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RESEARCH PAPER

Evolution of Dras arc in the backdrop of the India-Eurasia collision: evidence from the discovery of ammonite from Indus Suture Zone, Ladakh Himalaya, India

Prasenjit Barman[1,2] · Shruti R. Mishra[3] · Narendra K. Swami[4] · Arindam Roy[5] · Alok C. Pande[6]

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Abstract

We report Late Jurassic ammonite *Aulacosphinctes* sp. from the volcano-sedimentary sequences of the Dras Formation in the Ladakh Himalaya, India, for the first time. The Cretaceous Dras Formation, characterized by its thick layers of volcano-sedimentary deposits, preserves mainly foraminifera and radiolarians. In this paper, we try to bring about a perception change regarding the age of the Dras Formation. The discovery of *Aulacosphinctes* sp. from the Dras Formation—undoubtedly speaks for the Tithonian age. The interspersed nature of the volcano-sedimentary sequences of Dras Formation with the basalt of Dras volcanics further indicates episodic volcanism along the southern margin of Neotethyan ocean between India and Eurasia. This discovery prompts a reassessment of the palaeogeographic position and evolution of the Dras arc during the Late Jurassic.

Keywords *Aulacosphinctes* sp. · Late Jurassic · Dras arc · Dras formation · Ladakh · India

Introduction

Partitioned views and hypotheses prevailed over decades regarding the origin and evolution of Dras arc in Ladakh Himalaya, which is present in between the Indian and Eurasian continents along the Indus Suture zone. While some believe that, the Dras arc system developed on the southern margin of the Eurasian continent (Burg 2011; Bouilhol et al. 2013), others contemplated Dras to be an interoceanic island arc formed on the sea floor of Neo-Tethys between India and Eurasia (Coward et al. 1987; Corfield et al. 2001). A third hypotheses suggested its association with the Spongtang ophiolite-Spong arc (Klootwijk et al., 1979; Buckman et al. 2018; Walsh et al. 2019, 2021). Further debates include the protracted evolution and development of Dras arc within the Neotethys. Attempts were made in the past to resolve the timing of the development of the Dras arc system using the radiometric age of the volcanic and associated rocks, so as the biostratigraphic age from the arc-associated flysch sequences. Barring Walsh et al., (2021) who re-established the age of the Dras Formation as Late Jurassic based upon the radiometric age dating of the tuff layer (near Shergol), all other radiometric age data of the Dras volcanic and associated rocks have revealed a wide range of dates varying in between Albian to Maastrichtian (Honegger et al. 1982;

✉ Prasenjit Barman
barman.geology@gmail.com

✉ Shruti R. Mishra
shruti.ism@gmail.com

Narendra K. Swami
narendraswami92@rediffmail.com

Arindam Roy
addy.geol@gmail.com

Alok C. Pande
acpande1@gmail.com

1 State Unit: Tripura and Mizoram, Geological Survey of India, Northeastern Region, Agartala 799006, India

2 Department of Geology, Institute of Science, Banaras Hindu University (BHU), Varanasi 221005, India

3 Geological Survey of India, Central Region, Nagpur 440006, India

4 Geological Survey of India, Western Region, Jaipur 302004, India

5 Geological Survey of India, Central Headquarter, Kolkata 700016, India

6 Geological Survey of India, Northern Region, Lucknow 226024, India

Reuber 1989; Reuber et al. 1989; Robertson and Degnan 1994). However, the biostratigraphic age suggested that the development of the Dras arc was initiated during the Middle Jurassic (Callovian), based on the radiolarian chert associated with the Dras volcanic and continued till Late Cretaceous (Cenomanian) (Honegger et al. 1982; Dietrich et al. 1983). This idea could not garner much support when Reuber (1989) and Reuber et al., (1989) argued the Cenomanian as the initiation timing of Dras arc. They strongly contemplated, that the radiolarian chert may be part of the older oceanic crust (ophiolitic assemblage). Hence, there lies a great ambiguity regarding the initiation and temporal evolution of the Dras arc in the Indus Suture Zone. In this paper, we report the first-ever discovery of the Late Jurassic ammonite *Aulacosphinctes* sp. from the volcano-sedimentary sequences of Dras Formation. The specimen was recovered from the Dras Formation near Mangyu village, Ladakh. With the detailed systematic study of this taxa, we have tried to constrain the age of initiation of the Dras arc and the associated volcano-sedimentary sequences.

Geological setting

The Ladakh Himalaya in India exposes two distinct suture zones namely the Shyok Suture Zone (SSZ) and the Indus Suture Zone (ISZ) or Indus-Tsangpo Suture Zone (ITSZ) (Srikantia and Razdan 1980, 1985; Khan et al. 2009; Le Fort et al. 1994; Robertson and Degnan 1994; Rolland et al. 2002; Henderson et al. 2010). These suture zones prominently are constituted of ophiolitic melange, granitic batholiths, volcanics and volcano-sedimentary successions, shallow marine flysch, as well as the molassic sediments (Fig. 1). The SSZ separates the Karakoram and the Ladakh batholiths to its north and south respectively. Further to the south of the Ladakh batholith, ITSZ exposes volcano-sedimentary sequences, ophiolitic melange, flysch (Sangeluma Group) and molassic (Indus Group) sediments (Fig. 2 and Table 1). Tethyan sedimentary rocks (Zanskar unit) are located further south of the ITSZ. The focus of the current study is primarily within the ITSZ, specifically concerning the volcano-sedimentary rocks from the Dras Formation of Sangeluma Group.

The sedimentary sequences of the Sangeluma Group in the ITSZ are represented by four formations: Khalsi, Nindam, Shange, and Shergol formations (Barman et al. 2021, 2023). The Aptian-Cenomanian Khalsi Formation is stratigraphically placed above the volcano-sedimentary sequence of the Dras Formation (Fig. 3A). This formation predominantly consists of limestones and splintery shales, with some subordinate coarse-grained sandstones, tuffaceous shales, siltstones, and minor quartzarenites. Resting above both the Dras and Khalsi formations, the Nindam Formation exhibits a diverse composition, including shales, siltstones, sandstones, cherts, and limestones (Fig. 3B). Of particular interest, the limestones within the Nindam Formation

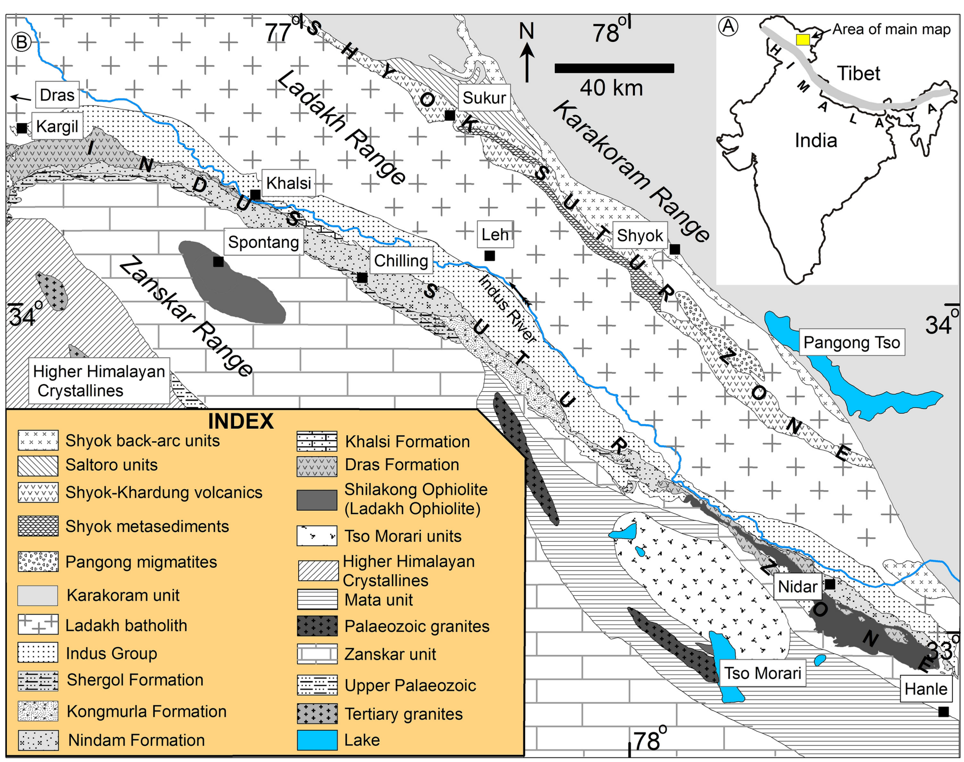

Fig. 1 **A** Map showing the greater Himalayan Mountain range between India and Tibet with a small box showing part of Ladakh region enlarged in main Figure B. **B** The generalized geological map of Ladakh, India showing major lithological and stratigraphical units with the locality where ammonite was recorded (after Barman et al. 2023)

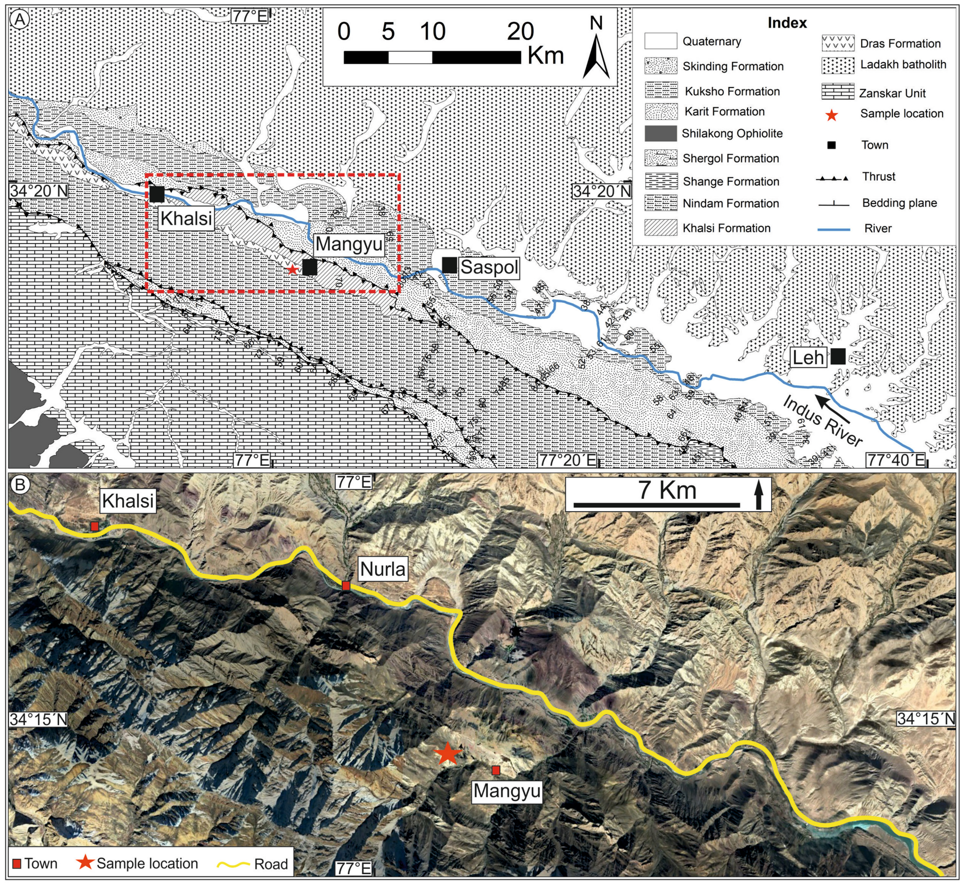

Fig. 2 Geological and location map of Mangyu area, Leh district, Ladakh, India. **A** Map showing the tectonic and lithological context of the study area with sample locality (modified after Barman et al. 2023). **B** Map showing the locality of *Aulacosphinctes* from Dras Formation (red dotted rectangle in Figure A)

Table 1 Lithostratigraphy of the study area showing the stratigraphic position of the different litho units in the Indus Suture Zone (after the Geological Survey of India 50 K series map compilation)

Tethyan Belt			Indus Belt		
Formation	**Group**		**Formation**	**Group**	**Age**
Quaternary			Quaternary		Pleistocene-Holocene
			Karit		Miocene
Shergol					Oligocene
Shange				Indus	Oligocene
	Sangeluma		Kuksho		Eocene-Oligocene
Nindam			Skinding		Eocene
Khalsi					Cretaceous
Shilakong Ophiolite			Ladakh Batholith		Cretaceous-Tertiary
Dras					Jurassic-Cretaceous
Undifferentiated Kuling-Lilang Group					Permian-Jurassic

contain several types of foraminifers, such as *Discocyclina* sp., *Astrocyclina* sp., *Alveolina* sp., *Operculina* sp., *Mellolids* sp., and *Cardites* sp. (Srikantia and Razdan 1985). These foraminiferal assemblages provide valuable clues regarding the age of the Nindam Formation, indicating it to be broadly of Eocene age. Stratigraphically resting over the Nindam Formation, the Shange Formation is characterized by radish shales, siltstones and occasional conglomerates. The Shergol Formation marks the uppermost flysch sequence within the ITSZ, and it is placed stratigraphically above the Kongmurla Formation. This formation comprises various litho units, including shales, sandstones, cherts, and conglomerates.

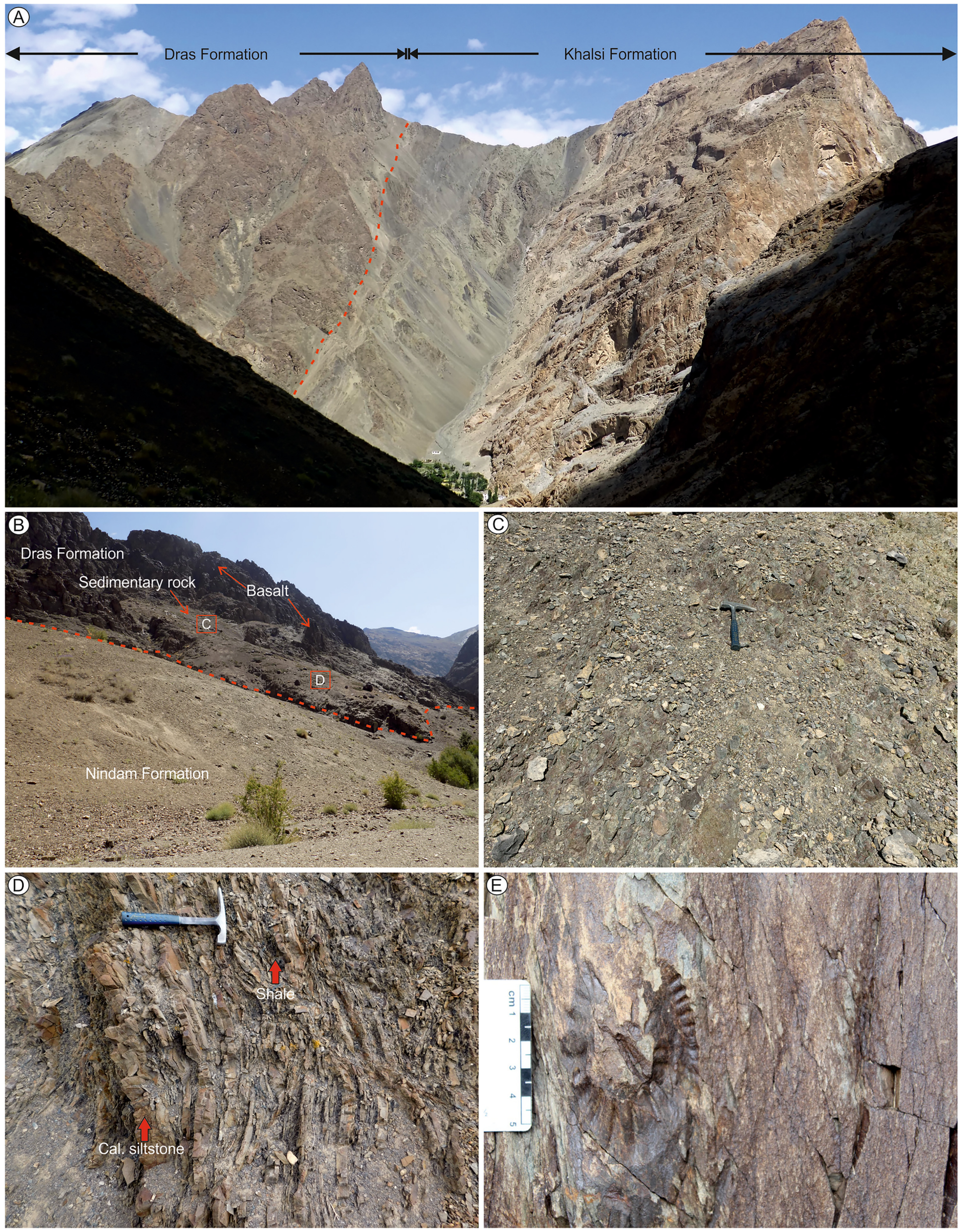

Fig. 3 Field photographs of Dras Formation. **A** Field photograph showing litho units of Dras Formation and overlying Khalsi Formation. **B** Field photograph showing the association of volcanogenic sedimentary sequence with the basalts of Dras Formation. The field photograph also shows unconformable contact between Dras Formation and the overlying Nindam Formation. **C–D** Field photographs representing the enlarged area marked in Fig. B. **C** Volcanogenic conglomerate having angular to subrounded clasts in silty-shale matrix occurs over the basalt of Dras volcanics. **D** Field photograph showing thinly bedded calcareous siltstones-sandstones intercalated with shales in Dras Formation. The ammonite specimen was recovered from the calcareous siltstones. E) Field photograph showing a broken mold of ammonite preserved in the calcareous siltstones

Although no age-diagnostic fossils have been discovered in the Shange and Shergol formations, the conglomerates within these formations contain limestone clasts bearing *nummulites*. These limestone clasts were derived from the Nindam Formation. As a result of this evidence, the age of the Shange and Shergol formations is inferred to be post-Eocene.

Dras Formation of Sangeluma Group comprises of volcanic rocks along with volcanogenic sedimentary litho units (Bhat et al. 2019; Honegger et al. 1982; Reuber 1989; Barman et al. 2023). The volcanic rocks of the Dras Formation include basalts, andesite, rhyolite and tuff. Minor dolerite dikes and sills are present within the volcanics. At places, ultramafic rocks are seen as obducted mantle components within the volcanics (Barman et al. 2021, 2023). The thickness of the Dras formation varies from place to place. The maximum thickness of this formation is about 5–6 km in the Dras area. The type-section of Dras Formation is located at Dras town, about 60 km away from Kargil, towards Srinagar on Leh-Srinagar Highway. The thickness of the Dras Formation is about 1.5 km in the study area. The basement of the Dras Formation is not exposed in the study area while unconformable contact is observed between the Dras Formation and the Nindam Formation which lies above the Dras Formation. Limestones, radiolarian cherts and volcaniclastics are the different components of flysch sequences of the Dras Formation. A conglomerate horizon made up of angular to subrounded clasts derived from the Dras volcanic is resting over the volcanic rocks (Fig. 3C). Thinly bedded calcareous siltstones, sandstones, and shales intercalation are notable litho units where ammonite was found (Fig. 3D–E). The ammonite specimen was recovered from the lower stratigraphic horizon of the Dras Formation considering the regional geological setting and wide age range of Dras volcanics.

Materials and methods

One in situ mold specimen (KCM01, Fig. 4A) was collected from the volcanoclastics of the Dras Formation (Fig. 5) in the Mangyu area, Ladakh India. Cast of the specimen was restored at the laboratory (Fig. 4B). Both the mold and cast of the specimen were used for the systematic study. Another unidentifiable mold of the ammonite was recorded in the same lithounit of the Dras Formation (Fig. 3E).

Repository and institutional abbreviation. The specimen is kept in a repository of the Geological Survey of India (GSI), Northern Region, Lucknow, India.

Systematic palaeontology

Order AMMONITIDA Hyatt 1889

Suborder AMMONITINA Hyatt 1889

Superfamily PERISPHINCTOIDEA Steinman 1890.

Family HIMALAYITIDAE Spath 1925

Type species. *Ammonites morikeanus* Oppel 1863, p. 281, Fig. 2a, b; by subsequent designation of Spath (1924, p. 16).

AULACOSPHINCTES sp. Uhlig 1910

Type species: *Ammonites morikeanus* Oppel 1863

Diagnosis: Dimorphic, coiling evolute, apertural section rounded to subquadrate, ribbing sharp and prominent, bifurcating or may be simple primaries, may be polyfurcating in the adult body chamber of macroconch, ventral furrow in younger specimens which disappears in the body chamber. Microconchs have lappets (Enay & Howarth, 2019).

Material. Mold of the ammonite recovered from the reddish siltstone.

Locality. Mangyu village, Leh district, Union Territory Ladakh, India (34°14´38.6´´N, 77°02´23.4´´E) (Fig. 2).

Stratigraphic horizon. Flysch sequence of Dras Formation.

Age. Tithonian (Late Jurassic).

Description. The description of the species is based on a plasticene cast prepared from mold recovered from reddish siltstone. Only the right lateral view of the specimen could be restored. The shell is evolute (umbilical diameter/shell diameter = 0.44) and incomplete. The umbilicus is wide and shallow with an inclined umbilical wall and gradual umbilical margin. Flank slightly convex up

Fig. 4 **A** Well preserved mold of Upper Jurassic *Aulacosphinctes* (specimen no. KCM01), Dras Formation. **B** Cast (restored at Lab) of *Aulacosphinctes* (specimen no. KCM01) shows bifurcation of the primary ribs above the mid-lateral height. **C** Line drawing of the *Aulacosphinctes* showing the diagnostic features. Scale bar 1 cm

to the ventro-lateral margin. Prominent and sharp primary ribs originate from the umbilical wall and take a slightly prorsiradiate curvature at the umbilical margin and then continue rectiradiately up to the venter (Fig. 4). The

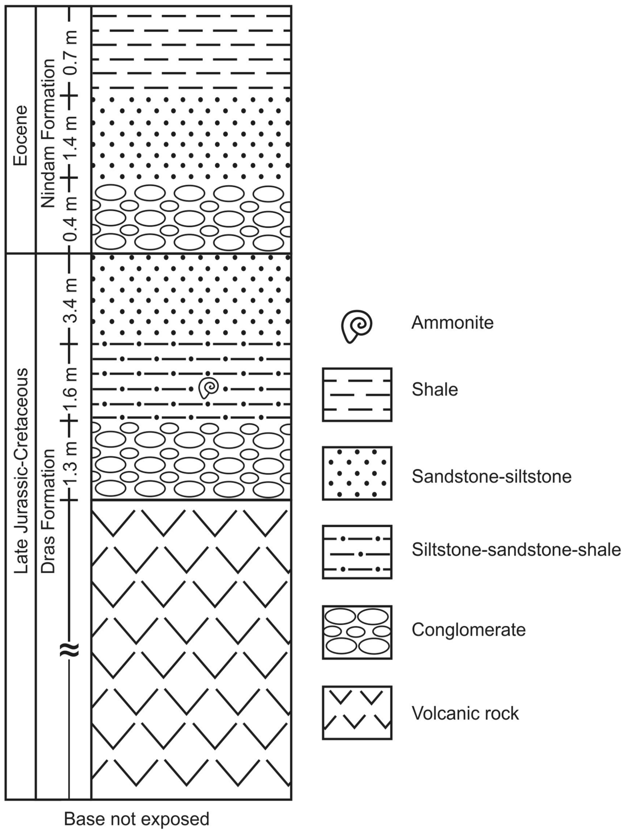

Fig. 5 Lithological column of Dras Formation from where ammonite has been recovered

primary ribs are 29 in number per half whorl. Inter rib space increases towards the outer whorl. The primary ribs bifurcated into two secondary ribs above the mid-lateral height. Secondary ribs are thinner than primary ribs. The thickness of the secondary ribs increases towards the outer whorl. Three constrictions are seen, one on the inner whorl and two on the outer whorl. The innermost part is covered with the sediment.

Stratigraphic Range: Tithonian (Upper Jurassic) horizons of Spiti Valley (India), Kutch (India), Jaisalmer (India); Pakistan, Madagascar, Spain,Yemen, Argentina, Tibet, USA, Italy, Peru and Chile.

Discussion. The present specimen resembles *Aulocosphinctes* (*Perisphinctes*) *infundibulum* reported from the Tithonian horizon of Spiti Shale Formation in Spiti Valley, Himachal Pradesh, India. But because of the absence of the ventral view of the specimen and in the absence of any other specimen, we have restricted ourselves to its generic identification i.e. *Aulacosphinctes* sp. Uhlig 1910.

Remarks Based on the morphology and ornamentation features the specimen is closely resembles to genus *Aulacosphinctes* Uhlig 1910.

Discussion

Controversy and discussion on timing of initiation of Dras arc on the Neotethyan ocean floor

Controversy exists regarding the timing of the formation of the Dras arc in the Neotethys. Both the radiometric as well as the biostratigraphic age have been relied upon for the age determination of the Dras arc.

The radiometric age of the Dras volcanics was determined either directly from the volcanics of the Dras Formation or from later intrusions that cut across the volcanics. Amphiboles from the porphyric tuff of the Dras volcanics, near Chiktan, were subjected to radiometric K–Ar dating, indicating an age of 78 ± 1 Ma (Sharma et al. 1978). Reuber et al., (1989) obtained ages of 105 and 95 Ma of Dras volcanics using the same method. Notably, an age of 78.5 ± 2.9 Ma was also determined from green amphibole in the porphyric tuff of the Dras volcanics, which was interpreted as secondary and related to deformation (Reuber et al. 1989).

Brookfield and Reynolds (1981) employed the hornblende $^{40}Ar/^{39}Ar$ method to determine an age of 82 ± 6 Ma for the syenite intrusion within the Dras volcanics near Kargil. Similarly, intrusive granodiorite within the volcanics at Mount Somau (also near Kargil) yielded K–Ar ages of 75 ± 3 Ma (for biotite) and 70 ± 3 Ma (for white mica) (Honegger et al. 1982). The granodioritic intrusive, formerly referred to as Ladakh intrusives, within the Dras volcanics near Kargil, provided ages of 103 ± 3 Ma and 101 ± 2 Ma using the zircon U–Pb method (Honegger et al. 1982; Schärer et al. 1984). A biotite K–Ar age of 94 ± 3 Ma was obtained from the diorite pluton intruded within the Dras volcanics at Mount Somau near Kargil (Reuber et al. 1989). This age was interpreted as a cooling age, with the crystallization age being older than the cooling age and close to the ages proposed by Honegger et al., (1982) and Schärer et al., (1984). Lately, Walsh et al., (2021) reported zircon U–Pb ages of 156 ± 1 Ma for trachydacite and 160 ± 3 Ma for felsic tuff from the Dras volcanics near Kargil and Shergol area.

In situ fossils are reliable for the depositional age of the sedimentary succession. The Dras Formation consists of very well-preserved volcanics as well as the volcano-sedimentary sequences. The sedimentary sequences in turn preserve a wide variety of fossil assemblages i.e. ammonites, bivalves, foraminifera, and radiolarian. Honegger et al., (1982) reported radiolarian chert that was associated with the Dras volcanics in the Dras area. They proposed the Middle-Late Jurassic age (Callovian-Tithonian) of the initiation of the Dras arc. Whereas, the *Orbitolina* recovered from the limestone associated with the volcanics suggested the Albian-Cenomanian age (Reuber et al. 1989). Thieuloy et al., (1990) reported Late Albian ammonite *Oxytropidoceras* sp. from the black shales which were intercalated with the volcanic near Kargil area. Barring Honegger et al., (1982), all other findings were suggestive of Cretaceous (Albian) time for the initiation of the formation of Dras arc.

The radiolarian chert which is associated with the Dras volcanic alongside the pillow lava suggests the Middle-Late Jurassic age of the initiation of the Dras arc. On the contrary, Reuber et al., (1989) and Reuber (1989) argued that the radiolarian chert was the part of oceanic crust i.e. part of ophiolitic sequences which was later obducted and juxtaposed with the Dras volcanics. It was a reasonable argument as pillow lava and deep marine radiolarian cherts are part of ophiolitic sequences. It is also obvious that in an arc system, pillow lava is common. The argument of whether the pillow lava is part of the oceanic crust or part of the newly created Dras arc needs to be verified in the future.

Another argument can be drawn that the present ammonite specimen could be part of the Tethyan sedimentary sequences particularly the Spiti Shale Formation which poses *Aulacosphinctes* in Zanskar and Spiti areas (e.g. Uhlig 1903, 1910; Oloriz and Tintori 1991; Pathak 1997). This assertion finds support in the deposition of the Sangeluma Group of rocks, encompassing the Dras Formation, atop the Tethyan sedimentary sequences. Thus, it's conceivable that our ammonite specimen may belong to the Spiti Shale Formation. This argument can be dismissed through the following reasons: (1) the litho units of the Sangeluma Group were deposited over the Permo-Triassic Kulling-Lilang groups of rocks (e.g. Srikantia and Razdan 1985) which do not contain *Aulacosphinctes*, and (2) sedimentary sequences of the Dras Formation are interspersed with the basalt of Dras volcanics (Fig. 2B) with no exposed-basement in this area. Thus, the finding of *Aulacosphinctes* sp. from the volcano-sedimentary sequences of the Dras Formation in the present study supports that the developments of Dras arc system were initiated during the Late Jurassic, particularly during Tithonian (145–152 Ma) or earlier than Tithonian in the Neotethyan ocean. Our data is substantiated by the latest radiometric age of Late Jurassic trachydacite (156 ± 1 Ma) and felsic tuff (160 ± 3 Ma) from Dras volcanics (Walsh et al. 2021). It is noteworthy to mention that the ammonite genus *Aulacosphinctes* is an important age diagnostic taxa for the Tithonian (Late Jurassic), especially in the Himalayas. In India, they are mostly reported from the Tithonian succession of Kachchh, Jaisalmer, Zanskar and Spiti basins (Uhlig 1903, 1910; Oloriz and Tintori 1991; Krishna et al. 1996; Pandey and Krishna 1996; Pathak 1997; Das 2002; Shome et al. 2005).

Aulacosphinctes have been reported from Late Jurassic successions in India, Pakistan, Tibet, Madagascar, Yemen, Italy, Spain, the USA, Chile, Peru and Argentina. While the genus predominantly thrived during the Tithonian period, some species have also been recorded from the Oxfordian to Berriasian intervals. For instance, *Aulacosphinctes moerickeanus, A. quadri, A. parvulus, A. berriaselliformis, A. sp.*, and *A. rectefurcatus* were identified in the Oxfordian-Berriasian succession of Andalucía, Spain (Olóriz and Rivas, 1978). Similarly, *A. humilis* and *A. retrosus* were documented in Kimmeridgian litho units of Antsalova, Madagascar (Collignon 1959; Besairie and Collignon 1972). The global distribution of *Aulacosphinctes* is summarized in Table 2.

The widespread distribution of *Aulacosphinctes* highlights its adaptability to diverse marine environments and its significance in biostratigraphic studies for correlating Tithonian-age marine sediments across different continents. The volcano-sedimentary litho units of the Dras Formation can be correlated with the other Tithonian marine successions (which poses *Aulacosphinctes*) by the present finding of *Aulacosphinctes* sp.

Palaeogeographic reconstruction of arc systems (subduction zones); prevailing debates and model from the present study

In context to the subduction of the Indian plate under Eurasia, the palaeogeographic position and evolution of the Dras arc always remained a matter of great debate, so as the development of multiple subduction zones and related arc systems especially the Spong arc and the Dras arc. Pederson et al., (2001) suggested the developments of Spongtang ophiolite in a MOR setting at *ca*. 177 Ma (Fig. 6A). Later Buckman et al., (2018) contemplated that the *ca*. 177 Ma gabbro represents the MORB type Neotethyan oceanic crust, on which Spong arc (Intra-oceanic island arc) formed as a result of the subduction process along an NNE-SSW transform fault at *ca*. 136 Ma. Similarly, Heitz (1986) suggested a 140 ± 15 Ma age for the Spong arc, while a 140–125 Ma age was assigned to the Spong arc by Reuber et al., (1989). Further, Pederson et al., (2001) also proposed a younger age (*ca*. 88 ± 5 Ma) for Spong arc. Thus, it is obvious that the Spong arc evolved through a geological time span (*ca*.140–88 Ma). Corfield et al., (2001) suggested that the Spong arc and Dras arc were developed above two different subduction systems in spite of many similarities (such as lithologies and ages) between them. In the contrary, Buckman et al., (2018), however, argued in favour of the same subduction setting for the development of Dras and Spong arcs. Additionally, Walsh et al., (2021) lately brought about a perception change by suggesting that the Dras arc was formed as an intra-oceanic island arc system by the subduction of Indian oceanic crust at *ca*. 160 Ma along a transform fault and almost perpendicular to the Indian margin on the

Table 2 Global distribution of genus *Aulacosphinctes*

Age	Locality	Country or state	Species	References
Oxfordian—Berriasian	Andalucia	Spain	*Aulacosphinctes moerickeanus*, *A. quadri*, *A. parvulus*, *A. berriaselliformis*, *A.* sp., *A. rectefurcatus*	Oloriz and Rivas (1978)
Kimmeridgian	Antsalova	Madagascar	*A. humilis*, *A. retrosus*	Collignon (1959); Besairie and Collignon (1972)
Tithonian	Wadi Hajar	Yemen	*A. spitiensis*, *A. natricoides*	Howarth and Morris (1998)
Tithonian	Menbu and Guchuo	Tibet, China	*A. moerikeanus*, *A. parvulus*, *A. hundesianus*	Li and Grant-Mackie (1988)
Tithonian	Glenn County, San Luis Obispo County, Tehama County, California	USA	*A. jenkinsi*, *A. diabloensis*, *A.* sp., *A.* sp. juv	Anderson (1945); Easton and Imlay (1955); Jones et al. (1969)
Early/Lower Tithonian	Ancona	Italy	*A. rectefurcatus*	Cecca et al. (1986)
Late/Upper Tithonian	Chicama Basin	Peru	*A. subvetustus*	Enay et al. (1996)
Late/Upper Tithonian	Cajón el Fierro	Chile	*A. proximus*	Larrain and Biró-Bagóczky (1985)
Middle Tithonian	Rio Maitenes	Chile	*A. proximus*	Salazar and Stinnesbeck (2016)
Middle Tithonian	Neuquen	Argentina	*A.* sp.	Leanza et al. (1990)
Middle Tithonian—Late/Upper Tithonian	Rio Maitenes	Chile	*A. proximus*	Salazar and Stinnesbeck (2016)
Late/Upper Tithonian—Early/Lower Berriasian	Cajón del Morado, Cruz de Piedra	Chile	*A. proximus*	Salazar Soto (2012)
Tithonian	Jaisalmer	India	*A.* sp.	Krishna et al. (1996); Pandey and Krishna (1996)
Tithonian	Zanskar	India	*A.* sp.	Oloriz and Tintori (1991)
Tithonian	Kachchh	India	*A.* sp.	Das (2002); Shome et al. (2005)
Late/Upper Tithonian	Spiti	India	*A.* sp., *A. latouchi*	Uhlig (1903, 1910); Pathak (1997)
Upper Tithonian	Shaikh Budin	Pakistan	*A. spitiensis*	Fatmi (1972)

Neotethys (Fig. 5B), whereas the Spong arc was evolved later at *ca*. 135 Ma (Fig. 6C). This contradiction raised a pertinent question regarding whether the Dras and Spong arcs developed within the same subduction system or they belong to two separate subduction systems.

The biostratigraphic and detrital zircon study of flysch sedimentary successions i.e. Kong and Chulung La formations (topmost Tethyan sedimentary successions) which are associated with the Spong ophiolite-Spong arc suggest that the sedimentation in the Kong and Chulung La formations continued till 54 Ma (Corfield et al. 2005; Najman et al. 2017). The collision between the Spong arc and India *ca*. 55 Ma shifted the marine system which resulted from the paucity of the younger detrital zircon (< 54 Ma) in the Kong and Chulung La formations. On the contrary, the flysch sequences that were associated with the Dras arc received a wide range of younger zircon populations (84 Ma: Nindam Formation, Walsh, et al. 2019; 54 Ma: Jurutz Formation, Henderson, et al. 2010). The 49 Ma biostratigraphic age of the topmost flysch sequence i.e. Nummulitic Limestone suggests the existence of a marine system in the Indus Suture Zone (Henderson et al. 2010). Thus, assuming the co-existence of the Spong arc and Dras arc in a single subduction system and collision of the Dras-Spong arc with India cannot possibly explain the occurrence of 49 Ma Nummulitic Limestone in the foreland basin of Dras arc. Considering the facts mentioned above, here we propose the Sapi-Shergol ophiolite basement on the Neotethyan ocean floor where the Dras arc was developed. It was a separate subduction zone than Spongtang (Fig. 6A).

Here, based on our finding of *Aulacosphinctes* sp. from the volcano-sedimentary sequence of Dras Formation, we propose that the Dras arc system was developed on a separate subduction system between Spong arc and Eurasia at around 160 Ma (on the southern margin of Neotethyan ocean) and it was subparallel to the Spong arc subduction system (Fig. 6). The initiation of the Dras arc in the Neotethyan ocean *ca*. 160 Ma and its continuity till 60–50 Ma (e.g. Walsh et al. 2021) explain the availability of two distinct youngest detrital zircon populations i.e. 90–100 Ma and 55–70 Ma in Kong and Chulung La formations. In addition, the presence of 90–100 Ma detrital zircon in the Kong and

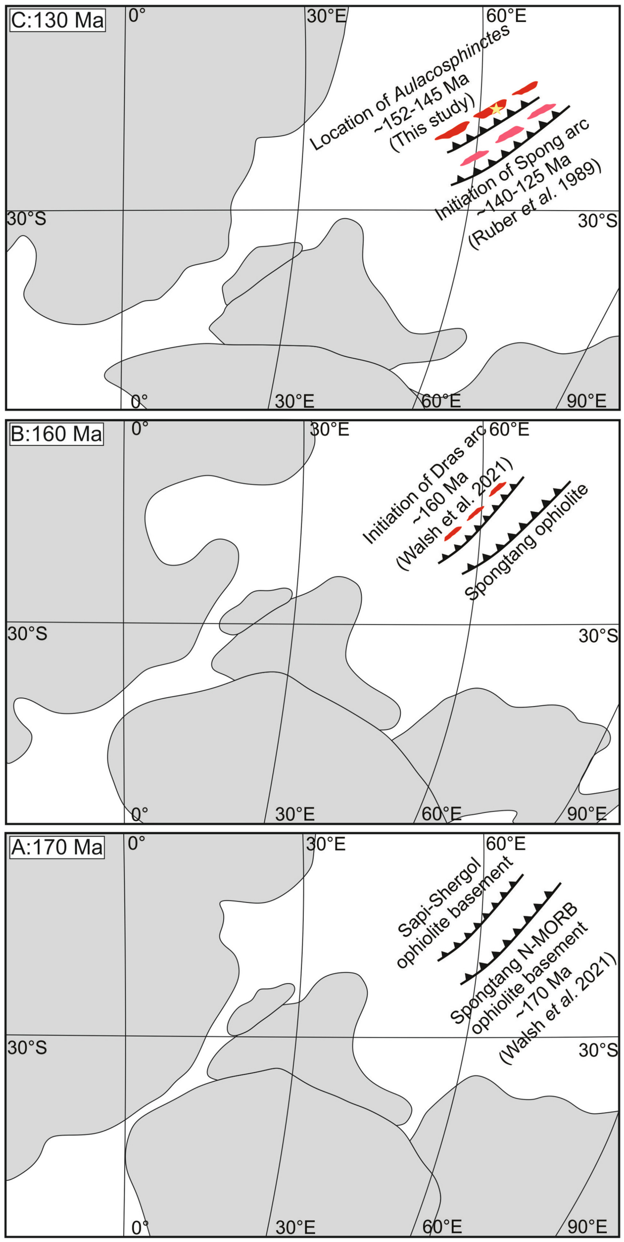

Fig. 6 Palaeogegraphic reconstructions of Dras arc using GPlate model of Müller et al., (2019). The interpretation of the palaeogeography of the Dras arc with time–space is adopted from Buckman et al., (2018) and Walsh et al., (2021). Our interpretation shows that the volcano-sedimentary sequences associated with the Dras arc system was initiated during Tithonian on the southern margin of the Neotethyan ocean. **A** Spongtang and Sapi-Shergol ophiolite basements developed on the Neotethyan ocean floor. B) Dras arc initiated (~ 160 Ma) on the Neotethyan ocean floor. C) Dras volcano-sedimentary sequence deposited around the Dras arc

Chulung La formations may also originate from the Spong arc. The first collision between the Spong arc and India at 55 Ma (e.g. Buckman et al. 2018) and the subsequent rising of Tethyan sedimentary sequences explain the shifting of marine facies both towards the north (Nindam basin) and south (Subathu basin) direction. The occurrences of the last marine signature i.e. Nummulitic Limestone (49 Ma) in the Indus Suture Zone suggests the later collision between the India-Spong arc and Dras arc occurred probably between 54 and 49 Ma. Recently, Mishra et al., (2024) reported 90 Ma youngest detrital zircon within the Subathu Formation in Uttarakhand, India. It is plausible that this particular detrital zircon originated from the Spong arc. Our hypothesis, suggesting the collision between the Spong arc and India followed by the uplift of Tethyan sedimentary sequences, gains support from the availability of 90 Ma detrital zircon in the Subathu basin, as well as the presence of 84 Ma and 54 Ma detrital zircon in the Nindam basin. Moreover, the scarcity of detrital zircon younger than 54 Ma in the Kong and Chulung La formations further reinforces this assumption.

The paleogeographic model (Fig. 6) from the present study certainly throws light on the protracted evolution of the Dras and Spong arc and its final collision with India. The discovery of *Aulacosphinctes* sp. was further strengthened by the radiometric data obtained by Walsh et al., (2021). However, more data on biostratigraphy as well as radiometric age will bring more conviction to say that the intra-oceanic arc initiation (Dras arc) was at least 50 Ma earlier than the present belief of *ca*. 100 Ma.

Conclusions

The record of ammonites is very scarce in the Indus Suture Zone. With the report of *Aulacosphinctes* sp. for the first time from the volcano-sedimentary sequences of Dras Formation, Ladakh India, it can be postulated that the development of Dras arc was initiated during the Late Jurassic on the southern margin of the Neotethyan ocean floor between India and Eurasia. The Dras arc was certainly separated from the Spong arc, both spatially and temporally. The deposition of volcano-sedimentary sequences of Dras Formation was started alongside of the developing Dras arc during the Late Jurassic. This sequence is time-equivalent to other Tithonian litho units that contain *Aulacosphinctes* across different continents.

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Declarations

Conflict of interest All authors declare that they have no conflicts of interest.

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