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Hughes, N.C., Myrow, P.M., Ghazi, S., McKenzie, N.R., and DiPietro, J.A., 2018, Cambrian geology of the Salt Range of Pakistan: Linking the Himalayan margin to the Indian craton: GSA Bulletin, https://doi.org/10.1130/B35092.1.

Data Repository

Supplemental Document 1: Spelling of Formation Names

Supplemental Document 2: Stratigraphy and Correlations of Pakistani Cambrian Rocks North of the Panjal-Khairabad Fault

Supplemental Document 3: Detrital zircon analysis

Table. Summary of SHRIMP U-Pb zircon results for sample 14-105, Tanawal Formation, Pakistan.

Figure DR1. Biostratigraphic correlation between the Salt Range, Indian craton, Lesser Himalaya, and Tethyan Himalaya based on modern taxonomy. Purple bar shows species-level correlation based on body fossils. Note that the earliest Cambrian record is highly condensed, and that the zone of correlation among Himalayan lithotectonic belts is of short duration. The age of the Nagaur Group trace fossil assemblage is early Cambrian, but its exact age is not precisely constrained. Modified from Hughes (2016, fig. 14), with attention drawn to the revised stratigraphic occurrence of cf. *Y. szechuanensis* which was reported from the Khussak and Jutana formations (Redlich, 1899), not from the Khewra Formation.

Supplementary Document 1: Spelling of Formation Names

The Stratigraphic Committee of Pakistan stated that the “spelling in the latest edition of the Survey of Pakistan map is to be used” for formation names (Rahman, 1967, A-11, p. 2,) and Fatmi (1973) thus spelt the Jhleum Group formation names as Khwera, Kussak, Jutana, and Baghanwala. However, the Pakistani code declared itself to be provisional until an international code was designated (Day *in* Rahman, 1967, p iii). Accordingly, we follow the International Subcommission on Stratigraphic Classification’s precept that “the spelling of the geographic component, once established, should not be changed” (Murphy and Salvador, 1999, p. 258) and thus use Noetling’s (1894) original spellings.

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Rahman, H., 1967, Stratigraphic code of Pakistan: Memoirs of the Geological Survey of Pakistan, v. 4, no. 1, p. 1-28.

Supplemental Document 2: Stratigraphy and Correlations of Pakistani Cambrian Rocks North of the Panjal-Khairabad Fault

Correlation between parts of Jhelum Group of the Salt Range, the Tal Group of the Indian Lesser Himalaya, and the Parahio Formation of the Indian Tethyan Himalaya is possible to a precision within a few million years based on shared brachiopod and trilobite taxa (Hughes, 2016). These correlation and others (e.g., a late Neoproterozoic diamictite in both the Lesser and Tethyan Himalaya) demonstrate a notable facies change between the upper Neoproterozoic and Cambrian rocks of the Lesser and Tethyan Himalaya (Myrow et al., 2015) that occurs within in Pakistan across the Panjal–Khairabad Fault. In the Peshawar basin to the north, rocks of Silurian and younger age have been palaeontologically dated (Pogue et al., 1992), but the ages of underlying Paleozoic and Neoproterozoic rocks are not well constrained (Figs. 3,4). North of the Panjal–Khairabad Fault near Misri Banda, the pre-Silurian Misri Banda Quartzite unconformably overlies carbonate, now assigned to the Ambar Formation (Pogue et al., 1992). Pogue and Hussain (1986) (Pogue and Hussain, 1986) and Pogue et al. (1992, p. 920) recognized the Misri Banda Quartzite as Ordovician based on the occurrence of the trace fossil *Cruziana rugosa*. The particular patterns of scratch mark corrugation and striation confirm an age constraint of Early to Middle Ordovician (Floian to Darrawilian) (i.e. ~477 – 458 Ma) for these rocks from the upper beds of the formation (MacNaughton, 2007;

Mángano et al., 2016). This is consistent with detrital zircon spectra data (Myrow et al., 2010, fig. 3).

As the Misri Banda Quartzite is Ordovician and sits unconformably on older deformed rock of sedimentary protolith (Palin et al., 2018), its stratigraphic position is apparently analogous to the Tethyan Thaple, Shian and Ralam formations of the Zanskar, Spiti and Kumaon regions of India, respectively, and its basal unconformity seemingly reflects the Kurgiakh orogeny that affected both the north India margin and other parts of equatorial Gondwana at the time (Myrow et al., 2016) (Figs. 3,4).

The ages of rocks beneath that unconformity are presently poorly constrained. These rocks include the siliciclastic Tanawal Formation and, where preserved, the conformably overlying carbonate-rich Ambar Formation (Pogue et al., 1992). We agree with Pogue et al. (1992, fig. 6) that the up to ~400 m thick Ambar Formation (Pogue et al., 1992), fig. 4) is likely correlative with the carbonate-rich Karsha Formation of Zanskar, which is of similar thickness (Gaetani et al., 1986; Myrow et al., 2006). The base of the Karsha was deposited at ~504 Ma (Hughes, 2016), fig. 14). Pogue et al. (1992, p. 917) argued for a Cambrian age for the Ambar Formation, based in part on the presence of shell fragments in the centers of pisoliths. If this correlation is correct, it would place the Tanawal Formation as correlative with the Parahio and/or the Phe formations of Zanskar, indicating that these Pakistani rocks correlate to the Indian Tethyan Himalaya, and that deposition of the Tanawal Formation may have extended into the early or middle Cambrian. Pogue et al. (1992, p. 916) reported that the Tanawal Formation is intruded by the Mansehra granite, dated using Rb/Sr isotopes as 516 +/- 16 Ma (LeFort et al., 1980), which provides an approximate minimum depositional age for the unit. This is further supported by recent evidence of metamorphism of these rocks around 475 Ma (Palin et al., 2018). A detrital zircon grain in our Tanawal sample (Tanaw-14-105) (Fig. 11) has an age of about 570 Ma with relatively narrow error estimates (+/- 7 Ma), suggesting a maximum depositional age of late Neoproterozoic. Its age distribution resembles that of Neoprotoerozic and Cambrian rocks in the region, including those of the Salt Range and Tethyan Himalaya, and it may be significant that it lacks its lack a prominent peak shown around 1.8 Ga that is characteristic of rocks of this age from Lesser Himalaya (Figs. 12,13). In summary, the thickness of the Tanawal Formation, its lack a prominent peak shown around 1.8 Ga, the presence of the Ambar Formation conformably above it, with the unconformably overlying Misri Banda Quartzite above that, are all reasons why we view the Tanawal Formation as more allied to the Tethyan Himalaya than the Lesser Himalaya (*contra* Palin et al., 2018), but we agree with those authors that all these areas were originally part of a continuous margin.

We disagree with Pogue et al.'s (1992) and Qasim et al.'s (2014, fig. 6; 2015, fig. 5) correlation of the Ambar Formation with the 580 m thick Sirban Formation of the Abbottabad area, south of the Panjal–Khairabad fault, from which no fossils are yet known. The Sirban Formation is stratigraphically overlain by earliest Cambrian (Terrenuevian) fossil-bearing deposits of the Tarnawai/Hazira Formation, and therefore must predate the late Terrenuevian and likely be of late

Neoproterozoic age. We thus correlate the Sirban Formation with the ~ 1000 m thick Neoproterozoic Krol Group of the northern Indian Lesser Himalaya (Jiang et al., 2002; Myrow et al., 2015, fig. 2). Likewise, we question Pogue et al.'s (1992, fig. 6) and Qasim et al.'s (2015, fig. 5) suggested correlation of the Ambar Formation with the lower Cambrian Jhelum Group of the Salt Range because, as detailed above, the Ambar Formation more likely correlates with the Karsha Formation of India, an uppermost middle Cambrian deposit that is ~8 million years younger than the fossiliferous part of the Jhelum Group (Hughes, 2016).

There are several other areas of Pakistan in which rock units have been mooted, on the basis of stratigraphic relationships, to be late Neoproterozoic or Cambrian. Possibilities include the highly deformed Manglaur Formation in Swat (Pogue et al., 1992) and the Shaghai and Landi Kotal Formations in the Khyber region (Pogue et al., 1992; Shah, 1977). In our view, too little is known of these rocks at present to consider them correlative, and that further work on the depositional ages of all units discussed is needed.

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Supplemental Document 3: Detrital zircon analysis

The Tanawal sample was analyzed at the Research School of Earth Sciences, Australia National University using a sensitive high-resolution ion microprobe (SHRIMP) using procedures given in Williams (1998). Zircon grains were imaged using reflected and transmitted light microscopy, cathodoluminescence (CL), and scanning electron microscopy (SEM). Sectioned grains were imaged using CL to determine their internal structures and to ensure that the ~20 μm SHRIMP spots were wholly within the youngest single age component (i.e., the rims). The SQUID Excel macro (Ludwig, 2001) was used to process the data. U/Pb ratios were normalized relative to a value of 0.0668 for the Temora reference zircon, equivalent to an age of 417 Ma (Black et al., 2003). Uncertainties given for individual analyses (ratios and ages) are at the 1s level (see Supplementary Document 4). Correction for common Pb was made either using the measured $^{204}Pb/^{206}Pb$ ratio in the normal manner, or for grains younger than ~800 Ma (or those low in U and so radiogenic Pb) the ^{207}Pb correction method has been used (see Williams, 1998). When the ^{207}Pb correction is applied it is not possible to determine radiogenic $^{207}Pb/^{206}Pb$ ratios or ages. In general the $^{207}Pb/^{206}Pb$ ages have been used in the probability density spectra for areas older than 800 Ma, whereas for zircons <800 Ma the $^{206}Pb/^{238}U$ age is used. The concentration of U, and thereby radiogenic Pb, is also taken into account for selecting preferred ages. A number of areas analyzed have been interpreted to be discordant and this has been based in part on the proximity to the concordia curve (using the total ratios, uncorrected for common Pb), and in part on whether the radiogenic $^{206}Pb/^{238}U$ age is part of a grouping of like ages, or a single outlier significantly younger than the inferred depositional age of the strata. Such interpreted discordant analyses have been excluded from the age spectra.

All Salt Range samples (Khewra, Khussak, and Bhaganwalla formations) collected for detrital zircon U-Pb geochronology were processed and analyzed at the UTChron laboratory, Department of Geological Sciences, University of Texas at. Zircon grains were extracted from sandstone samples using standard mineral separation techniques, which included crushing, passing samples over a density-separation water table, magnetic separation, and heavy liquids. Whole individual zircon grains were fixed on a ~1 inch resin mount with double-sided tape for analysis via laser ablation inductively coupled mass spectrometry (LA-ICP-MS). Mounts were placed into a Helex 9 sample cell, volume c.30 cm^3, and ablated with a 30 μm spot from a Photon Machines Analyte G2 ATLex 300si ArF Excimer laser. Ablated material was carried by helium gas to a ThermoFisher Element2 double-focusing magnetic sector ICP-MS for isotopic measurements. Data analysis was accomplished using Iolite (Igor Pro). Further details provided in the table below.

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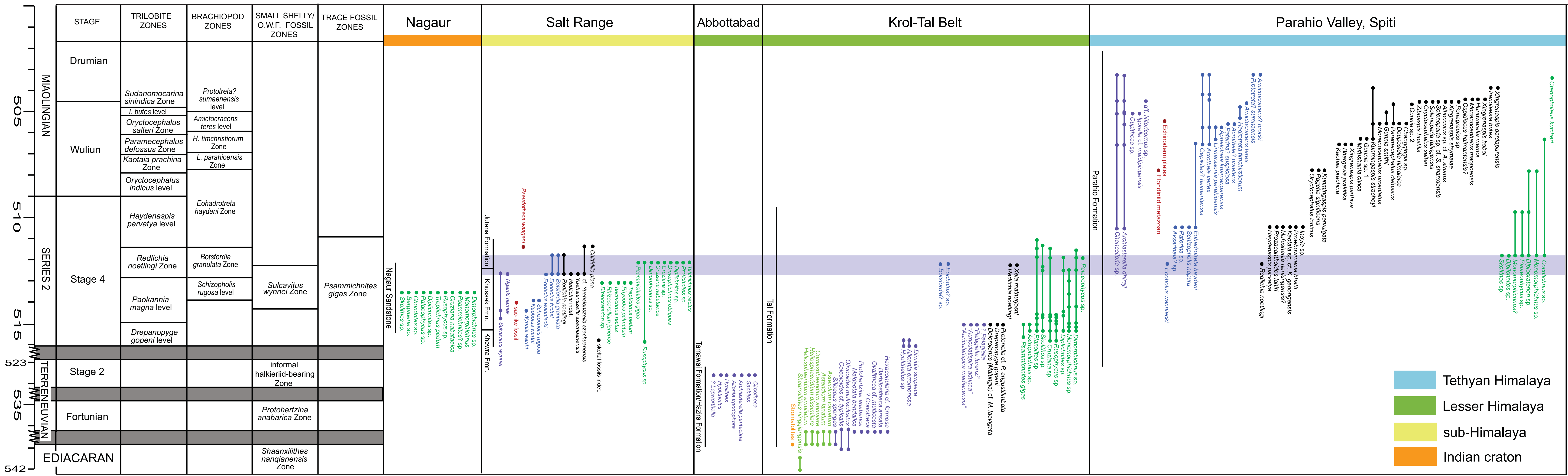
Data reporting Information for LA-ICP-MS U-Pb data

Laboratory & Sample Preparation	
Laboratory name	UTChron, Department of Geological Sciences, University of Texas at Austin
Sample type/mineral	Detrital zircons
Sample preparation	Conventional mineral separation, 1 inch resin mount, grain mount on double-sided tape
Laser ablation system	
Make, Model & type	PhotonMachines Analyte.G2 ATLex 300si ArF Excimer laser
Ablation cell & volume	Helex 9 sample cell, volume c.30cm^3
Laser wavelength	193 nm
Pulse width	≤ 4ns
Energy	6 mJ, laser attenuator 16%
Fluence	1.43 J.cm^{-2}
Repetition rate	10 Hz
Spot size	30μm
Sampling mode	6 preablation shots, 35 sec of baseline data collection, 300 ablation shots, 27 sec washout
Sample cell washout time (s)	<0.5 sec
Carrier gas	He: 0.5 L/min (ultrapure)
Ablation duration/depth	30 secs at ~0.5μm/sec for depth of 15-17 μm
ICP-MS Instrument	
Make, Model & type	ThermoFisher Element2 double-focusing magnetic sector ICP-MS
Sample introduction	Ablation aerosol (dry plasma)
RF power	1000-1100 W
Cooling gas	Ar: 16 L/min
Auxiliary gas	Ar: 0.79 L/min
Sample gas	He: 0.93-1.0 L/min
Make-up gas flow	N_2: 2 L/min
Detection system	Secondary electron multiplier (SEM)
Masses measured	202, 204, 206, 207,208, 232, 235, 238, 254
Dwell time	4 ms (238U); 16 ms (207Pb)
Sensitivity (238U)	0.4% (238U dry aerosol)
Data Processing	
Gas blank	35 second on-peak zero subtracted
Calibration strategy	GJ1 used as primary reference material, Pak1 (internal) used as secondary reference material
Reference Material info	GJ1 ^{206}Pb/^{238}U 601.7 ± 1.3Ma, ^{207}Pb/^{206}Pb 607 ± 4Ma (Jackson et al, 2004, Kylander-Clark et al., 2013)
Data processing package used	Iolite (Igor Pro)
Mass discrimination	^{206}Pb/^{238}U, ^{207}Pb/^{235}U and ^{208}Pb/^{232}U normalized to reference material
Common-Pb correction	None applied
Uncertainty level & propagation	Ages are quoted at 2 sigma absolute error, propagation is by quadratic addition. Reproducibility and age uncertainty of reference material are propagated.


STAGE
TRILOBITE ZONES
BRACHIOPOD ZONES
SMALL SHELLY/ O.W.F. FOSSIL ZONES
TRACE FOSSIL ZONES
Nagaur
Salt Range
Abbottabad
Krol-Tal Belt
Parahio Valley, Spiti
MIAOLINGIAN
SERIES 2
TERRENEUVIAN
EDIACARAN
Drumian
Wuliun
Stage 4
Stage 2
Fortunian
505
510
515
523
535
542
Sudanomocarina sinindica Zone
I. butes level
Oryctocephalus salteri Zone
Paramecephalus defossus Zone
Kaotaia prachina Zone
Oryctocephalus indicus level
Haydenaspis parvatya level
Redlichia noetlingi Zone
Paokannia magna level
Drepanopyge gopeni level
Prototreta? sumaenensis level
Amictocracens teres level
H. timchristiorum Zone
L. parahioensis Zone
Eohadrotreta haydeni Zone
Botsfordia granulata Zone
Schizopholis rugosa level
Sulcavitus wynnei Zone
informal halkieriid-bearing Zone
Protohertzina anabarica Zone
Shaanxilithes nangianensis Zone
Psammichnites gigas Zone
Nagaur Sandstone
Jutana Formation
Khussak Fmn.
Khewra Fmn.
Tal Formation
Tanawal Formation/Hazira Formation
Parahio Formation
Tethyan Himalaya
Lesser Himalaya
sub-Himalaya
Indian craton