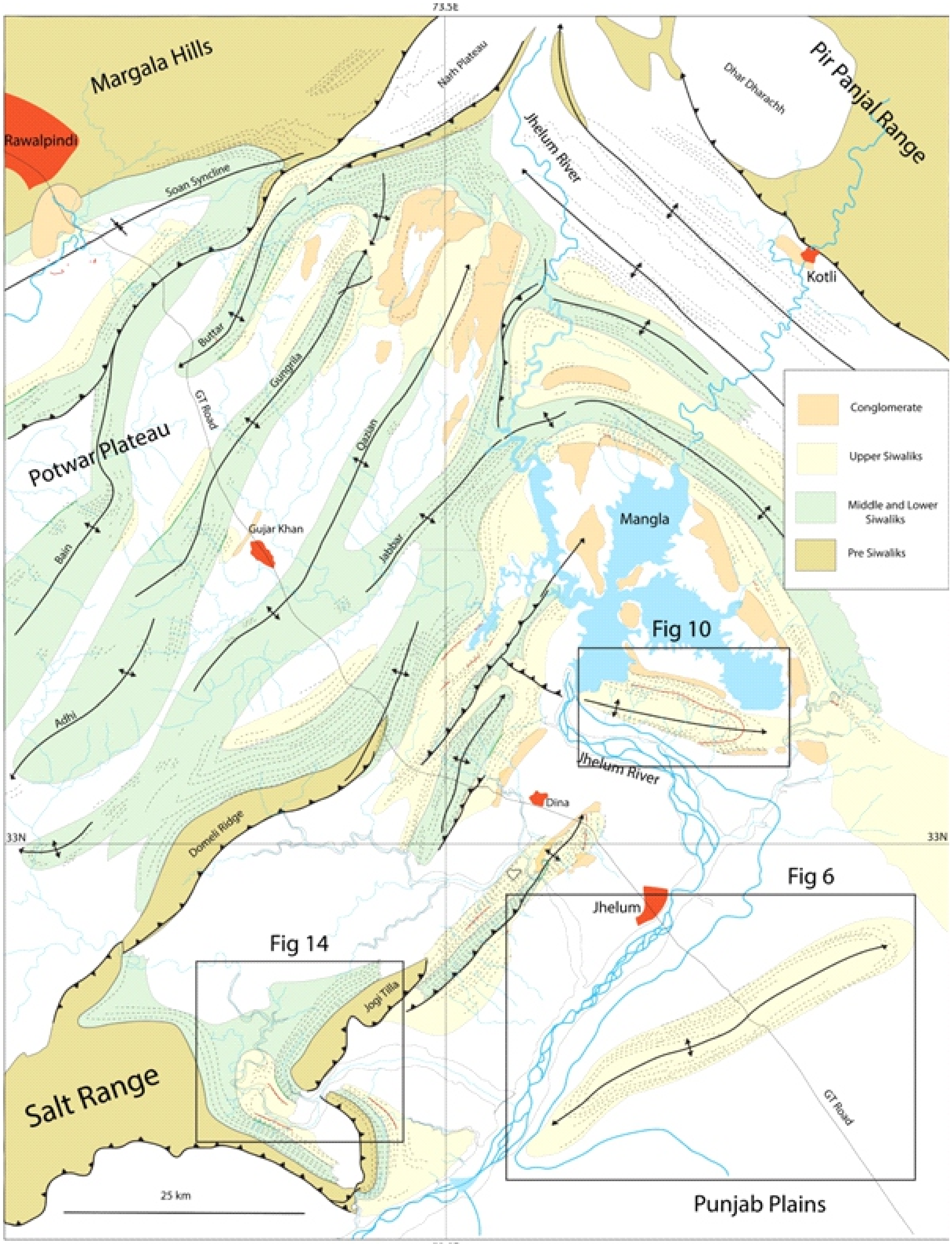

Fig. 2. Geologic map of the eastern Potwar Plateau made from a GoogleEarth base. The three study areas are indicated. Dashed lines are bedding strike lines interpreted from GoogleEarth. Red lines are volcanic ash outcrops.

This report is a retrospective analysis of some of these research findings and is designed to cement these results into the literature for future use. This study is based on Master's thesis work by Michael Keller and undergraduate senior thesis work by Carol Frost, Mike McMurtry and Charles Visser complementing research by Gary Johnson and Noye Johnson of Dartmouth College, Neil Opdyke of Columbia University, and Ev Lindsay of the University of Arizona; all under the collaborative guidance of Rashid Tahirkheli, Director of the Center of Excellence in Geology at Peshawar University.

While components of the materials discussed have been published Keller et al. (1977); Visser and Johnson (1978); G. Johnson et al. (1979); N. Johnson et al. (1982), the present report uses new high resolution imagery available from GoogleEarth and a revised geomagnetic polarity time scale to offer a refined vision of the earlier results. New time maps and new magnetic maps are presented that may be of value to students of paleontology and to those working on the deformational history of these splendidly exposed rocks.

3. Past work

3.1 Biostratigraphy

Early studies of these fluvial strata focused on the paleontological record. It was recognized that a well- preserved fauna spanning from Miocene to Recent time is present. These fossils tell a story of both immigration and local evolutionary change. The rocks have been subdivided into biostratigraphic horizons (biozones), based on fossil content; see for example: Wynne (1877); Pilgrim (1913); Cotter (1933); de Terre and Teilhard de Chardin (1936). This tradition of biostratigraphic subdivision has been followed upon by Barry et al. (1982, 1985, 2013); Khan, Hussain et al. (1992); Dennell et al. (2005); Patnaik (2013, 2016); Abbas et al. (2019); Akbar et al. (2020) and others. Figure 3 illustrates the faunal patterns observed in the past 5 million years and highlights an immigration event at about 2.7 Ma that saw new species of elephant, horse, and deer arrive in the Potwar region. Once a biostratigraphic succession is established, the contained fauna can be used to shed light on the relative age of rocks as the fossils can be calibrated and thus used for time control. As an example, any rocks containing Elephas hysudricus, Equus, or cervids must be less than 2.7 million years old.

3.2. Lithostratigraphy

In Pakistan, the molasse facies sediments are divided into the lower Rawalpindi Group - the Murree and Kam- lial formations; and the overlying Siwalik Group -the Chinji, Nagri, Dhok Pathan, and Soan formations, Fatmi (1973). It was recognized early on that these units are laterally variable and that rapid facies changes make geological mapping and correlation difficult Gill (1952 a, b). This has resulted in some confusion, and in cases, a multiplicity of local member names. This is the case in the Soan Formation which is perhaps better grouped as the Upper Siwaliks, a term we use in this report. From a genetic standpoint, the largely fluvial clastic rocks that were deposited during the Himalayan orogeny may be broadly considered to constitute the Siwalik Group. Figure 4 illustrates the stratigraphic nomenclature in the Potwar Plateau region.

3.3. Chrono stratigraphy

Detailed stratigraphic studies have located volcanic ash beds intercalated within the Siwalik rocks Ali et al. (1962), and these have been dated using fission track studies G. Johnson et al. (1982). A family of ash beds has been found across the eastern Potwar and extending into India Kumaraval et al. (2005). These air fall and lightly re-worked ash deposits are thought to have originated from volcanic eruptions in the Dash-e-Narwar area of Afghanistan. Zircon fission track dates of 2.56 +/- 0.21 - 2.86 +/- 0.18 (lower ash) and 2.40 +/- 0.20 Ma (upper ash) have been reported for a pair of widespread ash beds that straddle a normal to reversed magnetic polarity transition interpreted to be the Gauss / Matuyama chron boundary G. Johnson, et al. (1982).

In the early 1970's it was realized Opdyke (1972) that the record of the Earth's magnetic field is preserved in fine-grained clastic sediments, much as it is in the igneous rocks on the ocean floor. The same pattern of alternating normal and reversed magnetic field conditions that led to the recognition and calibration of sea floor spreading from mid-ocean ridges is recognized in the Siwalik sediments. As with sea floor spreading, the mag- netic field reversal patterns can be correlated to the time-calibrated history of the Earth's magnetic field (known as the Magnetic Polarity Time Scale, MPTS), allowing the definition of well-dated rock sections often kilome- ters thick. Over 35 of these measured and correlated sections exist in the eastern Potwar Plateau and this report synthesizes several of them.

Early remnant magnetic field studies in the Siwalik rocks were conducted by Wensink (1972), followed by workers from Dartmouth College and Columbia University Barndt et al. (1978).

Using paleomagnetic stratigraphy calibrated by radiometric dating, the faunal zonation of rock layers and their changing facies can be tied to absolute time. Work in Pakistan can be readily correlated into India Johnson and Vondra (1972); Ranga Rao et al. (1995); Tandon et al. (1984); Sangode et al. (1996); Burbank et al. (1996); Najman, et al. (2018), and beyond. Figure 5 illustrates the dating method.

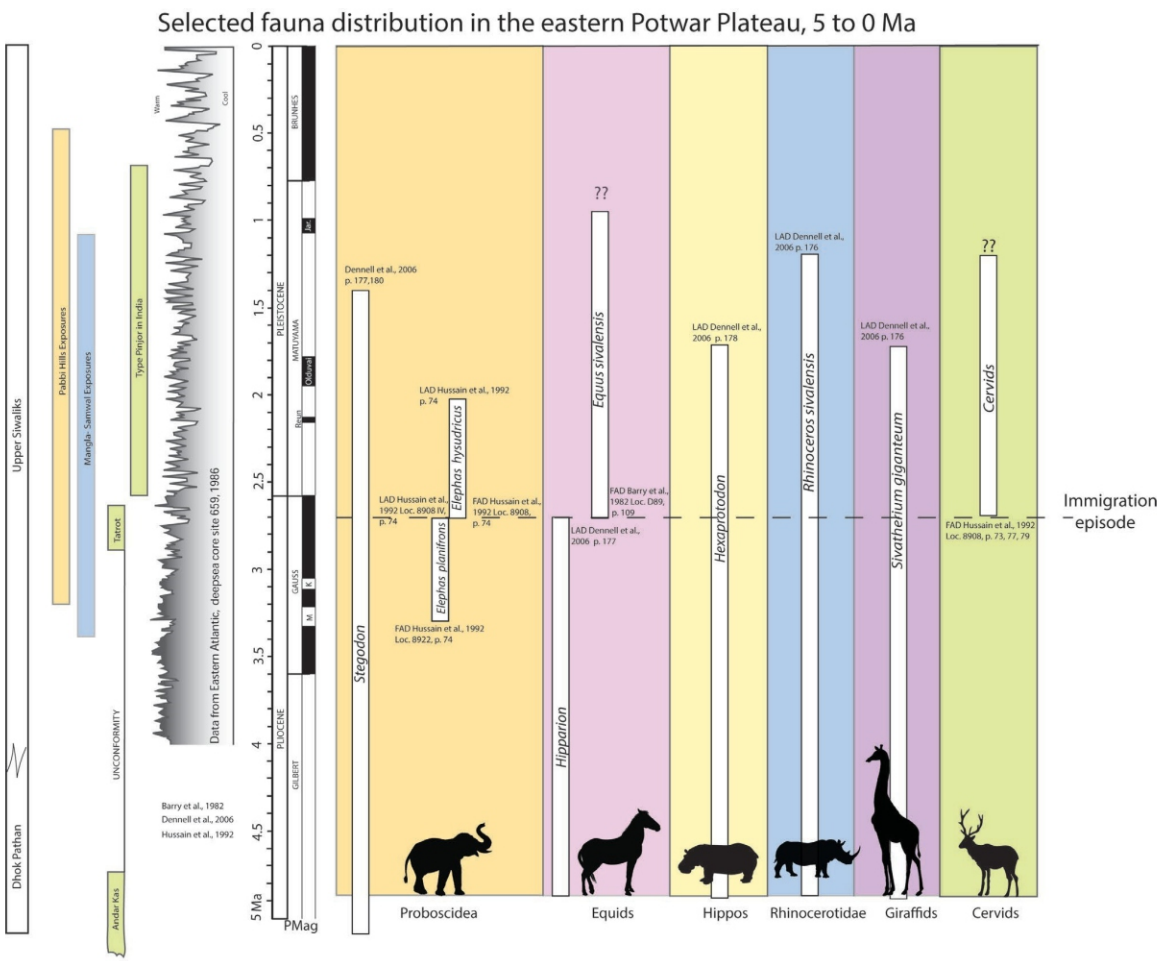

Fig. 3 Biostratigraphy of the Siwalik strata for the time period between 5 million years and the present. The time span of outcrops at the studied areas of the Pabbi Hills and Mangla Samwal are indicated as are the time spans of the Hasnot, Tatrot and Pinjor collecting areas. Faunal first appearance (FAD) and last appearance (LAD) datums are from Barry et al., 1982, Dennell et al., 2006, and Hussain et al., 1992. Climate data is from oxygen isotopes from forams.

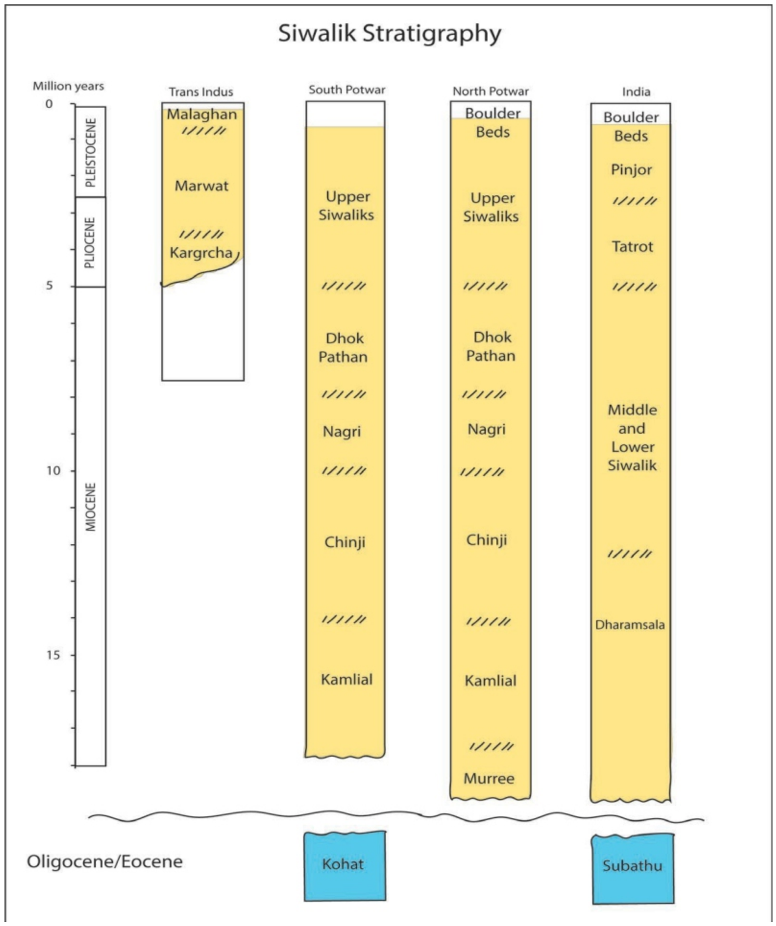

Fig. 4 Siwalik stratigraphic nomenclature tied to time. Hash marks indicate gradual facies transitions.

3.4. Isochrons

Detailed studies of lithology boundaries and magnetic polarity transitions indicate that sandstone beds can be considered to be essentially isochronous units, hence strike line maps can be proxies for time maps Visser and Johnson (1978); Behrensmeyer and Tauxe (1982).

4. Study Area

This paper illustrates three examples of time maps for the Upper Siwaliks of the eastern Potwar Plateau. The eastern Potwar Plateau and the Jhelum re-entrant Raynolds, (1980); Drewes (1995), reveal a broad region of folded strata exposing the Siwalik sediments in lightly vegetated terrain dissected by headward eroding tributaries to the Jhelum and Soan rivers. These outcrops provide ideal circumstances for the study and calibration of these sediments Burbank et al. (1996). Three study areas have been selected for updated mapping using GoogleEarth base maps (see figure 1).

4.1. Three Examples

4.1.1 Pabbi Hills anticline

The Pabbi Hills reveal excellent outcrops of the Upper Siwalik sediments exposed along a SW to NE trending anticlinal fold that has only recently been uplifted. These elongated hills extend for about 40 kilometers, with a width of 5-7 kilometers, and rise 150 meters above the Punjab plains SE of Jhelum city. The doubly-plunging anticline is crossed by the Grand Trunk Road and the Pakistan Rail line. Its southeastern flank dips more steeply, reflecting a NW dipping thrust fault at depth Pennock (1988). The youthful age of the youngest strata allows an interpretation that deformation started less than a million years ago Keller (1975); Keller et al. (1977).

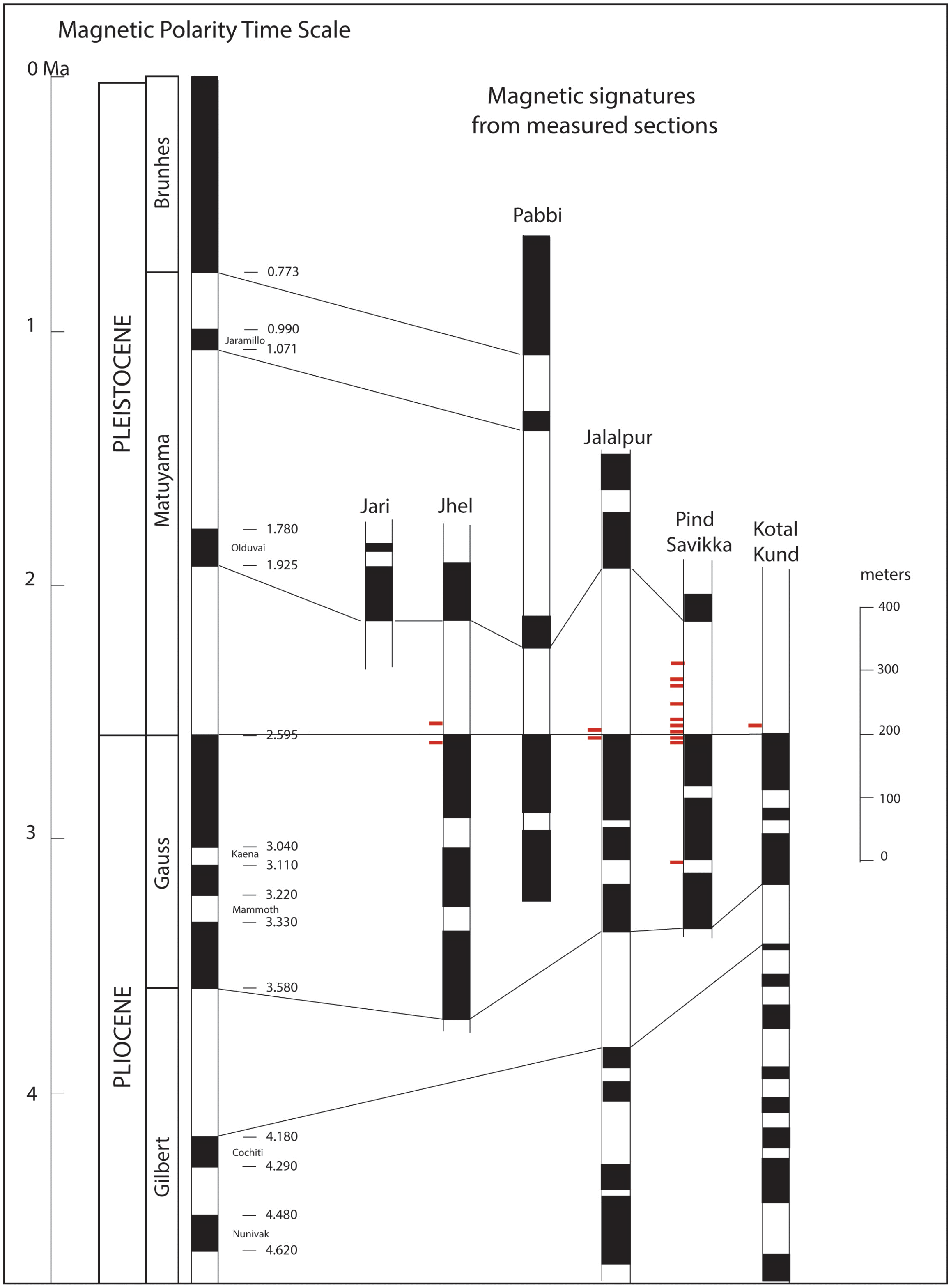

Fig. 5. Worldwide magnetic polarity time scale correlated to the stratigraphic sections discussed in the text. The age dates for the magnetic transitions for 2.595 Ma and younger are from the International Commission on Stratigraphy's web page at stratigraphy.org. The older transition dates are from the Texas A&M Ocean Drilling Program web site at ODP.tamu.edu. Red lines are volcanic ash beds.

Stratigraphic studies in this area began with Wynne (1877) and Theobald (1881) and were supplemented by observations of Pilgrim (1913) and deTerre and Teilhard de Chardin (1936) all of whom recognized the young nature of the sediments and their contained fossils.

More recently, faunal studies have been conducted by Bakr and Qureshi (1966); Bakr (1969); Dennell (2004, 2007, 2008); Dennell et al. (2005a, 2005b, 2006) and by Nanda et al. (2022). Dennell and his colleagues collected and studied over 40,000 fossil specimens during a systematic survey of several square kilometers and established a refined local biostratigraphy. Interestingly, the majority of this collection occurred in bone concentrations that may have been assembled by hyenas Dennell et al. (2008).

Paleoenvironmental analyses have been published by Jenkinson et al. (1989).

Figure 6 illustrates a strike line map of the Pabbi Hills derived from GoogleEarth imagery (Figure 7). A 1000-meter stratigraphic section was measured and sampled for paleomagnetic properties along the railroad, supplemented by additional samples in the axial portion of the fold and from a location on the southern end of the structure near Khohar Khurd village. This section was measured by Keller (1975) as part of his Dartmouth College Master's thesis, and was published in 1977 by Keller et al. (1977). This publication included the first mapped magnetic polarity zonation in Pakistan, a map that is only slightly modified in the present report as Figure 8. This measured section was later reviewed and placed in a larger context by G. Johnson et al. (1979) and Opdyke et al. (1979). Figure 9 takes the magnetic zonation map and translates it to geologic age. Age maps such as this will help paleontologists target search zones of selected ages for detailed studies of faunal evolution.

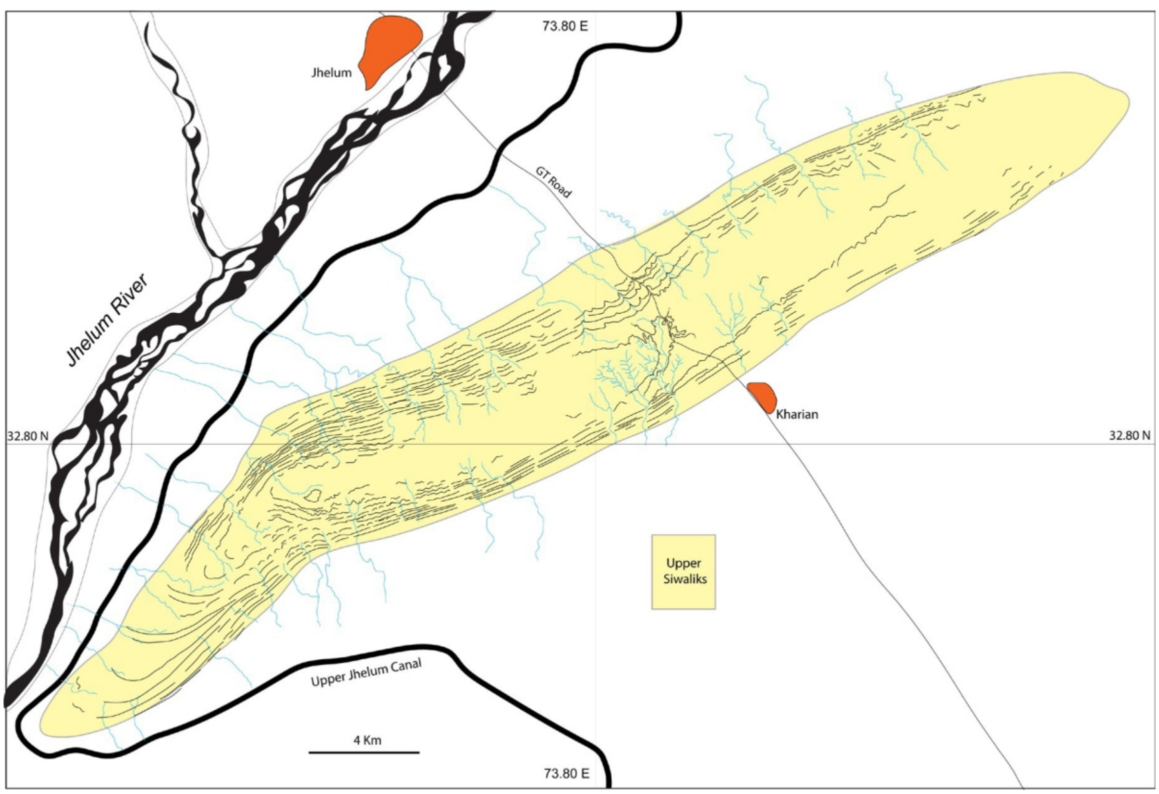

Fig. 6 Strike line map of the Pabbi Hills, interpreted from Google Earth.

Fig. 7 Oblique view from the SE of the Pabbi Hills from GoogleEarth.

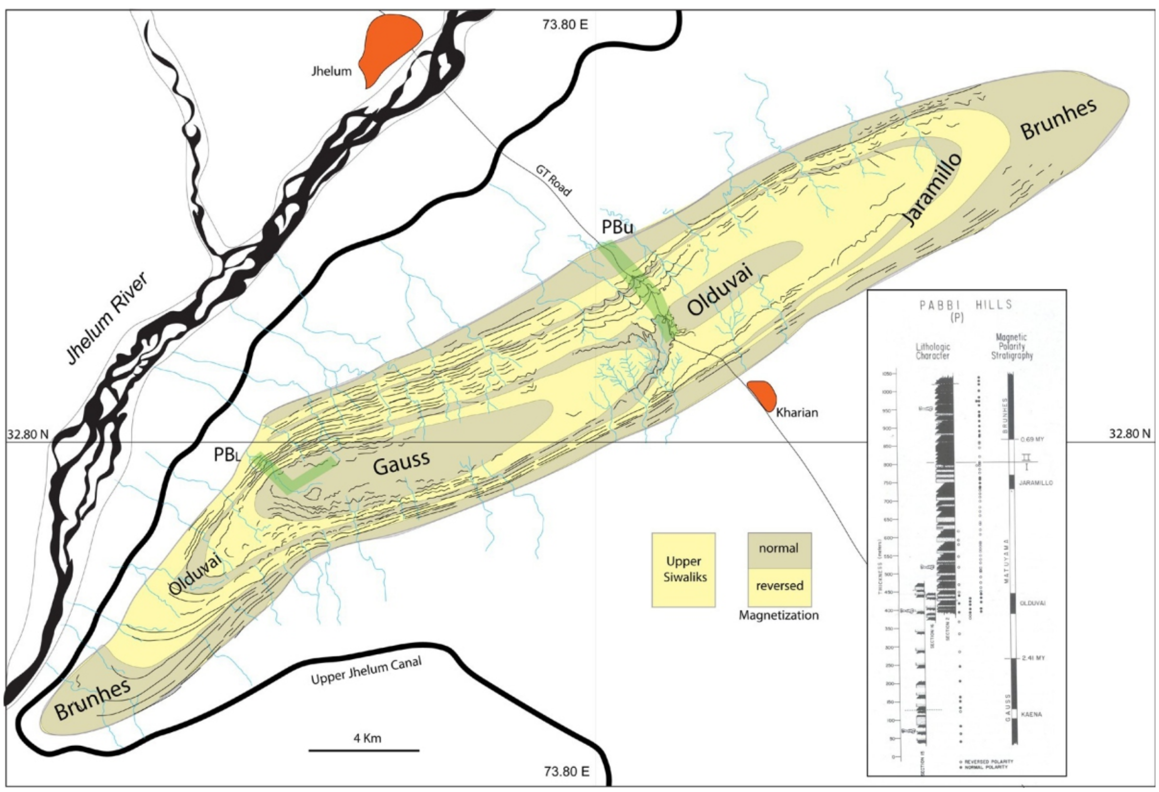

Fig. 8 Magnetic map of the Pabbi Hills. Map modified after Keller et al. 1977.

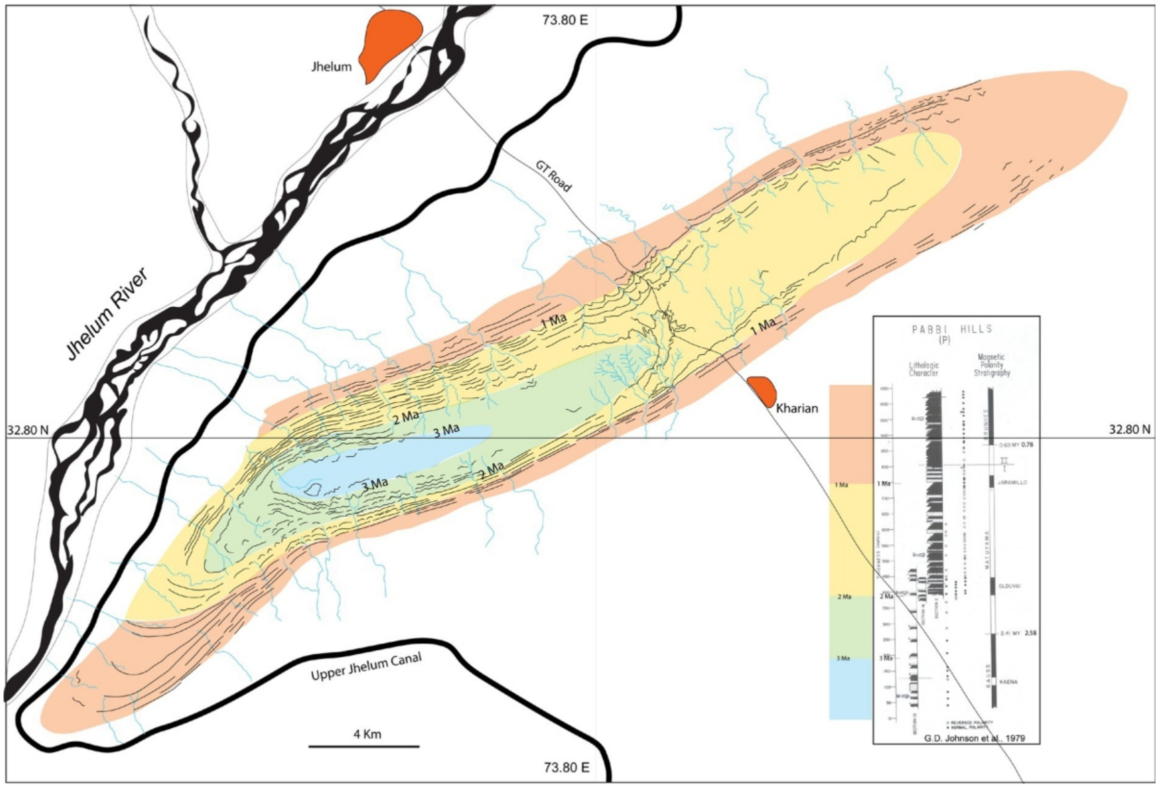

Fig. 9 Time map of the Pabbi Hills.

4.1.2 Mangla Samwal anticline

The Mangla Samwal anticline forms the southern buttress for the Mangla Reservoir. It has well-exposed strata in a series of incised streams that offer good outcrops of thick multi-storied fluvial channel sandstones deposited by the ancestral Jhelum River. Early work by Ali (1962) recognized an important volcanic ash marker bed in the area; subsequently, a pair of bentonitized volcanic ash beds have been dated G. Johnson et al. (1982) and mapped on the Mangla Samwal structure Visser (1976); Visser and Johnson (1978). The dates for the ash beds straddle the boundary between the Gauss and the Matuyama chrons and allow for the unambiguous calibration of the magnetic polarity record.

The work of Dartmouth/Peshawar collaborators established the basic magnetic pattern with a 750 m measured section in Jhel Kas G. Johnson et al. (1979); Opdyke et al. (1979). Before this, Visser, (1976) and Visser and Johnson (1978) documented the character of fluvial sedimentation in the interval bounded by a pair of regional- ly traceable volcanic ash layers. An additional 450 m section was measured at Jari by Raynolds (1980).

Facies patterns and sandstone bed thicknesses are tied to the geometry and evolving geomorphology of the Jhe- lum reentrant. For example, as the reentrant structures developed and focused the river flow, thick multi-storied sandstone beds were deposited along the axial Jhelum drainage. Peripheral areas received less channel depo- sition Raynolds (1980). In both the Pabbi Hills section and the Mangla Samwal section, a transition is evident from the older axial fluvial environments to the younger off-axis deposition of finer grained floodplain deposits. This reflects the transition from an axial drainage influenced setting to a more peripheral setting as the structural focus of the ancient Jhelum River was established. Rates of sediment accumulation were also influenced by the changing geomorphology Raynolds and Johnson (1985).

Stratigraphic subdivisions of the Upper Siwaliks on the Mangla Samwal structure were proposed by Arif (1985). These stratigraphic studies have been amplified with faunal studies by Hussain (1971) and Hussain et al. (1992)

tied into the magnetic stratigraphy, in which new range zones are proposed based on elephant biostra- tigraphy.

Figure 10 illustrates the strike line map made from Google Earth showing the location of two measured sec- tions. The Jhel Kas section was published by Johnson et al. (1979), and the Jari section was measured by Raynolds (1980). Figure 11 shows a GoogleEarth view of the Mangla Samwal fold.

Figure 12 is a magnetic polarity map that is an expansion of the magnetic polarity map published in G. Johnson et al. (1979, their figure 15). Figure 13 is the interpreted age map for this area.

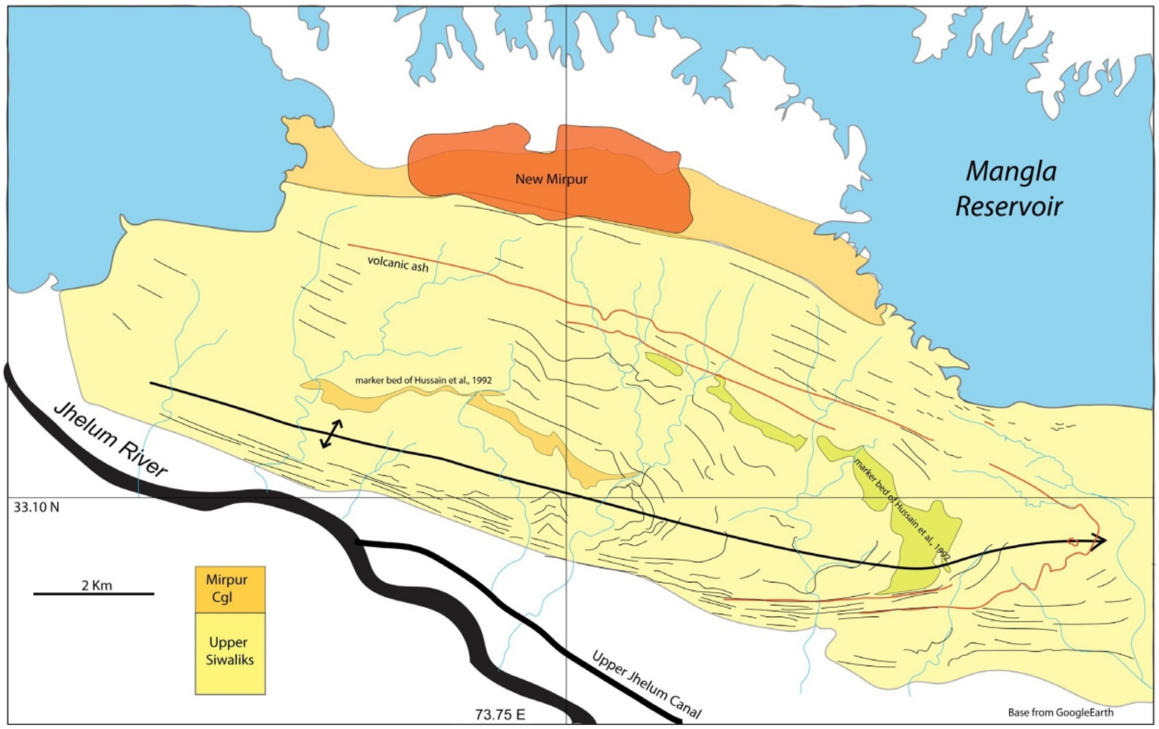

Fig. 10 Strike line map for the Mangla Samwal area, from GoogleEarth. Two marker beds defined by Hussain et al., 1992 are shown. Map modified after Visser and Johnson, 1978; Johnson et al., 1979; Raynolds, 1980, Hussain et al. 1992.

Fig. 11 Oblique view of the Mangla Samwal structure from GoogleEarth.

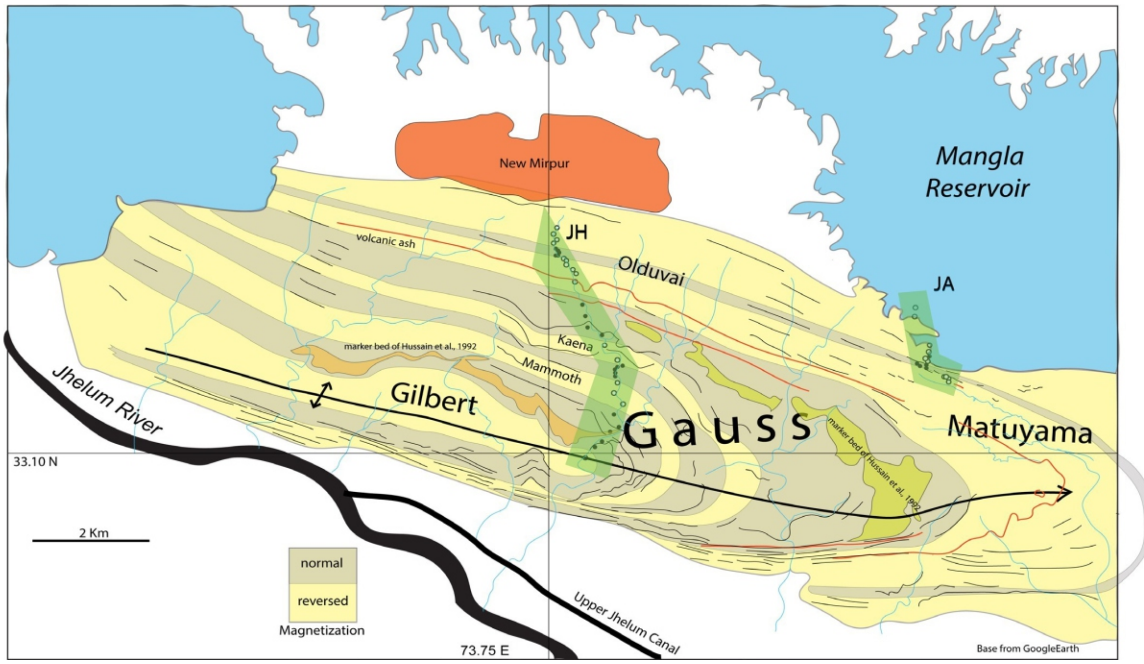

Fig. 12 Magnetic map of the Mangla Samwal area. Map modified after Visser and Johnson, 1978; Johnson et al., 1979; Raynolds, 1980, Hussain et al. 1992. JH and JA are measured sections from Visser and Johnson, 1978 and Raynolds, 1980 resepctively.

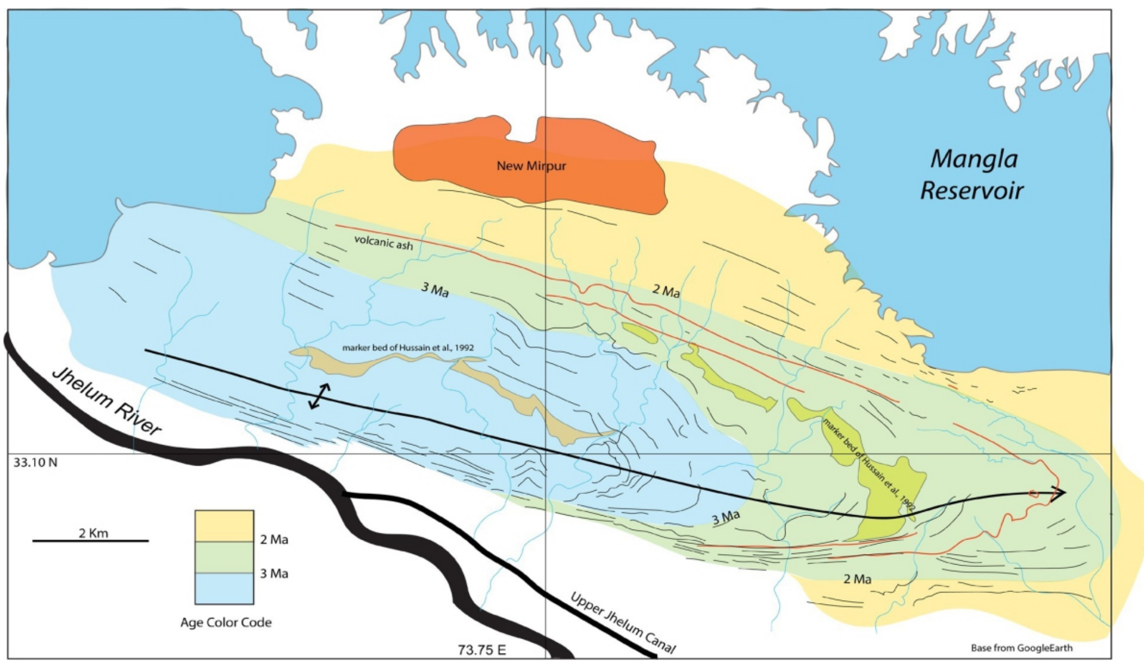

Fig. 13 Time map of the Mangla Samwal area.

4.1.3. Kotal Kund folded and faulted syncline

The Kotal Kund area represents a structurally complex set of faulted folds at the easternmost end of the Salt Range. Here the Jogi Tilla structure and the thrusted Salt Range structures meet and interplay, revealing excellent exposures of the full Siwalik succession.

While the lowermost units remain less studied, the middle and upper Siwaliks have been carefully measured and dated in a variety of sections.

Work by Frost (1979) demonstrated that unusually good preservation conditions and high rates of accumulation preserved as many as 13 volcanic ash beds in the vicinity of the Gauss Matuyama boundary.

Fossil collections in the Hasnot and Tatrot areas are well known in the literature (see for example Khan et al. (2014); Ghaffar et al. (2019); Khan and Flynn (2019). This has caused some confusion as an unconformity Opdyke et al. (1979 fig. 17); Abbas et al. (2019) separates the reversely magnetized fossiliferous Hasnot beds from the overlying normally magnetized younger unit that has been designated the type locality for the Tatrot fauna.

Figure 14 shows the strike lines and the location of four measured sections in this area and figure 15 shows an oblique GoogleEarth view of the area. The 2100 m Jalalpur section was measured in Jamarghal Kas on the east flank of Chambal Ridge, and first published by G. Johnson et al. (1979) and in an expanded version by N. Johnson et al. (1982). The 1800 m Kotal Kund Section was measured south of the village of Kotal Kund and was published by N. Johnson et al. (1982). The 600 m Pind Savikka section was measured by Frost (1979) and published by G. Johnson et al. (1982). The 1500 m Tatrot/Andar section measured near the villages of Bhan- dar, Hasnot and Tatrot was published by N. Johnson et al. (1982). Careful tracing of sandstone beds McMurtry (1980) allows section segments to be stacked and correlated with confidence.

Figure 16 illustrates the rock units in the Kotal Kund area colored by age as interpreted from the paelomagnetic stratigraphy. Figure 17 illustrates the rock units in the Kotal Kund are colored by formation name.

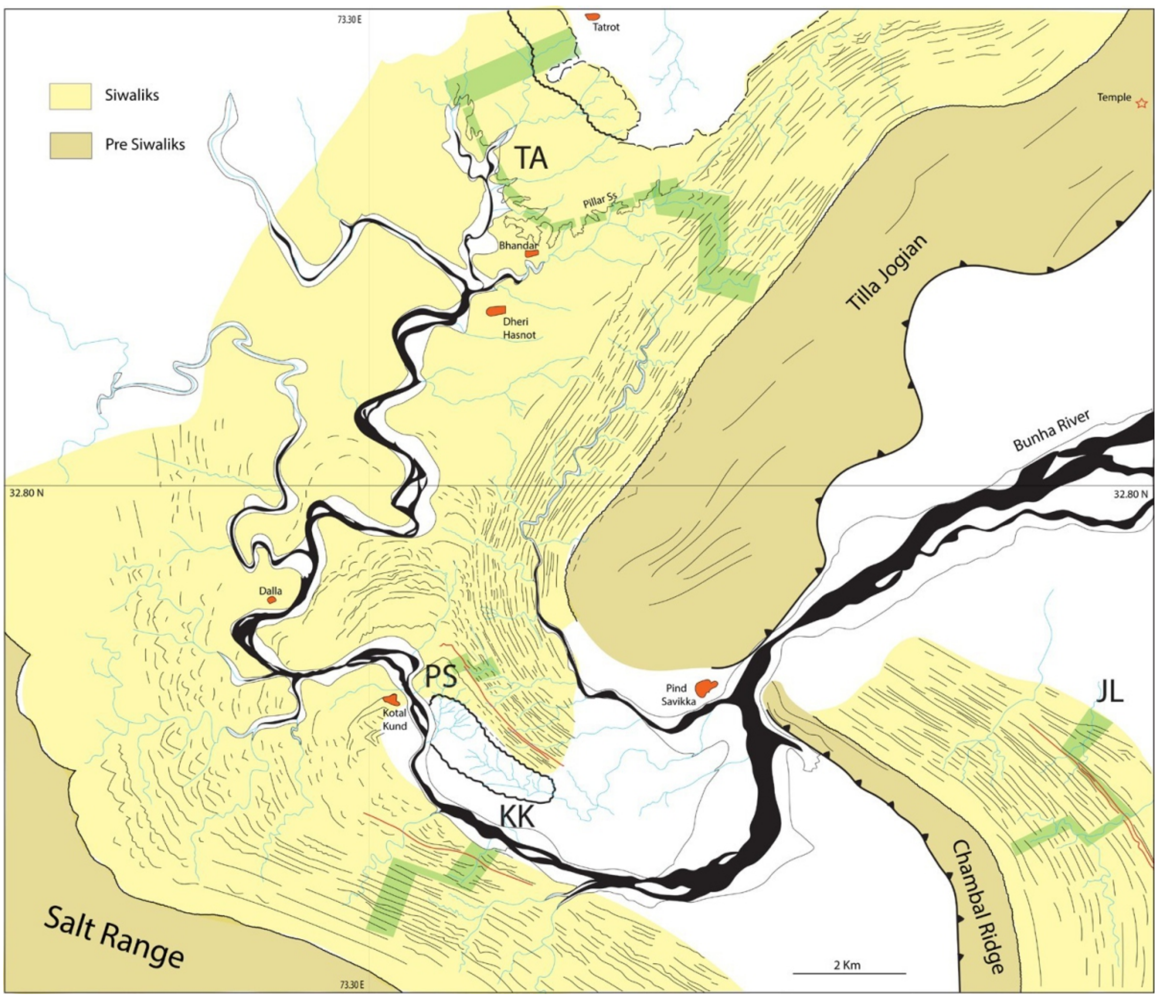

Fig. 14 Strike line map of the Kotal Kund area from GoogleEarth. Measured sections at Tatrot-Andar (TA), Pind Savikka (PS), Kotal Kund (KK), and along Jamarghal Kas (Jalalpur) (JL) are shown.

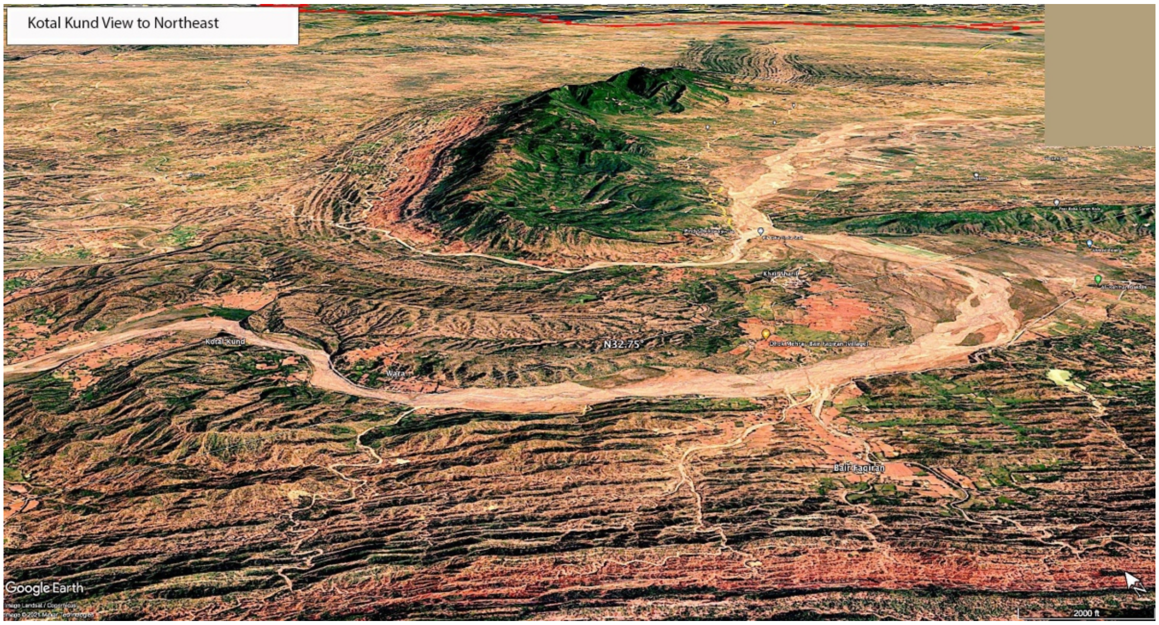

Fig. 15 Oblique view of the Kotal Kund area from the SW from GoogleEarth.

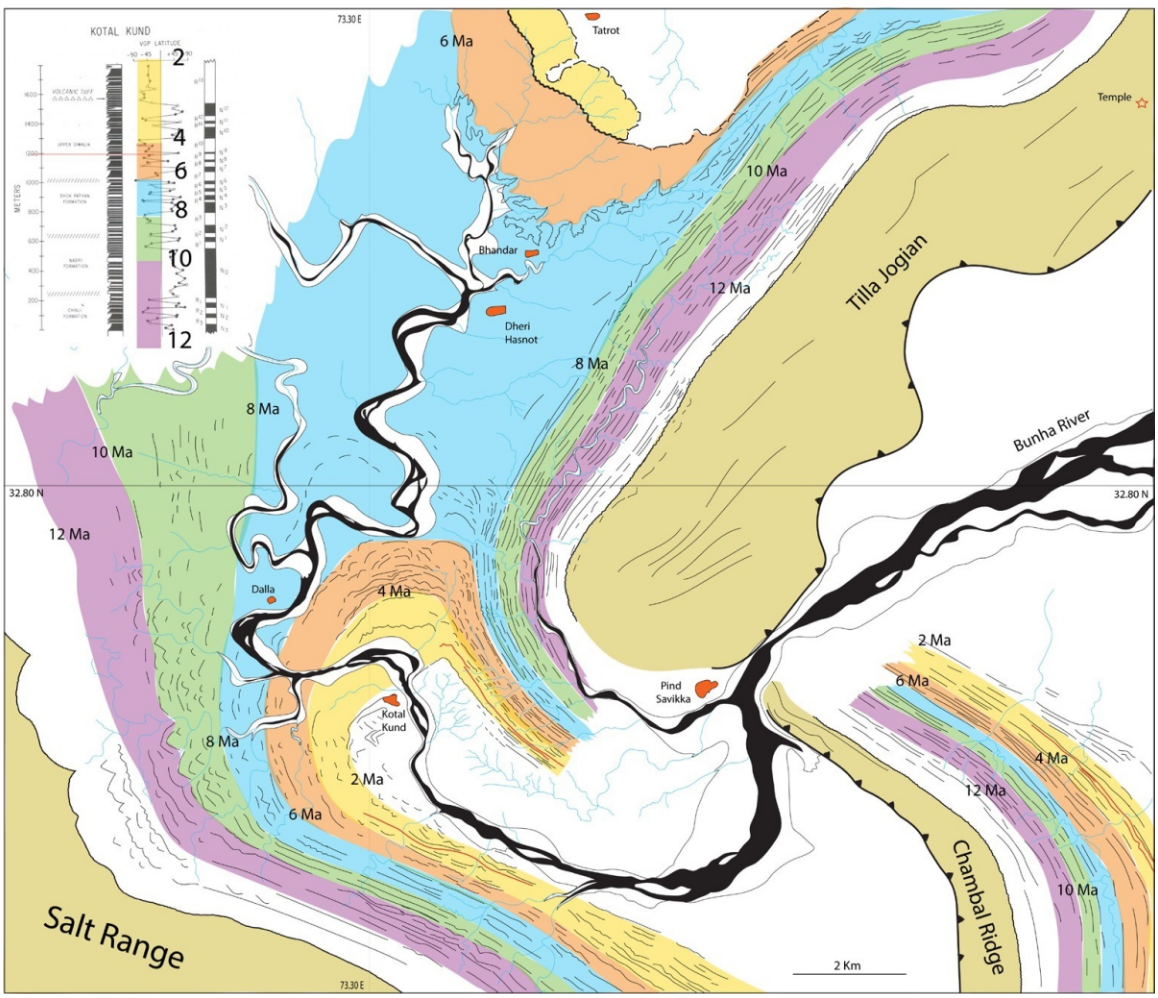

Fig. 16 Time map of the Kotal Kund area.

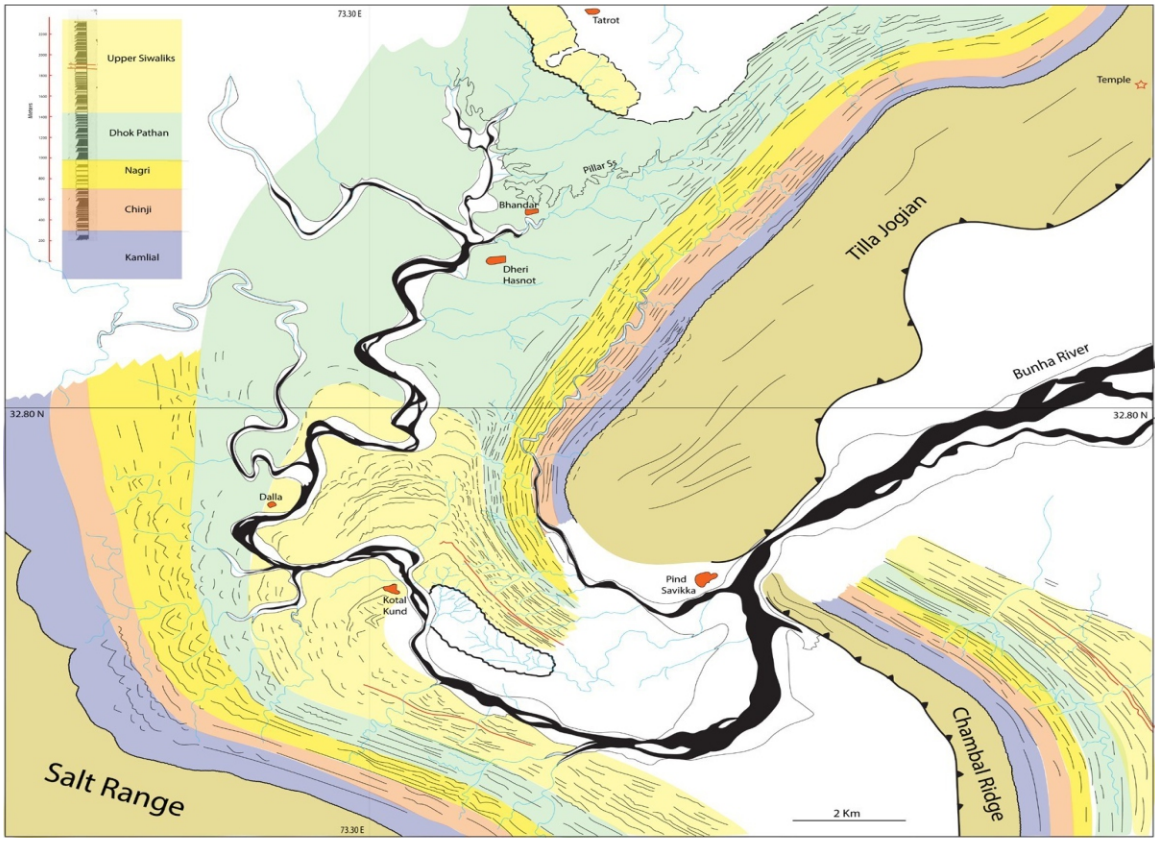

Fig. 17 Formation map of the Kotal Kund area.

4. Website containing paleomagnetic data

A website has been created at siwalikstratigraphy.org by the first author to host downloadable copies of all the magneto-stratigraphic sections measured in the Potwar region. This website is designed to make the materials easily accessible to researchers and students in Pakistan and cross the world.

5. Conclusions and suggestions for further work

These maps illustrate the potential to define the age of Upper Siwalik strata in areas where paleomagnetic stratigraphy is well documented. The precision of interpolated ages will depend on the nature of the outcrops and the proximity to established magnetic patterns. The maps in this report should allow fossils found in the Pabbi Hills and Mangla Samwal area to be dated to within a few 100,000 years. Due to steeper dips and more closely spaced time boundaries, this uncertainty will be greater in some places in the Kotal Kund area.

The age patterns reported here offer fruitful ground for further research by students and faculty interested in the Siwalik rocks and their history. Opportunities for expanded studies to refine the understanding of paleo-land- scapes, with river dimensions and flow directions together with improved calibration of faunal changes on these landscapes are clear. Future research can also build on these studies to enhance our understanding of the structural evolution of the Himalayan foothills and the Potwar Plateau and on the interplay between growing anti- clinal folds and the location and patterns of flowing rivers together with their impacts on sediment dispersal and accumula-tion patterns.

Acknowledgements

Robert Raynolds proposed the main concept and compiled the new maps used as figures in this paper. His dissertation research covered portions of this area and his geologic maps have been revised and redrafted for this publication. Gary Johnson supervised the original field-based research and contributed perspective from his earlier (and at the time ongoing) research in the Siwalik rocks of Pakistan and India. Carol Frost did original field research and mapping in the Kotal Kund

region of the eastern Salt Range. Michael Keller did original field research and mapping on the Pabbi Hills east of Jhelum. Michael McMurtry did original field research and mapping in the Hasnot area in the eastern Salt Range. Charles Visser did original field research and mapping in the Mangla area just south of Mangla Reservoir.

While portions of the above-mentioned work have been presented in thesis and manuscript format, the integrated approach presented in this paper is entirely new and offers a synthesis of many years of work. Widely scattered materials have been gathered together, redrafted in common formats, reinterpreted with modern eyes and here made available as a basis for further studies. All earlier work and contributions have been carefully acknowledged and referenced in the text and figure captions.

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