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Age and Provenance of the Nindam Formation, Ladakh, NW Himalaya: Evolution of the Intraoceanic Dras Arc Before Collision With India

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Abstract

The Dras Arc in NW India Himalaya is a belt of basaltic-andesites intercalated with arkose-dominated volcanoclastic rocks of the Nindam Formation situated along the Indus Suture between India and Eurasia. Debates exist as to whether these rocks developed in a forearc basin to the Eurasian margin or as part of an intraoceanic island arc system that collided with either India or Eurasia before final continental collision. Detrital zircons from the Nindam Formation yield U-Pb age spectra with dominant youngest age populations of ~84-125 Ma, corresponding with arc magmatism. Sandstone provenance analysis from the Nindam Formation indicates that the Dras Arc evolved from an undissected arc to dissected arc over a period of ~41 Myr. Slightly older, smaller populations occur at ~135-185 Ma, corresponding with reported ages of Neotethyan ophiolites (e.g., Spongtag). The basal section of the Nindam Formation reveals the presence of arc-derived basaltic-andesite and tonalite clasts, plus ophiolitic components sourced from an adjacent accretionary complex. There is a distinct absence of quartz or felsic granitic clasts, suggesting that the Nindam Formation did not develop as a forearc basin to the Ladakh Batholith of southern Eurasia but rather as separate intraoceanic island arc. A distinct "Gondwanan" signature occurs in all samples, with zircon age peaks at ~514-988, ~1000-1588, ~1627-2444, and ~2500 Ma. We suggest that the Dras and Spong arcs are the same intraoceanic island arc system that developed as a result of subduction initiation along NNE-SSW transform faults perpendicular to the Indian and Eurasia continents.

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Key Points:

- The Nindam Formation was deposited in an intraoceanic forearc basin as distal deposits, largely sourced from ~84–125 Ma Dras Arc rocks
- A distinct “Gondwanan” signature composed of Precambrian populations occurs in all samples
- The intraoceanic Dras Arc collided and accreted onto the passive margin of India before final continental collision

Supporting Information:

- Supporting Information S1
- Table S1
- Table S2
- Table S3
- Table S4
- Table S5

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Age and Provenance of the Nindam Formation, Ladakh, NW Himalaya: Evolution of the Intraoceanic Dras Arc Before Collision With India

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Abstract The Dras Arc in NW India Himalaya is a belt of basaltic-andesites intercalated with arkose-dominated volcanoclastic rocks of the Nindam Formation situated along the Indus Suture between India and Eurasia. Debates exist as to whether these rocks developed in a forearc basin to the Eurasian margin or as part of an intraoceanic island arc system that collided with either India or Eurasia before final continental collision. Detrital zircons from the Nindam Formation yield U-Pb age spectra with dominant youngest age populations of ~84–125 Ma, corresponding with arc magmatism. Sandstone provenance analysis from the Nindam Formation indicates that the Dras Arc evolved from an undissected arc to dissected arc over a period of ~41 Myr. Slightly older, smaller populations occur at ~135–185 Ma, corresponding with reported ages of Neotethyan ophiolites (e.g., Spongtag). The basal section of the Nindam Formation reveals the presence of arc-derived basaltic-andesite and tonalite clasts, plus ophiolitic components sourced from an adjacent accretionary complex. There is a distinct absence of quartz or felsic granitic clasts, suggesting that the Nindam Formation did not develop as a forearc basin to the Ladakh Batholith of southern Eurasia but rather as separate intraoceanic island arc. A distinct “Gondwanan” signature occurs in all samples, with zircon age peaks at ~514–988, ~1000–1588, ~1627–2444, and ~2500 Ma. We suggest that the Dras and Spong arcs are the same intraoceanic island arc system that developed as a result of subduction initiation along NNE-SSW transform faults perpendicular to the Indian and Eurasia continents.

1. Introduction

The collision and accretion of juvenile intraoceanic arcs and ophiolite complexes is an important mechanism of continental growth (Charvet, 2013; Lee et al., 2007; Rioux et al., 2007). Collisional events involving island-arc complexes colliding with continental crust can result in drastic, widespread deformation, for example, the Semail ophiolite on the Arabian margin (Searle et al., 2004) or the Luzon Arc colliding with Eurasia in Taiwan (Huang et al., 2008). Examples of arc-continent collisions also occur in older orogens such as Central Asia (e.g., Xiao et al., 2004) and western North America (e.g., Coney, 1989), where they are recognized as important “quantum” additions to the growth of continental margins (Aitchison & Buckman, 2012) compared to the usual accretionary processes (Cawood & Buchan, 2007). The recognition of oceanic, island arc terranes onto continental margins is often complicated by the intense deformation and fragmentation associated with collision, uplift, and subsequent erosion. Obducted island arc terranes transferred from the downgoing subducting plate to the overriding plate are often poorly preserved or completely missing due to the destructive nature of collision and subsequent erosion following uplift (Draut & Clift, 2013). This, combined with the zircon-poor nature of the predominantly mafic-intermediate (basaltic-andesitic) composition of magmatism within the early stages of most island arcs means that unveiling their inception and early history can be hard to ascertain. On the other hand, marine forearc basins can provide a near continuous detrital record of arc evolution while they remain a depocenter for material shed from the active arc. Well-preserved forearc basin sequences such as the Nindam Formation in Ladakh, NW India, permit study of the evolution of the Dras Arc before it collided with either India or Eurasia. Forearc basins record the history of arc massif unroofing and evolution, as well as the influx of detritus from more distal sources (Moore et al., 2015). These basins are not only important reservoirs for detritus shedding directly off the arc, they are also able to provide insight into

Figure 1. Regional tectonic setting of the Himalayan-Tibetan orogen, displaying Tethyan ophiolite remnants in black. Map modified from Buckman et al. (2018). DEM sourced from Global Mapper software (Global Mapper, L., 2009). The study area is shown with a red rectangle.

other allochthonous terranes which may have contributed detritus, as evidenced by detrital zircon populations and provenance studies.

The Dras Arc is located along the Indus Suture, the westerly extent of the Indus-Yarlung-Tsangpo Suture (IYTS) in NW India (Figure 1). To the west near the township of Kargil, it is dominated by basaltic andesites of the Dras Formation, while further east near the township of Khalsi it is dominated by forearc arkose-dominated volcanoclastic rocks of the Nindam Formation (Clift et al., 2000; Clift, Hannigan, et al., 2002; Robertson & Degnan, 1994). Given the unambiguous stratigraphic relationships between the Dras Formation and sedimentary Nindam Formation compared to the clearly faulted contacts marked by extensive mélange with the Indus Molasse and Ladakh Batholith to the north and the Indian Lamayuru Complex to the south, we use the term Dras-Nindam terrane to refer collectively to this mafic, island arc complex. The Dras-Nindam terrane is generally regarded as equivalent to the lower crustal Chilas Complex of the Kohistan Arc to the west in Pakistan (Bilqees et al., 2016; Khan et al., 1989; Schaltegger et al., 2002). However, debates exist as to whether the Dras-Nindam terrane developed as the forearc basin to the Eurasian margin (Fuchs, 1982; Honegger et al., 1982) or as a purely intraoceanic island arc that may have collided with either India or Eurasia before final continental collision (Clift et al., 2000; Corfield et al., 2001). In this paper, detailed field mapping, provenance studies, whole-rock geochemistry, and detrital zircon geochronology are presented to help resolve debate concerning the age and origin of the Dras-Nindam terrane and the nature of this arc-continent collision in relation to the final continent-continent collision of India and Eurasia.

2. Geological Setting

The IYTS separates Eurasian and Gondwanan continental rocks but also includes fragments of intraoceanic ophiolitic, island arc and seamount material accreted onto either continent before final collision (Aitchison

et al., 2003; Hébert et al., 2012). To understand fully and reconstruct the collision, it is imperative to distinguish between Eurasian, Gondwanan, or intraoceanic units across the suture.

2.1. Indian Passive Margin

2.1.1. Zaskar Supergroup

The Zaskar Supergroup occurs to the south of the Indus Suture, representing the shallow marine Indian passive margin (Fuchs, 1982; Gaetani & Garzanti, 1991; Garzanti et al., 1987). It consists predominantly of Permian to lower Eocene carbonates, shales, and sandstones. Importantly, this sequence structurally underlies obducted ophiolitic nappes, such as the Spong tang Massif (Reuber, 1986). The youngest known units overlying the Zaskar Supergroup are the Eocene Chulung La and Kong formations (Fuchs, 1982; Fuchs & Willems, 1990), with the youngest detrital zircon age of these units being 54 ± 2 and 56 ± 1 Ma, respectively (Najman et al., 2017).

2.2. Neotethyan Indus Ophiolites

2.2.1. Spong tang Ophiolite

The Spong tang Massif is located ~30 km south of the Indus Suture as an almost complete ophiolite klippe thrust over the Indian Zaskar Supergroup (Buckman et al., 2018; Fuchs, 1982; Gansser, 1964; Reuber, 1986; Searle, 1986). Gabbro from the Spong tang Ophiolite was initially dated by Pedersen et al. (2001) as 177 ± 1 Ma, using the zircon U-Pb (TIMS, thermal ionization mass spectrometry) method. The Spong Arc developed on top of, and into, the ophiolitic complex as subduction continued after arc initiation at ~135 Ma (Buckman et al., 2018) and up until at least 88 Ma as indicated by U-Pb age of a Spong Arc andesite (Pedersen et al., 2001). Baxter et al. (2010) reported Early Cretaceous radiolarian faunal assemblages from red cherts associated with the Spong Arc. The Spong tang Massif is generally interpreted as an Early Jurassic (Pedersen et al., 2001) fragment of mid-ocean ridge material that the Spong Arc developed on top of throughout the Cretaceous from ~135 Ma to at least 88 Ma (Buckman et al., 2018; Pedersen et al., 2001). There is a debate surrounding the age for emplacement of the Spong tang Ophiolite, with some proposing obduction between 75 and 60 Ma (Searle, 1986), while others prefer an emplacement age between 55 and 50 Ma (Buckman et al., 2018; Garzanti et al., 2005) based on the fact that the Spong tang Ophiolite is thrust over the youngest Eocene Chulung La and Kong formations (Najman et al., 2017) that are units of the Indian Zaskar Supergroup.

2.2.2. Nidar Ophiolite

The Nidar Ophiolite, preserved in eastern Ladakh, is located to the east of the Spong tang Massif (Ahmad et al., 2008; Mahéo et al., 2004) and developed at about the same time (130–110 Ma) as the Spong Arc (Mahéo et al., 2004). The presence of ~55 Ma eclogites (Tso Moriri) to the south of the Nidar Ophiolite records subduction of Indian continental rocks (Panjal Traps) associated with arc collision (de Sigoyer et al., 2000). This corresponds well with the Eocene emplacement age established at Spong tang (Buckman et al., 2018).

2.3. The Dras-Nindam Terrane

The Dras-Nindam terrane extends some 400 km along the Indus Suture in the Ladakh Himalaya and is 15-km wide (Clift et al., 2000; Fuchs, 1982; Reuber, 1989; Robertson & Degnan, 1994; Figure 2a). To the north, the complex is faulted against the Ladakh Batholith and associated forearc basin material of the Tar Group (Henderson et al., 2010). The fault is marked by the serpentinite-matrix Mongyu Mélange (Robertson, 2000; Figure 2b). This mélange contains blocks of the adjacent Dras-Nindam terrane and Eurasian-derived Tar Group. To the south, the Dras-Nindam terrane is thrust over the highly disrupted Lamayuru Complex, which represents the mud matrix mélange developed at the faulted contact with Indian continental rocks (Robertson & Degnan, 1993). Slivers of disrupted ophiolitic mélange also occur along this southern contact and contain numerous basalt, chert, gabbro, and blueschist blocks (Corfield & Searle, 2000; Groppo et al., 2016; Honegger et al., 1989; Robertson, 2000; Robertson & Degnan, 1994). Most of the deformation within the Dras-Nindam terrane is the result of large-scale north directed, backthrusting and folding attributed to postcollisional (continent-continent) uplift of the High Himalaya (Searle et al., 1988). The succession is largely an intact overturned sequence, aside from localized faulting. The Dras-Nindam terrane can be divided into four structural units; (i) the Dras Arc, (ii) Suru Formation, (iii) Naktul Formation, and (iv) Nindam Formation. The Chilling Formation, demonstrating arc-derived sedimentation is also described.

Figure 2. Regional tectonic setting of the Dras-Nindam terrane, Ladakh NW India. (a) Extent of the Dras-Nindam terrane along the Indus Suture, including major tectonic units; (b) inset geological transect through the Nindam Formation between the townships of Khalsi (north) and Lamayuru (south). The youngest indistinguishable zircon population is given for each sample. Adapted from Robertson and Degnan (1994) and Steck (2003).

2.3.1. Dras Formation

The Dras Formation, informally referred to as the Dras Volcanics, consists of a belt of basaltic-andesitic volcanic rocks and associated volcanoclastic turbidites situated between the Ladakh Batholith and associated Indus Group/Molasse deposits to the north and the Indian Lamayuru Complex to the south. The mafic volcanic rocks have geochemical signatures typical of modern day, juvenile island arc environments in which there is little or no continental influence (Dietrich et al., 1983; Robertson & Degnan, 1994). The Dras Arc has been correlated with the Kohistan Arc of Pakistan (Clift, Hannigan, et al., 2002) and may be similar to the Zedong terrane in Tibet (Aitchison et al., 2000; McDermid et al., 2002). Correlations with the Kohistan

Arc have been made on the basis of geographic proximity, radiometric ages, and common lithologies (Coward et al., 1987; Khan et al., 1993; Robertson & Degnan, 1994), but it is important to note that there is no continuous exposure between the Dras and Kohistan arcs. Honegger et al. (1982) and Schärer et al. (1984) produced zircon U-Pb ages for gabbroic to granodioritic plutons of 103 ± 3 and 101 ± 2 Ma, respectively. These plutons intrude the Dras Formation, indicating it is at least 100 Ma. Reuber (1989) produced K-Ar dates of the Dras Formation ranging between 105 and 95 Ma and an age range between 98 and 92 Ma for a diorite that intruded into the volcanic rocks. Diorite plutons within the Dras Arc are geochemically similar to the calc-alkaline Ladakh and Gangdese batholiths of the Trans-Himalayan intrusive suites, in that they are calc-alkaline, albeit more intermediate than the granitic Ladakh Batholith. For that reason, Coward et al. (1987) interpreted the Kohistan-Dras Arc as originally a single entity that collided with Eurasia at ~100 Ma. Similarly, other researchers propose that the Kohistan and Ladakh terranes were once a single entity, referred to as the Kohistan-Ladakh island arc. They suggest that the Dras Arc is a component of this Aleutian-style island arc system which developed on the southern margin of Eurasia, which has the Nindam Formation developing as the equivalent forearc basin sequence (Bouilhol et al., 2013; Burg, 2011).

2.3.2. Suru Formation

The Suru Formation (Robertson & Degnan, 1994) is the western-most part of the Dras-Nindam terrane and incorporates island arc intrusive rocks, extrusive and related volcanoclastic/sedimentary material. Large blocks of neritic limestone were interpreted by Robertson and Degnan (1994) as collapsed oceanic atolls. This unit is up to 5-km thick and is considered to represent the interior of the Dras Arc. Structurally, the Suru Formation overlies Neotethys oceanic crust and mantle-derived material, including pillow basalts, gabbros, and ultramafic rocks (Honegger, 1983; Reuber, 1989). The Suru Formation can be divided into the Dras I and Dras II subunits (Reuber, 1989), which represent a lower metamorphosed and deformed unit, and an upper, unconformably overlying unmetamorphosed and less-deformed unit, respectively. Robertson and Degnan (1994) describe the Dras II subunit as acidic volcanic rocks and fine-grained volcanoclastic turbidites. They suggest this largely undeformed and nearly horizontal unit represents postcollisional magmatism, whereby the intraoceanic Dras Arc collides with Eurasia, and is overlain by volcanic and associated material of the Dras II subunit (Robertson & Degnan, 1994). The Suru Formation overlies Callovian-Tithonian radiolarian cherts (Honegger, 1983). Within the lavas of this formation, interbedded calcareous units yielded foraminifera (*Orbitulina*; Reuber, 1989), while an ammonite (*Oxytropidoceras*) reported from nearby Kargil was presumed to be mid-Cretaceous (late Albian; Thieuloy et al., 1990). The oldest K-Ar and U-Pb ages are 110–90 Ma, while the youngest are 80–60 Ma (Honegger et al., 1982; Reuber, 1989; Sharma, 1987; Sharma et al., 1978).

2.3.3. Naktul Formation

The Naktul Formation structurally overlies the Suru Formation and is composed of coarse-grained volcanoclastic material intercalated with minor basic intrusive rocks, limestones, and chert (Reuber, 1989; Sutra, 1990). The formation is elongated in outcrop and exposed east of the township of Kargil. It is devoid of any arc plutonic rocks. Robertson and Degnan (1994) interpreted this formation to represent a marginal-arc setting, with sedimentation occurring along the flanks of the Dras Arc. The Naktul Formation and the Nindam Formation are separated from each other by a thin strip of serpentinite-matrix mélange. Within the Naktul Formation *Orbitulina* and other foraminifera are assigned Aptian-Cenomanian in age (125–94 Ma) by Sutra (1990), with Robertson and Degnan (1994) reporting Late Cretaceous foraminifera ages. Basaltic dykes cross-cutting ultramafic basement of the Naktul Formation have been dated at 97 ± 7 Ma using K-Ar (Reuber, 1989).

2.3.4. Nindam Formation

The Nindam Formation overlies the Suru and Naktul formations and is the easternmost part of the Dras-Nindam terrane, representing the most distal facies of this stratigraphic sequence. It comprises up to 2.5 km of interbedded volcanoclastic turbidites and shales, with minor pelagic carbonates and a conglomerate package dominated by limestone clasts. Robertson and Degnan (1994) provided detailed stratigraphic and petrographic descriptions of sections through the Nindam Formation. They interpreted the Nindam Formation to have developed in a deep marine environment, dominated by juvenile volcanoclastic lithofacies, calci-turbidites, minor chert and tuff and some mass-flow conglomerates derived from the nearby Dras intraoceanic arc complex. Between the townships of Lamayuru and Khalsi (Figure 2b), the Nindam Formation is an overturned sequence demonstrating overall stratigraphic younging toward the north. In the eastern section of the Nindam Formation, *Globotruncana*, and various macrofossils have been

biostratigraphically placed as Upper Cretaceous (Sutre, 1990), while other beds exhibit redeposited shallow water microfossils assigned as Lower Cretaceous (Sutre, 1990). Isotopic dating of the Nindam Formation has not been undertaken previously.

2.3.5. Chilling Formation

The Eocene Chilling Formation, previously referred to as the Chilling Molasse (Fuchs, 1986) or Khalsi Molasse (Clift, Carter, et al., 2002) was first recognized and described by Sterne (1979) as a unit faulted between the Zaskar Supergroup and the Nindam Formation. The unit consists of green-purple-red siltstones, shales, and mass-flow conglomerates. Clasts within the conglomerates of the Chilling Formation include ophiolitic-derived peridotite, gabbro, basalt, chert, and volcanoclastic material, similar in composition to blocks within the southern *mélange* zone (Urtsi-Wanlah-Shergole *Mélange*) located along the southern contact of the Dras-Nindam terrane. Other clasts have been sourced from the Zaskar Supergroup and Lamayuru Complex and include nummulitic limestone and quartzite, respectively. Chrome spinels from the Chilling Formation are geochemically similar to in situ samples taken from the Spongtag Ophiolite, for which Baxter et al. (2016) used to illustrate arc-derived sedimentation in NW India during the earliest Eocene.

2.4. Collisional *Mélange* Zones

Two distinct *mélange* zones flank the Dras-Nindam terrane (Figure 2). The Mongyu *Mélange* occurs along the northern margin near the township of Khalsi and has been described in detail by Robertson (2000). It is well exposed along strike, trending east-west for ~30 km between the villages of Mongyu in the east to Hungru in the west, where it separates the volcanoclastic sandstones and turbidites of the Nindam Formation in the south from the shallow-water platform carbonates of the Lower Cretaceous Khalsi Limestone in the north (Robertson, 2000). The southern *mélange* zone occurs along the contact between the Dras-Nindam terrane and the Indian Zaskar Supergroup. It includes the Urtsi, Wanlah and Shergol *mélanges* and grades into the mud-matrix *mélange* of the Lamayuru Complex (Danelian & Robertson, 1997; Robertson & Sharp, 1998). The Urtsi-Wanlah-Shergol *Mélange* has been interpreted as either representing the Late Jurassic oceanic basement of the Nindam Formation (Sutre, 1990) or a thrust-bound subduction-accretionary complex (Searle et al., 1987; Sinha, 1990; Thakur, 1990).

2.5. Eurasian Margin

The southern margin of Eurasia consists of the Jurassic to Cretaceous (162–95 Ma) continental Karakoram Arc in the Ladakh region (Borneman et al., 2015; Heuberger et al., 2007; Le Fort et al., 1983), which was active until closure of the Shyok Ocean and collision with the Jurassic Shyok ophiolite-arc complex (Robertson & Collins, 2002). For a detailed review see Saktura et al. (2019). Closure of the Shyok Ocean coincides with onset of the Ladakh Arc.

2.5.1. Ladakh Batholith

The Ladakh Batholith, extending for ~600 km, is bound in the north by the Shyok Suture Zone and to the south by the Indus Suture (Singh et al., 2007). The batholith consists of calc-alkaline (I-type) intrusive rocks ranging from gabbroic to granitic in composition (Honegger et al., 1982; Singh et al., 2007; White et al., 2011) and associated extrusive rocks of the Khardung Formation, which are andesitic to rhyolitic in composition (Dunlap & Wysoczanski, 2002). The Ladakh Batholith is generally accepted as the equivalent of the Kohistan Batholith in Pakistan but separated by the Nanga Parbat Syntaxis. Together, these two entities are commonly referred to as the Kohistan-Ladakh island arc; (Bouilhol et al., 2013; Ewing & Müntener, 2018). The Ladakh Batholith intrudes Jurassic rocks of the Shyok ophiolite (Reuber, 1990). Honegger et al. (1982) suggested the Ladakh Batholith was episodically active between 110 and 40 Ma, with the most voluminous and pervasive phase occurring at ~60 Ma. Zircon dating by White et al. (2011) indicated that the Ladakh Batholith was emplaced episodically between 66 and 46 Ma. They proposed that the bulk of the batholith was emplaced between 63 and 55 Ma, with a final phase of magmatism resulting in aplitic cross-cutting leucogranites, pegmatitic dike swarms, and subvolcanic dikes at ~46 Ma, which also constrains the maximum age of final continent-continent collision. They found no evidence for an older 103–101 Ma magmatic phase similar to ages reported for the Kargil Intrusive Complex (Honegger et al., 1982; Schärer et al., 1984), which led Buckman et al. (2018) to suggest that the Kargil Intrusive Suite may represent the core of the Dras Arc, which it intrudes into, rather than representing an older phase of the separate Ladakh Arc.

Table 1
Framework Modal Results of the Nindam Formation Volcaniclastics

Samples	Q	F	L	Qm	Qp	P	K	Lv	Lc	Total point counting values
15ND02	3	32	65	2	0	17	15	41	24	312
15ND03	6	6	88	5	1	5	1	65	23	308
16NI01	7	25	68	5	2	13	13	25	42	365
16NI02	4	9	88	4	0	5	4	32	55	337
16NI03	5	14	81	5	0	6	8	32	49	348
16NI06	6	6	88	5	0	3	3	62	26	415
16NI08	3	47	51	3	0	19	28	19	32	316
16NI09	5	24	71	5	0	9	15	37	34	388
16NI13	4	29	67	3	1	24	6	54	13	377
16NI16	2	43	55	2	0	37	6	44	11	316
Average (%)	4	24	72	4	0	14	10	41	31	

Note. Q = total quartz; F = total feldspar; L = total lithic fragments (including chert); Qm = monocrystalline quartz; Qp = polycrystalline quartz; P = plagioclase; K = K-feldspar; Lv = volcanic rock fragment; Lc = chert fragment. Raw point-counting data are available in the supporting information (Table S2).

2.5.2. Tar Group (Ladakh Forearc Basin)

From base to top, the Tar Group consists of the Jurutze Formation, Khalsi Limestone, Sumda Formation, Chogdo Formation, and finally a distinct Nummulitic Limestone unit (Henderson et al., 2010). These units were deposited in a shallow marine forearc basin to the Ladakh Batholith (Clift, Carter, et al., 2002; Garzanti & Van Haver, 1988; Sinclair & Jaffey, 2001; Steck et al., 1993). The group consists of Cretaceous (Albian) to lower Eocene clastic rocks and carbonates, including interbedded siltstones, shales and sandstones, debris-flow immature turbidites, conglomerates and breccias, and deep marine limestones to shallow-water platform carbonates (Clift, Carter, et al., 2002). The Jurutze Formation and the Khalsi Limestone are the oldest sections of the Tar Group and are juxtaposed against the Nindam Formation to the south. This south dipping thrust fault is marked by the Mongyu Mélange (Robertson, 2000; Figure 2). The Lower Cretaceous (Aptian-Albian) Khalsi Limestone includes interbedded limestone with deep marine turbidites with minor siltstone and shale (Brookfield & Andrews-Speed, 1984; Clift, Carter, et al., 2002). The Jurutze Formation has a youngest detrital zircon population of 53.4 ± 1.4 Ma with almost all ages between 53 and 100 Ma, reflecting the age range of the Ladakh Batholith (Henderson et al., 2010). The

overlying, granite-rich, conglomerates of the Sumda and Chogdo formations contain detrital zircon populations between 50 and 100 Ma again reflecting almost exclusively Ladakh Arc provenance. The overlying Nummulitic Limestone has a biostratigraphic age of 49.4–50.8 Ma (Green et al., 2008), which correlates closely with the youngest detrital zircon age of 52.5 ± 0.7 Ma (Henderson et al., 2010), but also shows the first sign of a change in provenance with the presence of an additional 150–160 Ma detrital zircon population.

2.6. Postcollisional Indus Group

The Indus Group (commonly referred to as the Indus Molasse) unconformably overlies the Tar Group and consists of mid Eocene to early Miocene postcollisional sedimentary deposits, which record the timing of continental collision between India and Eurasia; but the age and stratigraphic relations of these highly deformed and disrupted units are debated (Brookfield & Andrews-Speed, 1984; Clift et al., 2001; Garzanti & Van Haver, 1988; Henderson et al., 2010; Henderson et al., 2011; Searle et al., 1990; Sinclair & Jaffey, 2001; Van Haver, 1984). The Indus Group has been divided into a number of formations; importantly, recent work by Henderson et al. (2011) has revealed that the youngest detrital zircon population of 41 Ma in the Upper Nimu Formation may represent the latest stage calc-alkaline magmatism of the Ladakh Batholith and thus constrain the onset of final continental collision.

3. Methods

3.1. Field Investigations

Samples were collected along two stratigraphic traverses from the Dras Formation and the Nindam Formation (Figure 2). See supporting information (Table S1) for sample localities and lithological descriptions. The traverse through the Dras Formation was between the townships of Kargil (NW) and Shergol (SE). The traverse through the Nindam Formation was between the townships of Khalsi (NE) and Lamayuru (SW) on the new road along the Yapola River tributary of the Indus River (Figure 2b) which replaced the Lamayuru Loops road along which Robertson and Degnan (1994) conducted their work.

3.2. QFL Point Counting

The modal composition of 10 volcaniclastic sandstones (Table 1 and supporting information Table S2) of the Nindam Formation was determined by adopting the point counting method of Dickinson and Suczek (1979). The detrital grains of the Nindam Formation are categorized as monocrystalline quartz (Qm), polycrystalline quartz (Qp), total quartz (Q), plagioclase (P), K-feldspar (K), and total feldspar (F). The unstable lithic fragments consist of volcanic/metavolcanic rocks (Lv) and minor fragments of both sedimentary/metasedimentary (Ls) and metamorphic (Lm) rocks. However, total lithic fragments (L) stands for unstable lithic fragments and chert (Lc) fragments (Lv + Ls + Lm + Lc). If chert is in high abundance,

then it is considered a lithic fragment, rather than a subtype of quartz (i.e., polycrystalline or monocrystalline quartz).

3.3. Whole-Rock Geochemistry

Fifteen volcanoclastic, six shale, and seven basaltic-andesite samples (supporting information Table S3), were crushed using a tungsten carbide TEMA ring mill. Fused buttons were made for X-ray fluorescence major element analysis. Depending on elemental concentrations estimated in trace element analysis, different types of flux were used. Pure metaborate was used for high silica samples, 57% tetraborate to 43% metaborate was used for ultramafic samples, and 12% tetraborate to 22% metaborate was used for mafic samples. Sample (400 mg) was added to each flux (300 mg for pure metaborate). Pressed pellets for trace element analysis were created by mixing ~5 g of sample with a polyvinyl acetate binder and pressed into an aluminum cup using a hydraulic hand press. Trace element pressed pellets were then oven dried at 60 °C for 12 hr. Whole-rock geochemical analysis was conducted using a SPECTRO XEPOS energy dispersive polarization X-ray fluorescence spectrometer at the University of Wollongong, Australia. Additional trace elements and the rare earth element (REE) analyses were undertaken at Australian Laboratory Services (ALS) Minerals Division, Brisbane, Australia using ICP-MS (geochemical procedure code ME-MS81). Li metaborate and Li tetraborate were used as fluxes with and after fusing in a furnace, the resultant melt was dissolved in nitric, hydrochloric, and hydrofluoric acid mixes. This solution was then analyzed by ICP-MS. Standards, OREAS 120 and STSD-1, as well as five sample duplicates and three blanks, were analyzed in order to determine the error tolerance. All were within 10% of error.

3.4. Zircon U-Pb Geochronology

3.4.1. Zircon Preparation

Zircons were separated at the Institute of Hebei Regional Geology Survey, China. The samples were chipped in a precontaminated jaw crusher, using a subsample first. Chips were thoroughly washed with water, then dried prior to being ground into a coarse powder using a jaw crusher. The coarse powder was separated into heavy and light fractions using heavy liquids to obtain the >3.31 zircon-bearing fraction. The heavy fraction was washed and dried prior to being passed through a Franz Isodynamic Magnetic Separator to obtain zircons (normally the nonmagnetic fraction at 2A). Zircon grains were examined using a binocular microscope, handpicked and mounted with standard TEMORA II grains on a glass plate with double-sided tape, which were then cast with epoxy resin in a mold. TEMORA II was distributed as several clusters of grains in different parts of the zircon mount to increase confidence in the accuracy of calibration of U-Pb across the entire mount when analyzed by ion microprobe. The mounts were then polished with 1- μ m diamond paste to reveal approximately half sections through the zircons. Transmitted and reflected light photomicrographs were taken, along with cathodoluminescence (CL) imaging. The CL images were obtained using a Scanning Electron Microscope (SEM) JEOL JSM-6490LV with a 15-kV conventional tungsten filament thermionic source coupled with a Gatan MonoCL4 used in polychromatic mode at the Electron Microscope Centre (EMC), Innovation Campus, University of Wollongong.

3.4.2. LA-ICP-MS

A total of 791 zircon grains were chosen from eight samples (supporting information Table S4) for detrital zircon U-Pb dating using the LA-ICP-MS instrument at the University of Queensland (UQ), Australia. One hundred forty-four unknowns were rejected on the basis of not having concordant U-Pb ages or having $Sr(cps) \geq 2,000$. The rejected grains were excluded from age assessments. The zircon 91500, which has a $^{206}Pb/^{238}U$ age of 1062.4 ± 0.4 Ma and $^{206}Pb/^{207}Pb$ age of 1065.4 ± 0.3 Ma, was used as the primary reference material (Wiedenbeck et al., 1995). TEMORA II was also employed as a secondary reference material, which has a $^{206}Pb/^{238}U$ age of 416.78 ± 0.33 Ma (Black et al., 2004). Laser ablation was undertaken using an ASI RESOLUTION 193 ArF nm excimer laser system. Following evacuation of air, He carrier gas was introduced into the laser cell at a flow rate of 0.35 L/min. A 0.05 L/min of N_2 gas was also introduced to the laser cell to enhance the measurement sensitivity. The gas mixture was then introduced into the plasma torch of a Thermo iCAP RQ quadrupole ICP-MS with 0.85 L/min Ar nebulizer gas. No reaction gas was employed. The laser was run with a 30- μ m diameter round spot at 10 Hz, with a measured instrument laser-fluence (laser pulse energy per unit area) of $2.9 J/cm^2$. For each spot, 5 s of blank was collected, followed by 25 s of ablation and 10 s of wash out. Prior to data acquisition, ICP MS signals were optimized during tuning. Parameters particular to the analytical session that include ~400 K cps of ^{238}U counts, ~1 of $^{238}U/^{232}Th$,

and ~ 0.21 of $^{206}\text{Pb}/^{238}\text{U}$ were achieved for measuring NIST612 glass using line scans of $3\text{ }\mu\text{m/s}$, 10 Hz , $50\text{ }\mu\text{m}$ round laser pit, and 3 J/cm^2 . The following isotopes were collected using a single collector: ^{88}Sr (dwell time = 0.005 s), ^{91}Zr (dwell time = 0.001 s), ^{200}Hg (dwell time = 0.01 s), $^{204}\text{Pb} + ^{204}\text{Hg}$ (dwell time = 0.01 s), ^{206}Pb (dwell time = 0.045 s), ^{207}Pb (dwell time = 0.055 s), ^{208}Pb (dwell time = 0.01 s), ^{232}Th (dwell time = 0.01 s), ^{238}U (dwell time = 0.01 s). A single cycle took $\sim 0.155\text{ s}$. Therefore, during a 25-s ablation, ~ 160 measurements were made on each mass. Reduction of raw data was accomplished using the program *IOLITE* (Paton et al., 2011). No common Pb correction on 91,500 zircon was undertaken. From the session, a $^{206}\text{Pb}/^{238}\text{U}$ age of $419.0 \pm 1.1\text{ Ma}$, uncorrected for common Pb (95% confidence, $n = 93$, MSWD = 7.7) for the TEMORA II secondary reference material was obtained, which has a TIMS $^{206}\text{Pb}/^{238}\text{U}$ age of $416.78 \pm 0.33\text{ Ma}$ determined by ID TIMS (Black et al., 2004). $^{206}\text{Pb}/^{238}\text{U}$ ages are reported for $<1000\text{ Ma}$ grains, whereas $^{207}\text{Pb}/^{206}\text{Pb}$ ages are reported for $>1000\text{ Ma}$ grains.

3.4.3. SHRIMP

A total of 50 grains from samples 15ND02 and 15ND03 (supporting information Table S5) were chosen for zircon U-Pb dating using the SHRIMP-RG (Sensitive High Resolution Ion Microprobe-Reverse Geometry) instrument at the Australian National University (ANU). Zircon mounts were cleaned and coated with $\sim 10\text{ nm}$ of high purity Au ($>99.999\%$) before analysis and followed the analytical procedure of Williams (1998). Two unknowns were rejected on the basis of not having concordant U-Pb ages. The rejected grains were excluded from age assessments. Sites within the zircon grains were selected according to their apparent reflectance (brightness) on the polished surface (information gained from reflected light photomicrographs), along with well-formed structure (information gained from CL images). Particular note was made to avoid analyzing cracked or damaged zircons and dark zones within grains (indicative of high U + Th content). U-Th abundance was calibrated based on the reference zircon SL13 (U = 238 ppm). After site selection was made the instrument was alternated between running manually and programmed to run automated at night. A total of five cycles were made at each of the nominal mass stations: ^{196}Zr , ^{204}Pb , background $^{204.1}\text{Pb}$, Pb (^{206}Pb , ^{207}Pb , ^{208}Pb), ^{238}U , ^{248}ThO ($^{232}\text{Th} + ^{16}\text{O}$), and ^{254}UO ($^{238}\text{U} + ^{16}\text{O}$). Parameters particular to the analytical session include a spot size of $\sim 15\text{--}20\text{ }\mu\text{m}$, with the primary O_2^- ion beam of 5 nA . TEMORA II was analyzed for U-Pb calibration after every three to four analytical sites (17 times in total). Five analyses of TEMORA II had to be rejected based on anomalously low UO/O ratios (<3.65 versus typically ~ 6). On the basis of higher Zr count rates, it is possible that the rejected grains were in fact not zircon, but another Zr-bearing mineral species (possibly baddeleyite). The raw data were reduced using the program *POXI-SC* developed by ANU, which combines the functionality of the previous two ANU applications, *Prawn* and *Lead*. Quoted errors on isotopic ratios also take into account nonlinear fluctuations in ion count rates above that expected from counting statistics alone (Williams, 1998). This is particularly important for old, damaged high U + Th zircons, where damage has resulted in postcrystallization heterogeneity of species on the sub-micron scale, as now revealed by atom probe-analysis (Peterman et al., 2016). Reliance on counting statistics only of such targets would result in underestimation of analytical error. Correction for common Pb was made in accordance to the measured ^{204}Pb and common lead composition for the likely age of the sample from Cumming and Richards (1975). $^{206}\text{Pb}/^{238}\text{U}$ were corrected using the TEMORA II standard with a concordant age of $416.78 \pm 0.33\text{ Ma}$ (Black et al., 2004). The reduced and calibrated data were then assessed and plotted using *Isoplot 4.1* (Ludwig et al., 2003). Calculated mean ages were presented at 95% confidence. $^{206}\text{Pb}/^{238}\text{U}$ ages are reported for $<1000\text{ Ma}$ grains, whereas $^{207}\text{Pb}/^{206}\text{Pb}$ ages are reported for $>1000\text{ Ma}$ grains.

4. Results

4.1. Field Relations

The Nindam Formation section between Lamayuru and Khalsi consists of deep marine, volcanoclastic turbidites, hemipelagic shales and silty limestones, and minor mass-flow conglomerates. The minimum stratigraphic thickness of the unit is $\sim 4.1\text{-km}$ thick (Figure 2). The dominantly fine-grained facies of the unit make up just over half of the formation and include red and green shales interbedded with planar bedded siltstones and calciturbidites. The medium- to coarse-grained facies include planar, bedded volcanoclastic calciturbidites with minor conglomerate lenses as described in detail by Robertson and Degnan (1994). To the north the Nindam Formation is bound by the Mongyu Mélange, which crops out along the road and occupies a thrust fault that dips at $\sim 35^\circ$ to the south (Figure 3a). Kinematic S-C fabrics in the mélange

Figure 3. Field relations of the Nindam Formation. (a) The Nindam Formation is bound to the north by the serpentinite-matrix Mongyu Mélange, which outcrops along the road and occupies a thrust fault that dips $\sim 35^\circ$ to the south. Kinematic S-C fabrics present in the mélangé are represented in yellow. Position: 34.32083°N , 76.83833°E ; (b) flute clast structures in the basal section of distal turbidites from the Nindam Formation. Position: 34.29361°N , 76.80028°E ; (c) flame structures within the turbidites with younging direction indicated by a black arrow. Position: 34.29750°N , 76.83194°E ; (d) interbedded green sandstone and red shale. Beds at this locality range from 2–10 cm. Position: 34.29383°N , 76.80006°E ; (e) representative Nindam Formation conglomerate, with clasts including limestone (ls), shale (sh), chert (ch), and basalt (bas). Position 34.29916°N , 76.82138°E ; (f) representative Indus Group (Hemis-Nurla Molasse) conglomerate, with clasts including granite (gr), shale (sh), and quartz (Qz). Position 34.32944°N , 76.83694°E .

indicate the Nindam Formation has been thrust northward over the Tar Group to the north, which locally includes the Cretaceous Khalsi Limestone. Overlying the Tar Group on the northern side of the Indus River are the postcollisional Indus Group sedimentary rocks. The measured Nindam Formation section (Figure 2b) is generally overturned and steeply dipping with younging toward the north as determined

from graded beds and sedimentary flame structures (Figures 3b–3d). There are no observable unconformities or breaks in sedimentation suggesting the entire 4.1-km thickness accumulated continuously in a deep marine setting on the flanks of the Dras Arc, which outcrops extensively along-strike farther west, near the township of Kargil. The Nindam Formation is faulted against the highly disrupted Lamayuru Complex of the Indian margin to the south. This contact is usually marked by the presence of serpentinite-matrix mélange containing basalt, chert, limestone, and volcanoclastic blocks as described by Robertson (2000) for the Urti Mélange (Figure 2).

4.2. Petrography and Mineralogy

4.2.1. QFL Diagrams

The Nindam Formation volcanoclastic sandstones are poorly to moderately sorted. Clasts vary from angular to subrounded and are surrounded by a fine-grained, silty matrix which is generally cemented by calcite (Figure 4). Lithic fragments are the most abundant detrital component contributing on average 71% of modal composition. Lithic volcanic rocks (average 41%) are more abundant than lithic chert (average 31%), with little to no sedimentary rock lithic fragments observed (Table 1 and supporting information Table S2). The volcanic lithic fragments are mafic volcanic rocks ranging from basalt to basaltic-andesite. They are generally characterized by the presence of plagioclase laths as phenocrysts. No felsites or microgranitic fragments were observed. The lithic chert fragments exhibit typical cryptocrystalline texture. Feldspar fragments constitute ~24% of the Nindam Formation volcanoclastic sandstones. Plagioclase fragments are generally altered, exhibiting seritization. Quartz occurs as subordinate amounts, making up an average of only 4% of the detrital components with monocrystalline quartz (average 4%) more abundant than polycrystalline quartz (<1%). The rare grains of monocrystalline quartz exhibit undulose extinction. Other detrital components of the Nindam Formation volcanoclastic sandstones are carbonates, alteration products, pyroxenes, micas, and amphiboles in order of decreasing abundance. Calcite is exhibited as both matrix and detrital grains. Alteration products, including chlorite with minor kaolinite, occur as rims around grains, matrix material, and replacement alteration. There are rare grains of augite and orthopyroxene. Mica is represented by minor biotite as thin flakes. Hornblende also occurs as a rare detrital component. The modal sandstone ternary plots for the Nindam Formation volcanoclastic rocks demonstrate an almost linear trend, from undissected arc to transitional arc (Figure 5). In contrast, the Indus Group (Henderson et al., 2010) demonstrate a very different spread of data which fall in the fields of transitional arc, dissected arc, and basement uplift.

4.3. Geochemistry

Whole-rock major and trace element compositions of samples from the Dras Formation, Nindam Formation, and Indus Group are given in Table S3. Our geochemical analyses are combined with previous analyses of Nindam Formation by Clift et al. (2000) and Dras Volcanics by Bhat et al. (2019) and Corfield et al. (2001). Loss on ignition values for the sedimentary rock samples are about 8 wt.% reflecting the carbonate cement and minor alteration while volcanic rock samples are only ~4 wt.% loss of ignition. The M (mafic)-F (felsic)-W (weathering) ternary diagram (Ohta & Arai, 2007) indicates that the majority of samples fall in the field of fresh calc-alkaline/mafic igneous rocks (Figure 6a) indicating minimal weathering, from source to sink.

4.3.1. Alteration

To account for modern weathering, homogenous samples were selected for analysis where surficial layers were removed and only central, fresh rock was used for analysis. The degree of ancient weathering was assessed using the MFW indices of Ohta and Arai (2007). The MFW ternary diagram (Ohta & Arai, 2007) indicates that samples from the Dras Formation (basalts, $n = 29$) and Nindam Formation (volcanoclastic sandstones, $n = 31$) fall in the fields of fresh alkali basalt to calc-alkali andesite (Figure 6a) indicating minimal weathering of the samples. Shales from the Nindam Formation ($n = 7$) have also been plotted on the MFW ternary diagram, with some samples showing intermediate weathering (Figure 6a). Immobile elements, including the high field strength elements and REE, which are less susceptible to both weathering and hydrothermal alteration, are used in lithological classification and tectonic discrimination (MacLean, 1990). Those elements regarded as mobile, including large ion lithophile elements have only been used with those samples regarded as fresh rock (see MFW ternary diagram fields, Figure 6a), evidenced by field and

Figure 4. Representative photomicrographs of the Nindam Formation volcanoclastics. (a) Poorly to moderately sorted, detrital grains varying from angular to subrounded (XPL, sample 16NI08); (b) volcanic lithics have undergone significant alteration (PPL, sample 16NI08); (c) lithic fragments are the most abundant detrital component, with volcanic fragments (basaltic-andesite) making up the majority followed by lithic chert fragments (XPL, sample 16NI06); (d) volcanic lithic fragments are mafic volcanics ranging from basalts to basaltic-andesites. They are generally characterized by the presence of plagioclase laths as phenocrysts (PPL, sample 16NI08); (e) plagioclase fragments are generally altered, exhibiting internal grain seritization. Less altered grains display typical multiple twinning (XPL, sample 16NI01); (f) quartz occurs as subordinate amounts, making up an average of only 4% of the detrital component with monocrystalline quartz (average 3%) more abundant than polycrystalline quartz (<1%; PPL, sample 16NI01). Where Bt = biotite; Cc = calcite cement; Chl = chlorite; Kfs = K-feldspar; Lc = lithic chert; Ls = lithic sedimentary; Lv = lithic volcanic; Opq = opaque mineral; Pl = plagioclase; Qz = quartz; Zrn = zircon.

petrographic observations. Additionally, because samples were crushed using a tungsten carbide TEMA ring, trace amounts of W, Cr, Co, and Sc may be compromised, and thus are not used in interpretations.

4.3.2. Dras Formation

The Dras Formation rocks are characterized by SiO_2 contents between 45% and 58% and are generally classified as basaltic andesites (Figure 6b). Two samples are classified as ultramafic based on <45 wt.% SiO_2 (ranging 41–43 wt.%), and one other sample is classified as intermediate (59 wt.%). The volcanic rocks have high $\text{Fe}_2\text{O}_3^* + \text{MgO}$ contents (usually 9–24 wt.%, average 17 wt.%; where Fe_2O_3^* represents total iron as Fe_2O_3).

Figure 5. Ternary diagram of the Nindam Formation volcaniclastic samples based on the point-counting method of Dickinson and Suczek (1979). Where, Q = total quartz: monocrystalline quartz (Qm) + polycrystalline quartz (Qp); F = total feldspar: plagioclase (P) + alkali-feldspar (K); L = total lithics (including chert): volcanic fragments (Lv) + sedimentary fragments (Ls) + metamorphic fragments (Lm) + chert fragments (Lc).

Ratios of K_2O/Na_2O are 0.03–0.77, average 0.31. TiO_2 contents range from 0.4–3.9 wt.% (average 0.87 wt.%). Some high MgO (>8 wt.%), low TiO_2 (<0.5 wt.%) samples are present possibly indicating the presence of boninitic lavas, as defined by Crawford et al., 1989; Figure 6c). The Dras Formation rocks consistently plot in the volcanic arc array in immobile discriminant plots (Figures 6d and 6e). Primitive mantle-normalized trace and REE patterns are characterized by pronounced negative Nb and Ta anomalies and variable enrichment in large ion lithophile elements (Rb, Ba, Th) typical of suprasubduction zone arc magmas (Pearce & Peate, 1995). A negative Ti anomaly is associated with boninitic samples and reflects high degrees of partial melting (Figure 6f).

4.3.3. Nindam Formation

The Nindam Formation volcaniclastic sandstones are characterized by generally low SiO_2 contents (45–60%). This is consistent with derivation from a predominantly mafic source region as reflected by the abundance of basaltic to andesitic lithic clasts in the conglomerates and sandstones. The volcaniclastic sandstones have high $Fe_2O_3^* + MgO$ contents (usually 5–13 wt.%, average 9 wt.%) with one sample with 23 wt.%. Ratios of K_2O/Na_2O are 0.05–2.61, average 0.67. TiO_2 contents range from 0.5–0.9 wt.% (average 0.7 wt.%). The weathering plot of Ohta and Arai (2007) shows that detritus forming the Nindam Formation underwent very little weathering prior to deposition (Figure 6a). This is consistent with derivation off an active island arc that was largely submerged and underwent very little subaerial weathering, or rapid source to sink in an active environment, and thus the sandstone whole-rock geochemistry can be used as being representative of the volcanic source region of the Dras Arc. Indeed, the Nindam Formation sandstones plot congruent to the Dras Formation within island arc fields of basalt discrimination plots and show similar mafic (Figure 7a), island arc signatures (Figure 7b) using the sandstone geochemical discriminant plots of Roser and Korsch (1986, 1988). The Nindam Formation volcaniclastic rocks also plot congruent to the Dras Formation on the primitive mantle-normalized spider diagram (Figure 6f).

Figure 6. Geochemical plots. (a) Mafic-Felsic-Weathering (MFW) ternary diagram of Ohta and Arai (2007); (b) total alkali versus silica (TAS) diagram of Le Maitre et al. (1986); (c) TAS diagram for high-Mg rocks (Le Bas, 2000); (d) immobile and trace element tectonic discrimination diagrams of Meschede (1986); (e) Volcanic rock tectonic discrimination ternary diagram of Wood (1980); (f) REE spider plot, normalized against Primitive Mantle (McDonough & Sun, 1995).

4.4. Detrital Zircon Geochronology

4.4.1. Detrital Zircon Description

Ten volcaniclastic samples from the Nindam Formation were selected for detrital zircon U-Pb dating (Tables S4 and S5). Samples were collected perpendicular to strike across the formation between the

Figure 7. Geochemical plots. (a) Major element sedimentary discriminant function analysis diagram of Roser and Korsch (1988); (b) major element tectonic discrimination diagram of Roser and Korsch (1986).

townships of Lamayuru and Khalsi (Figure 2). Detrital zircon grains are subhedral to euhedral, clear to transparent purple in color and range between 70 and 250 μm in their longest dimension. Some grains are rounded to subrounded, suggesting that they had extensive residence times in sedimentary systems. Aside from these, the majority of the grains, both fragments and whole crystals, show magmatic oscillatory zoning in CL images. Where oscillatory zoning is observed, it is commonly truncated by the grain's external surface. Grain exteriors when examined in transmitted light, often demonstrate pitting. These features are common across all populations, not only older, detrital grains. Eight hundred and forty-one grains in total were analyzed using a combination of LA-ICP-MS ($n = 791$) and SHRIMP ($n = 50$). Out of these, 695 analyzed spots acquired concordant U-Pb ages (Text S1 and Figure S1.1). The youngest population of each sample was determined by examining the youngest analytically indistinguishable group and taking the weighted mean average of those zircons grains with concordant $^{206}\text{Pb}/^{238}\text{U}$ ages (Ma), where $n \geq 2$ and $\text{MSWD} \leq 1$ (Text S1 and Figure S1.2).

4.4.2. Detrital Zircon Populations

CL images of representative zircon grains are shown in Figure 8. All detrital zircon U-Pb ages are plotted as histograms in stratigraphic order (Figure 9). Most (66%, $n = 430$) of the zircons analyzed fall in the Lower to Upper Cretaceous (Aptian to Santonian, 84–125 Ma) age range. Detailed detrital zircon U-Pb geochronology descriptions are provided in Text S1. Zircon U-Pb data using LA-ICP-MS and SHRIMP are provided in Table S4 and Table S5, respectively.

Other older, detrital zircon populations include

1. Precambrian (total = 18%, $n = 115$):
 - a Neo-archean (>2500 Ma, $<1\%$, $n = 2$)
 - b Paleo-proterozoic (Siderian to Statherian, 3%, $n = 18$, 2444–1627 Ma)
 - c Meso-proterozoic (Calymmian to Stenian, 8%, $n = 54$, 1588–1000 Ma)
 - d Neo-proterozoic (Tonian to Edicaran, 6%, $n = 41$, 988–541 Ma)
2. Cambrian to Lower Devonian (Fortunian to Lochkovian, 2%, $n = 10$, 540–418 Ma)
3. Permian to Upper Triassic (Roadian to Rhaetian, 1%, $n = 9$, 271–205 Ma)
4. Lower to Upper Jurassic (Pliensbachian to Tithonian, 12%, $n = 75$, 185–145 Ma)
5. Lower Cretaceous (Valanginian to Barremian, 1%, $n = 8$, 138–126 Ma)

Figure 8. Representative zircon grains from samples (top) 15ND02 and (bottom) 15ND03 of the Nindam Formation. The yellow circles denote SHRIMP analytical sites and corresponding $^{206}\text{Pb}/^{238}\text{U}$ ages (if <1000 Ma) and $^{207}\text{Pb}/^{206}\text{Pb}$ ages (if >1000 Ma).

5. Discussion

5.1. Maximum Depositional Age

The youngest analytically indistinguishable zircon population within the Nindam Formation is 84 ± 1 Ma (1σ , MSWD = 0.95, $n = 3$) and came from the stratigraphically uppermost sample (16NI16) at the northern end of the traverse (Figure 2). The youngest zircon population for the lowermost (southernmost) unit sampled (16NI02) is 102 ± 1 Ma (1σ , MSWD = 0.02, $n = 2$). Generally, the youngest zircon population in each sample becomes progressively younger up-sequence (Figure 9) indicating that deposition of the Nindam Formation was contemporaneous with active volcanism of the Dras Arc. This is consistent with the model argued by Amato and Pavlis (2010) that the youngest grains in forearc basins are typically synchronous with sedimentation. The exception is sample 16NI13 (Figure 9), which has a youngest zircon population of 99 Ma but is underlain by samples with a youngest zircon population of 94 Ma and overlain by a sample with 84 Ma and therefore does not fit the overall northward younging trend. There are three

Figure 9. Probability density distribution plots from volcaniclastic rocks of the Nindam Formation, displayed in stratigraphic order where the top of the diagram is the northernmost sample.

explanations for this. (A) The sample does not contain zircons sourced from contemporaneous volcanism at the time of deposition but rather sourced slightly older, more deeply eroded arc volcanic rocks. (B) The youngest syn-depositional zircons are volumetrically swamped by more abundant, slightly older zircons, and sampling did not detect the rarer younger zircons in this sample. In which case, with 56 grains

analyzed, then it is 95% certain that such a “missed” age group forms <1.4% of the zircon population (Compston & Pidgeon, 1986; Dodson et al., 1988). (C) Minor folding and/or faulting within the sequence has disrupted or reversed the stratigraphy locally, resulting in a sample being slightly out of sequence with those to the north and south. Distinct, asymmetric tight folds were mapped in the midpart of the section and correspond with sample 16NI08 being younger (~91 Ma) than the overlying samples (Figure 2b).

Sedimentation rates in forearc settings is generally high, albeit variable (Einsele, 2013). Our results show a difference in depositional age between the base (~102 Ma) and the top (~84 Ma) of the Nindam Formation, indicating deposition over at least 18 Myr for this portion of the forearc basin sequence. This equates to an average sedimentation rate of 228 m/Myr, which is comparable to sedimentation rates in modern forearc basins such as Izu-Bonin Forearc (100–300 m/Myr) and New Hebrides/Vanuatu Forearc (44–180 m/Myr); (Underwood et al., 1995).

The youngest zircon population when all samples are combined spans a period from 84–125 Ma, consistent with previously reported fossil ages (Reuber, 1989; Robertson & Degan, 1994; Suture, 1990; Thieuloy et al., 1990). This large (66% of total grains analyzed) youngest zircon population dominates, reflecting the flux of material from the active arc at the time of sedimentation. This same situation of arc detritus dominating forearc basins has also been shown for modern (e.g., Mariana and Tonga arcs, Western Pacific) and ancient (e.g., Jurassic Talkeetna Formation of Alaska) settings (Draut & Clift, 2006). This probably corresponds with the lifespan of the Dras Arc, suggesting it initiated around 125 Ma and was active for at least 41 Ma. The Dras Arc may have been active for longer, up until its eventual collision with India, leading to its extinction. However, the upper (younger) part of the Nindam Formation is truncated against the thrust fault marked by the Mongyu Mélange on the northern contact of our section and consequently there is no way of knowing how much of the upper Nindam Formation is missing in the section between Khalsi and Lamayuru. In the Zaskar Gorge section, the Nindam Formation is faulted against the Jurutze Formation which has a youngest detrital zircon age of 53 ± 1 Ma (Henderson et al., 2010). The Jurutze Formation has previously been interpreted as a younger continuation of the Nindam Formation (Clift et al., 2001; Clift, Carter, et al., 2002) but also part of the same Tar Group sequence which stratigraphically grades up into the Sumda and Chogdo formations (Henderson et al., 2011). While the Jurutze Formation has a similar age and provenance to the Chogdo Formation and may be part of the same sequence, we think that comparisons between Cretaceous Nindam Formation and the Eocene Tar Group are incompatible and therefore the supposed stratigraphic relationship between Nindam and Jurutze formations is suspect and requires further validation. The upper (younger) sections of accreted ophiolites and arcs are usually the first to be eroded in an active arc-continent collision (Draut & Clift, 2013) given that the sequences are not dramatically tilted (e.g., Oman Ophiolite), so it is possible that the youngest portions of the Dras-Nindam terrane are completely missing or only locally preserved, for example, the Paleocene? Dras II volcanics south of Kargil (Robertson & Degan, 1994). The detrital record of syn-collisional to postcollisional conglomerates, such as the Chilling Formation, may provide answers as to the upper extent of arc activity but no such data exists at present for this unit.

5.2. Provenance

5.2.1. Petrological and Geochemical Signatures

The dominant lithic clasts within the Nindam Formation conglomerates and volcaniclastic sandstones are basaltic to andesitic volcanic rocks and pelagic limestone with minor amounts of chert and siltstone. There is a distinct lack of quartz clasts, which is consistent with interpretations by Robertson and Degan (1994) of deposition within a forearc basin of an intraoceanic island arc of a predominantly mafic composition. Interpretations of the Nindam Formation as being the forearc basin of the southern margin of Eurasia (Fuchs, 1982; Henderson et al., 2010; Honegger et al., 1982; Najman et al., 2017) are at odds with the geological evidence presented here and by Robertson and Degan (1994) that the Nindam Formation represents the forearc basin of an intraoceanic island arc system. The Ladakh and Karakoram arcs are characterized by continental magmatism dominated by felsic, silica-saturated compositions. Clasts of igneous rocks of this type are not observed anywhere within the Dras-Nindam terrane. The distinct absence of quartz combined with whole-rock geochemical data suggests that the source of the Nindam Formation sediment is volcanic island-arc derived. Basalts of the Dras Formation are characterized by low Nb/La ratios, low Nb concentrations, and low enrichment of incompatible elements, including negative Nb, Ta, K, and Ti anomalies in REE plots which are consistent with intraoceanic island arc signatures (Figure 6f and Table S3). In contrast,

samples collected from the Tar and Indus groups north of the Mongyu Mélange, which separates them from the Nindam Formation, contain abundant granite clasts (Figure 3f) and are generally more silica rich (Figures 7a and 7b and Table S3).

5.2.2. Pre-Cretaceous Detrital Zircon Populations

The Nindam Formation contains pre-Cretaceous detrital zircon that are significant in terms of provenance. A distinct age peak between 135 and 185 Ma (11%) occurs in all samples. This coincides with ages (88–170 Ma) reported from the Spongtang Ophiolite and associated Spong Arc (Buckman et al., 2018; Pedersen et al., 2001). Our interpretation of these grains being sourced from the Spongtang Massif, presumably a much larger ophiolitic thrust sheet that was thrust over the northern margin of India then is present now, fits the observation of abundant ultramafic and serpentinite clasts at the base of the Nindam Formation. The interpretation of the Dras and Nindam formations as the forearc basin of the Ladakh Arc (Fuchs, 1982; Henderson et al., 2010; Honegger et al., 1982; Najman et al., 2017) is inconsistent with the ages reported from the Ladakh Batholith which range from between 75 and 45 Ma (White et al., 2011) which is much younger than the youngest (~84 Ma) portions of the Nindam Formation reported here. The only other potential source region for these Jurassic to Lower Cretaceous zircons would be the Jurassic-Cretaceous (162–95 Ma) Karakoram Batholith on the southern margin of Eurasia (Borneman et al., 2015; Heubeger et al., 2007; Le Fort et al., 1983). However, this continental arc is dominated by felsic, silica-saturated magmatism and was situated on the northern margin of the Mesotethys Ocean (Shyok Ocean), which separated Eurasia from the northward-moving Lhasa terrane (Li et al., 2016; Zhou et al., 2016). The Dras-Nindam terrane developed south of the Karakoram and Ladakh arcs within the Neotethys Ocean, and therefore, it is unlikely that detritus from the Karakoram Arc made its way across the Mesotethys Ocean, around the Lhasa terrane, and across the Neotethys Ocean before entering the forearc basin of the Dras Arc. It is more likely that the forearc region of the Dras Arc was host to the earlier Spongtang Ophiolite and Spong Arc, which eroded directly into the adjacent forearc basin of the Nindam Formation contributing 11% of total zircon grains analyzed.

A small number of Permian to Triassic (200–271 Ma) zircons occur and make up less than 1% of the total population and may represent material derived from the Permo-Triassic Panjal Traps of India (Rehman et al., 2016; Shellnutt et al., 2011). Anomalously high Th/U is expected from such mafic rocks. The eight grains produced an average of 0.73, with the highest ratio being 1.05. Although these values are not extraordinarily high, they do suggest the grains are derived from mafic rocks. Detrital zircon studies of Eurasian-derived samples with the Himalayas are commonly distinguished by their distinct Mesozoic peaks associated with the magmatism within the Qiangtang Arc (Zhai et al., 2013). The fact that the Nindam Formation appears devoid of Carboniferous to Triassic zircons suggests it was not sourcing detritus from the active, southern Eurasian margin. A small (2%) population of Early Paleozoic (418–540 Ma) zircons is present within the Nindam Formation. This is consistent with derivation from northern Gondwana which experienced the Kurgakh Orogeny (Myrow et al., 2016) or equivalent “Bhimphedian Orogeny” of Cawood et al. (2007) during the Cambrian to Ordovician.

A distinct “Gondwanan” Precambrian detrital component can be identified within most samples, with input ranging between 6% and 42% (average 18%) of total grain ages. Unlike many intraoceanic island arcs that are dominated by a unimodal detrital zircon population (Draut & Clift, 2013; Manton et al., 2017; Zhang et al., 2019) the Dras-Nindam terrane contains a distinct Gondwanan inheritance reflecting input from a continental source. There are no reports of any Gondwanan basement to the Dras Arc from which these zircons could have been sourced. The Neotethys was bound to the south and north by peri-Gondwanan terranes of northern India and the Lhasa terrane, respectively (Figure 11), so either, or both, of these peri-Gondwanan terranes could have been a source region. Submarine fans may well have dispersed sediment from either Lhasa or India in a manner similar to the channeling of Himalayan-derived sediment into the Bay of Bengal and along the Sunda Trench as far south as Sunda Strait, with sediment being transported up to ~3,000 km (Moore et al., 1982). Similar sediment transport distances have been reported for the Hikurangi Channel off the east coast of New Zealand, which sees gravity flows and deep-water currents moving sediment north into the Kermadec Trench, some ~2,000-km distance (Lewis & Barnes, 1999). Therefore, it is entirely possible that the Precambrian zircons in the Nindam Formation were sourced from either the northern margin of India or the Lhasa terrane and migrated along the trench or forearc basin associated with the Dras intraoceanic island arc. It is worth noting that the Lhasa terrane had docked with

Figure 10. Compilation detrital zircon data sets from major Himalayan terranes. Dras-Nindam terrane (this study) detrital zircon ages compared to ages from the Indian passive margin (Najman et al., 2017), Lhasa terrane (Lai et al., 2019), Kohistan-Ladakh Arc (Najman et al., 2017), Gangdese Batholith (Najman et al., 2017), and Xigaze terrane (Hu et al., 2016). Those data sets on the left have ages ranging from 0–3000 Ma. Those data sets on the right show a subset of the former from 0–250 Ma. For a full list of references used to compile these data sets, refer to the supporting information (Text S2).

Eurasia by the Late Cretaceous and was bound by the Trans-Himalayan Batholith to the south. If this active continental margin was a source region to the Nindam Formation, a zircon signature similar to the Xigaze Group in Tibet (Figure 10) should be recorded, but this is not the case. Thus, we suggest that the Gondwanan inheritance observed in the Nindam Formation is derived entirely from the Indian margin into an originally NNE-SSW trending trench, as proposed by Buckman et al. (2018), which initiated along a major transform fault (Figure 11). If the original orientation of the Dras Arc and subduction complex was perpendicular to the northern margin of India, then this would allow the migration of Indian-derived sediment into either the backarc, forearc, or trench in manner similar to the Barbados Trench striking perpendicular to the South American continent (Macdonald et al., 2000).

Figure 11. Time-space tectonic reconstruction for the Neotethyan Dras Arc. Plate reconstructions are modified from the GPlates model of Seton et al. (2012). Modifications of the model are based on new paleomagnetic data for the Lhasa terrane (LT) by Zhou et al. (2016) and Li et al. (2016) who have the Lhasa terrane much further south from the Triassic to Cretaceous than in the model of Seton et al. (2012). Likewise, paleomagnetic data from Klootwijk et al. (1979) has the Ladakh Batholith positioned further south at 23°N. This reconstruction builds on the model of Buckman et al. (2018) who proposed that the Spongtag ophiolite and Dras Arc evolved as an intraoceanic island arc system that developed as a result of spontaneous subduction at ~136 Ma along a NNE-SSW transform fault in the Neotethys Ocean. This ophiolite-arc complex collided with India at ~55 Ma at roughly equatorial latitude while the Ladakh Batholith (Trans-Himalayan Batholith) developed closer to the southern margin of Eurasia before final continental collision at ~35 Ma.

5.3. Tectonic Implications

5.3.1. Where and When Did the Dras Arc Form?

The youngest zircon population within the Nindam Formation shows that the Dras Arc was active between 125 Ma to at least 84 Ma, although it may have continued being active until its final collision with Gondwanan continental crust during the Eocene. All geological evidence points toward the Dras Arc forming in an intraoceanic island arc setting within the Neotethys between the northern margin of India and the southern margin of the Lhasa terrane, which was an active continental margin in Tibet (Gangdese Batholith) but transitional to an island arc in Ladakh and Kohistan. The orientation of the trench and arc is normally interpreted as roughly E-W at 90° to the overall spreading direction, possibly also to reflect the fact that it was eventually accreted onto the E-W trending margin of northern India which now controls the orientation of the IYTS. However, Reuber (1986) and Buckman et al. (2018) suggested the original orientation of the subduction zone responsible for formation of the suprasubduction zone ophiolites and subsequently the Dras Arc may have been more of a N-S orientation that coincided with major transform faults formed during separation of the Lhasa terrane from northern Gondwana (India). Transform faults are important sites of

potential subduction initiation due to the juxtaposition of old and new ocean crust with contrasting density (Stern, 2004; Stern & Bloomer, 1992; Zhou et al., 2018). Recent paleomagnetic studies of the Semail Ophiolite in Oman (Morris et al., 2016) reveal that it initiated in a NE-SW orientation before being rotated 90° about a hinge point on the NW Arabian margin. We suggest that the Himalayan Neotethyan ophiolite-arc complexes, including the Dras Arc, were initially formed in a similar manner along roughly N-S orientated transform faults between India and southern Eurasia. A N-S trending trench and arc system between the Lhasa terrane and Indian block would potentially funnel sediment from both continental blocks into submarine fans dispersing sediment along the axis of the trench and subsequently into the developing accretionary complex and forearc basin (Figure 11). It is important to note that a classic accretionary complex associated with the Nindam Formation is not observed. Instead, there is a serpentinite matrix *mélange* at the faulted contact between the base of the Nindam Formation and the Lamayuru Complex (India), which contains abundant peridotite-gabbro-basalt-chert blocks. Similarly, in the basal units of the Nindam Formation clasts in mass-flow conglomerates show this same clast assemblage. It may be that the accretionary complex was tectonically eroded upon collision with India and incorporated into the *mélange*. The Nindam Formation may well have been deposited in an extensional forearc basin before the process of arc-continent collision changed the setting to being tectonically erosive.

5.3.2. Collisional History of the Dras Arc

The question of whether the Dras Arc first collided with Eurasia or India is controversial. Early researchers (Coward et al., 1987; Honegger et al., 1982; Khan et al., 1993; Searle et al., 1999) interpret these arcs as being part of the same system, which sees northward subduction underneath the southern margin of Eurasia. Fuchs (1982) and Honegger et al. (1982) suggested that this arc evolved throughout the Jurassic to Cretaceous in a forearc region of a convergent margin on the southern margin of Eurasia. In their interpretation, the forearc basin developed on top of ophiolitic basement in front of the Ladakh Batholith as part of a single subduction complex responsible for the consumption of the entire Neotethys Ocean, before the onset of the India-Eurasia continent-continent collision at ~55 Ma. Although this model is elegant in its simplicity, there are inconsistencies that do not fit the hypothesis, revolving around evidence that some ophiolite and arc terranes along the Indus Suture appear to have completely juvenile, intraoceanic characteristics rather than having developed in marginal continental basins.

Intrusive suites of the Kohistan and Ladakh batholiths are similar in both age and composition to the Gangdese Batholith (Figure 10); therefore, it is likely that these entities are in fact related (Ravikant et al., 2009; Reichardt et al., 2010; Shellnutt et al., 2014; Weinberg & Dunlap, 2000). We emphasize that the southern margin of Eurasia was an active continental margin throughout most of the Carboniferous to Mesozoic and as such should be a major sediment contributor to any proximal basin developing along its margin. The distinct lack of Carboniferous to Jurassic detrital zircon populations in the Nindam Formation but the presence of a distinct Indian (Gondwanan) signature indicates that the Dras Arc developed as an intraoceanic island arc separate to the continental arc (Karakoram and Qiangtang arcs) developing on the southern margin of Eurasia. Corfield et al. (2001) and Clift et al. (2000) have noted the juvenile, intraoceanic nature of the Dras Arc and associated Nindam Formation, along with ophiolites along the Indus Suture all of which have no provenance links to felsic volcanism associated with the Ladakh Batholith. Corfield et al. (2001) suggested that the Dras Arc developed above a separate subduction system to both the southern margin of Eurasia (Ladakh Batholith) and the Spong Arc. They invoked three north dipping subduction zones to explain the coeval development of these three separate entities and interpret the Dras Arc to have collided with Eurasia following the closure of the Shyok Ocean preceding final continent-continent collision of India and Eurasia. The results presented here align with the interpretation of the Dras Arc being juvenile and intraoceanic in nature. However, the strong 135–185 Ma inheritance in the Nindam Formation (Figure 10, Text S1, and Figure S1.1) reflects uplift and erosion of the suprasubduction zone Spong Arc Ophiolite and associated Spong Arc into the forearc basin of the slightly younger Dras Arc as suggesting they may be part of the same subduction complex (Buckman et al., 2018). Changes in the dip of subduction systems result in alternating periods of extension or compression, which can easily uplift and expose forearc ophiolites or accretionary prisms to erosion into adjacent depocenters, and this is reflected in the ophiolitic (peridotite, chert, limestone) clast compositions in the basal sections of the Nindam Formation. Thus, we provide an alternate model of accretion which sees the Dras Arc colliding with the passive margin of India before final continent collision (Figure 11).

6. Conclusions

The Nindam Formation volcanoclastic rocks represent distal deep-marine deposits sourced largely from the Dras Arc and record Cretaceous intraoceanic island arc activity spanning a 41-Myr period between ~84 and 125 Ma. The youngest detrital zircons in each of the samples becomes progressively younger up through the sequence indicating deposition at the base began at ≤ 102 Ma and continued until ≤ 84 Ma at the top of the sequence.

A distinct “Gondwanan” zircon signature composed of Precambrian peaks at ~514–988 Ma, ~1000–1588 Ma, ~1627–2444 Ma, and ~2500 Ma occurs in all samples and derived from the northern Indian margin via far-traveled sediment.

All geological evidence suggests the Nindam Formation was deposited in an intraoceanic forearc basin setting with little to no influence from continental rocks. Therefore, the Dras-Nindam terrane does not represent the forearc basin to the southern Eurasian margin nor the forearc to the Ladakh Batholith but is more akin to island arc development associated with the Indus suprasubduction zone ophiolites.

Minor and slightly older detrital zircon populations occur at ~135–185 Ma and these correspond with reported ages of intraoceanic Neotethyan ophiolites, such as Spongtag and Nidar, which probably represent ophiolitic forearc basement to the Dras Arc and establish a link between the Spong and Dras arcs. Given that Spongtag Ophiolite and Spong Arc were clearly obducted onto the Indian margin during the early Eocene, we suggest that the intraoceanic Dras + Spong Arc first collided and accreted onto the passive margin of India rather than Eurasia prior to continent-continent collision of India and Eurasia.

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