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Belemnite biostratigraphy of the upper Jurassic to lower Cretaceous strata in the Surghar range, NW Pakistan: Systematic and Paleobiogeographic implications

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Abstract

Four belemnite genera and twelve age-diagnostic species were identified from the from Upper Jurassic–Lower Cretaceous sequence of the Chichali Formation, northwest Pakistan. Four local biozones were established based on the identified belemnites. These biozones are arranged from base to top as follows; *Hibolithes pilleti/Hibolithes jaculoides/Hibolithes hastatus* Zone of Kimmeridgian age, *Hibolithes marwicki marwicki/Hibolithes arkelli* Zone of Tithonian age, *Belemnopsis malucana* Zone defines Tithonian–Berriasian boundary, and *Neohibolites ewaldi/Hibolithes longior/Belemnopsis jonkeri* Zone of Velanginian age. The biostratigraphic and paleogeographic occurrences of belemnites in the Tethyan and Boreal Realms were used to identify the migration pathways and distinctive paleobiogeographic provinces of belemnites. The paleoceanic settings closely linked the Upper Jurassic strata (~Biozones 1–2, representing the Kimmeridgian–Tithonian range) in the Tethyan and the Boreal Realms. The Lower Cretaceous (~Biozone 3, representing the Berriasian) strata also reveal a persistent oceanic connection between the Indo-Pacific and Mediterranean Provinces. However, the Boreal and Tethyan Realms were also connected in the Lower Cretaceous (~Biozone 4, representing the Velanginian strata) by shallow-water routes.

Keywords: *Belemnites; Biostratigraphy; Jurassic-Cretaceous; Paleobiogeography*

1. Introduction

Belemnites, the most well-known extinct cephalopod after ammonites, lived during the periods of history known as the Jurassic and Cretaceous; both groups became extinct at the Cretaceous–Paleogene boundary (Mutterlose 1988; Iba et al. 2014). In the earliest Jurassic, belemnites were restricted to the European region, but from then on, they achieved a worldwide distribution. Thus, they can potentially be used for correlation on a global scale. Based on the occurrences of different belemnite assemblages, Gradstein and Ludden (1992) recognized two distinct faunal realms, the Tethyan and the Boreal Realms. The Tethyan Realm constituted modern-day southern and central Europe, eastern Africa, Madagascar, Antarctica, South America, New Zealand, Indonesia, Australia, and India, while the Boreal Realm encompassed most parts of modern-day Russia and northern Europe (Gradstein and Ludden 1992). Based on the occurrence of the genus *Belemnopsis*, the Tethyan Realm was further divided into two biogeographic provinces: the Mediterranean Province (including southern Germany, the Alps, France, Spain, Morocco, Sicily, Crimea, and Bulgaria) which lacks *Belemnopsis*, and the Indo-Pacific Province (including the eastern Africa, India, Australia, Indonesia, New Zealand, and Antarctica), which is dominated by the endemic *Belemnopsis* (e.g. Stevens 1965; Combemorel 1972; Mutterlose 1988; Doyle and Howlett 1989; Gradstein and Ludden 1992; Mutterlose and Wiedenroth 2008). Pakistan lies in the Indo-Pacific Province, which constituted a major segment of the eastern Tethyan Realm (Ahmad et al. 2015, 2016).

In Pakistan, a rich belemnite fauna with limited known taxonomic and biostratigraphic information has been reported from the Upper Jurassic–Lower Cretaceous deposits of the Chichali Formation, exposed in the Surghar Range of the Upper Indus Basin in Pakistan (Fig 1; Spath 1930; Fatmi 1972, 1977). Based on the ammonoid fauna, an Oxfordian to Hauterivian age has been assigned to the lower and middle members of the Chichali Formation (Spath 1930; Fatmi 1972, 1977). Masood et al. (2009) reported age-diagnostic spores and pollen and assigned an Upper Jurassic to Lower Cretaceous age to the Chichali Formation in the Kala Chitta Range of Pakistan. Khan (2013) presented a detailed investigation of the dinoflagellates of the Chichali Formation and inferred that it is of Kimmeridgian–Valanginian age.

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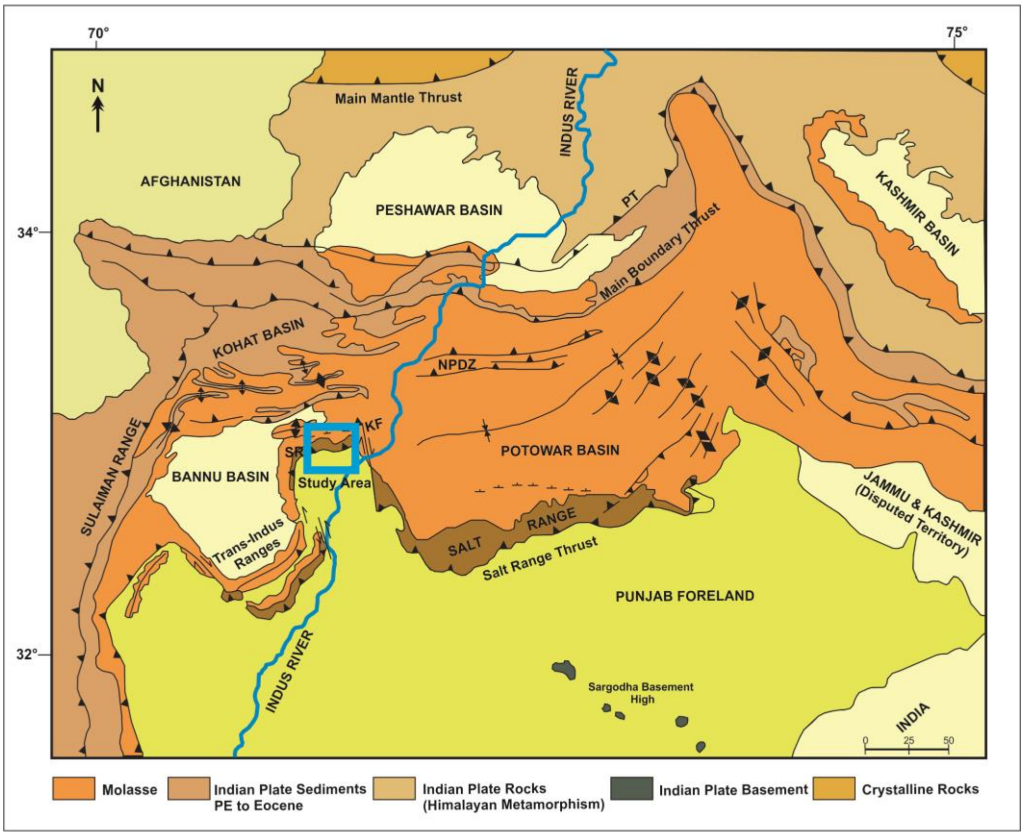

Fig 1. The geographic location and tectonic framework of the Upper Indus Basin and location of the Chichali Nala Section in the Surghar Range, Northwest Pakistan (modified after Yeats and Hussain 1987)

Historically, belemnite faunas have been successfully used as tools to establish the biozones and paleobiogeography of the Boreal Realm, Indo-Pacific and Mediterranean Provinces of the Tethyan Realm (Favre 1876; Pugaczewska 1961; Riegraf 1981; Mutterlose 1986; Doyle and Kelly 1988; Challinor 1991; Doyle and Mariotti 1991; Gradstein and Ludden 1992; Janssen 1997; Peter and Mutterlose 2009; Mariotti et al. 2013; Khan 2013). In this study, we aim to use the belemnite fauna for taxonomy and biostratigraphy to better constrain the age of the Chichali Formation. Rich in belemnites, the Chichali Formation also provides a good opportunity for a biostratigraphic comparison with the faunal elements of the Indo-Pacific Province in the eastern Tethys, the Mediterranean Province in the western Tethys, and the Boreal Realm to establish belemnite migration pathways and paleobiogeographical patterns.

2. Geological Background

Indus Basin is the largest sedimentary basin of Pakistan (Shah 2009). Based on its sedimentary history and structure, the Indus Basin is divided into the Upper and Lower Indus basins (Fig 1). The Upper Indus Basin includes the Trans-Indus Range (TIR) on the west side of the Indus River and the Salt Range on the eastern side of the Indus River (Fig 1). The study area (the Chichali Nala section) lies in the east-west trending Surghar Range that represents the eastern extremity of the TIR (Fig 1). The Surghar Range was once a part of the Salt Range, but the right-lateral strike-slip Kalabagh Fault truncated it to the north (Fig 1). The stratigraphy of the Salt Range in the Upper Indus Basin is represented by sedimentary fill of Precambrian to recent age (Fig 2), while in the Chichali Nala section; Upper Jurassic to Cretaceous rocks constitute the Chichali and Lumshiwal formations (Shah 2009). The Chichali Formation is an approximately 70-m-thick siliciclastic unit mainly comprised of sandy, organic-rich glauconitic shales interbedded with soft, fine-grained glauconitic and ridge-forming sandstones (Fig 3a). The lower contact of the Chichali Formation is disconformable with the Jurassic Samana Suk Formation, while its upper contact with the Lumshiwal Formation is transitional (Fig 3b). Chichali Formation is divided into the lower, middle, and upper members (Khan 2013). The lower member (~23m thick) is composed of sandy, organic-rich glauconitic shales interbedded with soft, fine-grained glauconitic sandstones. The rocks of this member are riddled with belemnites (Fig 3c).

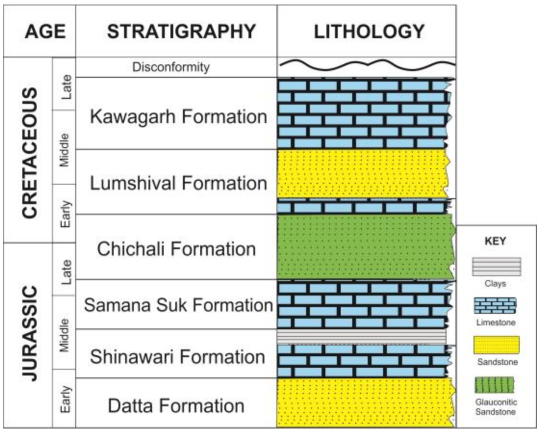

Fig 2. The generalized Jurassic and Cretaceous stratigraphy of the study area in Upper Indus Basin (Shah 2009).

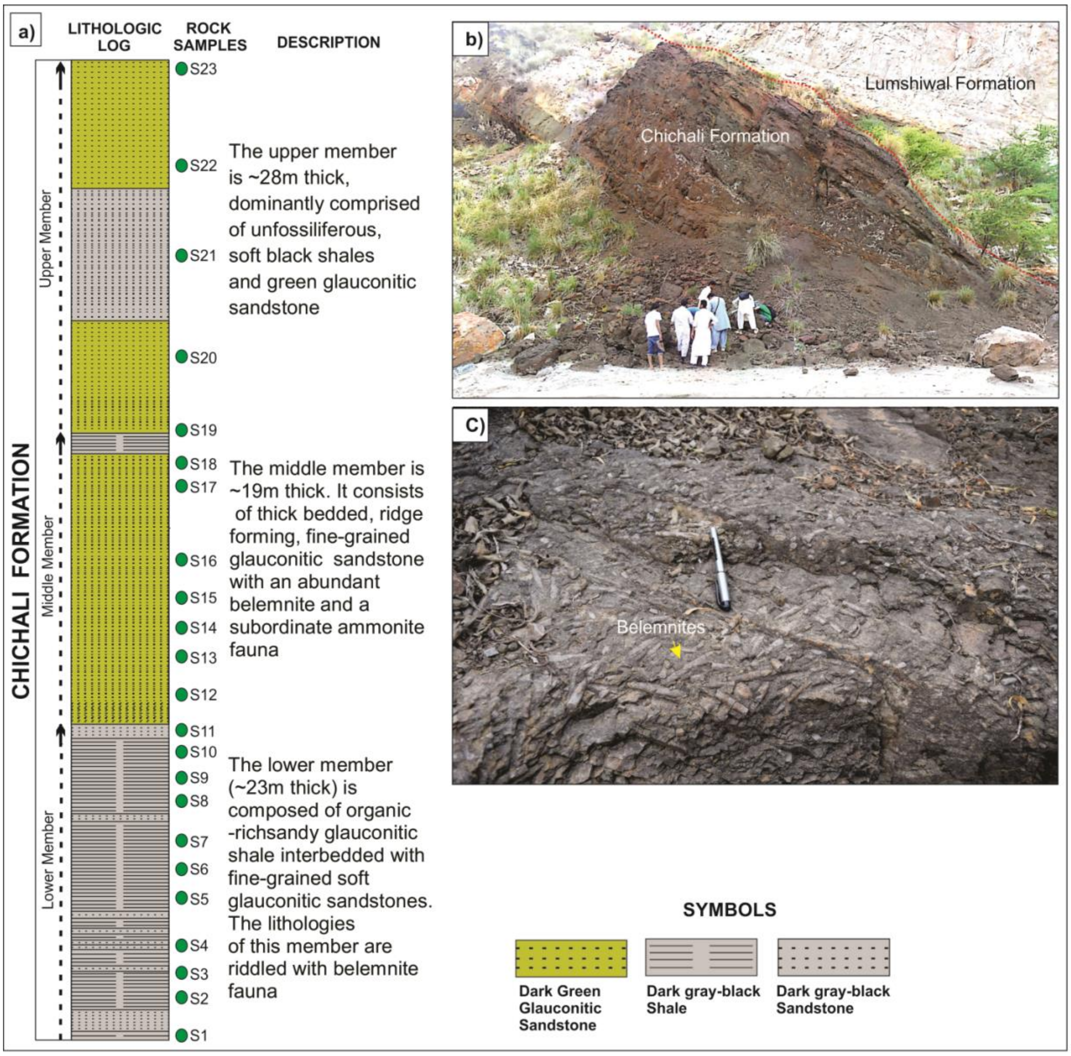

Fig 3. (a) The composite lithostratigraphic log of the Upper Jurassic-Lower Cretaceous Chichali Formation, exposed in the Chichali Nala Section (b) South looking view of the outcrops of Chichali Formation, showing a sequence of dark blakish shales, green glauconitic sandstones in the lower part and ridge forming sandstone in the middle-upper part. The upper contact with Lumshival Formation is transitional (c) View of the belemnites fauna found in the lower member of Chichali Formation

The middle member is ~19m thick and consists of thick-bedded, ridge-forming, fine-grained glauconitic sandstones with an abundant belemnite fauna and a subordinate ammonite fauna. The upper member is ~28m thick and dominantly comprised of soft, unfossiliferous black shales and green glauconitic sandstones (Figs 3a, 3b).

3. Materials and Methods

This study sampled the belemnite fauna from the parts of the Chichali Formation and around 23 outcrop samples were collected at variable intervals of 1–4m. All of the belemnite specimens were recovered from the lower and middle members, while the upper member was devoid of any fauna. Among the collected belemnite specimens, only 26 were found to have very fragile but complete rostra. In the laboratory, hardened steel chisels and awls were used to loosen the samples from the surrounding dirt and debris. The fragile and partially broken specimens were hardened with magic epoxy glue. For finer work, the samples were treated with hydrochloric acid to clean the rostra. We identified 12 belemnite species, and the studied specimens are available for reference in the repository of the Museum of Geology (Showcase 10, labels B1–B26) at the Department of Geology, University of Peshawar, Pakistan.

The taxonomic diagnosis of 4 belemnite genera and 12 species (Figs 4-5) enabled the construction of a local comparative biostratigraphic range distribution chart (Fig 6), a global biostratigraphic comparison chart (Fig 7), a species diversity plot (Fig 8), and migration pathway/paleobiogeographic charts for the Kimmeridgian–Valanginian strata in the study area and other areas of the Tethyan and Boreal Realms (Figs 9-10). We summarize here some of the diagnostic morphological characters (i.e. rostra, cross section, and grooves) of the belemnites that were helpful for species-level discrimination. Belemnite rostra are generally bullet-shaped, and there are three basic morph types: cylindrical, conical, and hastate. The sizes of the rostra were classified as small (<60mm), medium (60–80mm), or large (>80mm; Jeletzky 1966; Doyle and Kelly 1988). A transverse or cross-sectional cut shows the shape of a surface perpendicular to the apical line; the cross sections of belemnites are generally circular, elliptical, and pyriform or subquadrate (Doyle and Kelly 1988). Two types of grooves have been defined: apical and alveolar (Doyle and Kelly 1988). The grooves occur either on the ventral or dorsal sides-or, in some genera, on both the ventral and dorsal sides. The grooves are of great diagnostic importance at the level of genus and higher. The taxonomic classification used below mainly follows Jeletzky (1966).

4. Results

4.1. Systematic paleontology

Class CEPHALOPODA Cuvier (1795)
Subclass COLEOIDEA Bather (1888)
Order BELEMNITIDA Zittel (1895)
Suborder BELEMNOPSEINA Jeletzky (1965)
Family BELEMNOPSEIDAE Naef (1922)

4.1.1. Genus *HIBOLITHES* Montfort (1808)

Species *Hibolithes hastatus* Montfort (1808) (Fig 4: B1a-b)

Synonymy

1808 *Belemnites hastatus* Denys de Montfort

Diagnosis

The shape of the guard is subhastate with a long, sharp apex. The transverse section is compressed at the alveolar region and becomes circular at the stem and apical regions (Fig 4: B1a-b).

Geographic distribution: In northwest Europe, *Hibolithes hastatus* has been found in Bajocian to Aptian strata (Challinor 1990). It is also known from the Mediterranean Province and New Zealand in Middle Jurassic rocks. In Upper Jurassic rocks, *Hibolithes hastatus* is found in the Mediterranean Province, India, Madagascar, South America, Antarctica, New Zealand, and Indonesia. In Lower Cretaceous strata, it has been reported from the Mediterranean Province, Madagascar, Australia, Indonesia, North America, Northern Europe, and Papua New Guinea (Gradstien and Ludden 1992).

Age in Pakistan: Kimmeridgian–Tithonian

Species *Hibolithes jaculoides* Swinnerton (1937) (Fig 4: B2a-b)

Synonymy

1892 *Belemnites jaculum* Swinnerton; p. 257-260, pl. VII, fig. 2-3

1937 *Hibolites jaculoids* Swinnerton, p. XXV

1952 *Hibolites jaculoids* Swinnerton, p. 54, pl. 14, fig. 17, 18

1978 *Hibolites jaculoids* Swinnerton; Mutterlose, p. 99, pl. 4, fig. 1-3; pl. 5, fig. 5; pl. 6, fig. 1

1978 *Hibolites jaculoids* Swinnerton; Doyle and Kelly, p. 19, pl. 1, fig. 11-15; pl. 2, fig. 8, 9

Diagnosis

The outline of the guard is club-shaped. The outline is symmetrical, and the transverse section is depressed at the guard (Fig 4: B2a-b).

Geographic distribution: This species has been reported from the Lower Cretaceous (Valanginian to Hauterivian) age strata of northwestern Europe and Russia, while in South America it has been found in Valanginian to Berriasianage strata (Doyle and Mariotti 1991).

Age in Pakistan: Kimmeridgian–Tithonian

Species *Hibolithes longior* Schwetzoff (1913) (Fig 4: B3a-b)

Synonymy

1861 *Belemnites pistilliformis* Blainville; Loriol, p. 17-18, pl. I, fig. 1

1939 *Hibolites longior* Schwetzoff; Krymgol, p. 10-11, pl. I, fig. 7

1964 *Hibolites longior* Schwetzoff; Stoyanova-Vergilova, p. 138, 144 (?), 145 (pars)

1970 *Hibolites longior* Schwetzoff; Stoyanova-Vergilova, p. 13-14, Pl. III, figs. 1-2 (?), 3.
1984 *Hibolites subfusiformis* (RASPAIL) morphe B; GAYTE, Pl. I, fig. 1.
1994 *Hibolites longior* Schwetzoff; Vašíček et alii, p. 24 (pars), 43, 80 (pars), Pl. 25, figs. 7-8 [Late Hauterivian].
1995 *Pseudohibolites longior* (Schwetzoff); Riegraf, p. 103.
1997 *Hibolites cf. longior* Schwetzoff; Baraboshkin & Yanin, p. 15 [Late Valanginian].
2002 *Hibolites longior* Schwetzoff; Topchishvili et alii, p. 64-65, Pl. VI, figs. 1-2 [latest Hauterivian; = Hibolithes sp. nov. gr. Cigaretus STOYANOVA-VERGILOVA, 1965].
2004 *Hibolithes longior* Shvetsov; Janssen & Főzy, p. 37, Pl. II, figs. 20-21 (pars cum syn.).

Diagnosis

The outline of the guard is hastate to subhastate. The guard is elongated. The transverse section is depressed. The narrow, shallow alveolar grooves are preserved. The outline of the guard is symmetrical (Fig 4: B3a-b).

Geographic distribution: It is widely distributed in the circum-Mediterranean region (Mutterlose and Wiedenroth 2008).

Age in Pakistan: Kimmeridgian–Valanginian

Species *Hibolithes marwicki* Stevens (1965) (Fig 4: B4a-b)

Synonymy

1965 *Hibolithes marwicki marwicki* Stevens pl. 18, fig. 1-9, 11-17; pl. 19, fig. 1-9, 13-18.
1986 *Hibolithes aff. marwicki marwicki* Mutterlose figure 4a, b.
1999 *Hibolithes marwicki* Stevens, Challinor fig. 45-70.

Diagnosis

The guard of the specimens is elongate with a sub hastate shape. The profile is asymmetrical. The cross section is circular at the stem and apical regions and becomes compressed at the alveolar region (Fig 4: B4a-b).

Geographic distribution: *H. marwicki* resembles *H. lagoicus*, which was recorded from Upper Jurassic rocks in Indonesia *(*Mutterlose 1986). *H. marwicki* has also been reported from New Zealand in Upper Jurassic (Tithonian) strata (Gradstein and Ludden 1992).

Age in Pakistan: Tithonian

Species *Hibolithes aff. verbeeki* Kruizinga (1921) (Fig 4: B5a-b)

Synonymy

1921 *Hibolites verbeeki* Kruizinga; p. 179, pl. 6, fig. 1
1927 Hibolites flemingi Spath; p. 13, pl. 1, fig. 2
1932 Hibolites flemingi Spath; Besairie, p. 8, pl. 4, fig. 3
1936 Hibolites flemingi Spath; Besairie, p. 146, pl. 22, figs. 19, 20

Diagnosis

The specimen is a completely preserved, medium-sized belemnite. The outline of the guard is subhastate. The cross section of the guard is depressed at the posterior end and circular in the alveolar region. The shallow, narrow alveolar groove is preserved but does not reach the larger thickness of the guard. The phragmocone is also well preserved (Fig 4: B5a-b)

Geographic distribution: *H. verbeeki* has been reported from Kimmeridgian and Tithonian strata in the Indo-Pacific Province and Somaliland (Gradstein and Ludden 1992).

Age in Pakistan: Kimmeridgian–Tithonian

Species *Hibolithes aff. arkelli* Stevens (1965) (Fig 4: B6a-b)

Synonymy

1986 *Hibolithes aff. marwicki*, Mutterlose, p. 8-10, figures 6a-b, g-j.
1999 *Hibolithes arkelli* Stevens, Challinor, p. 381-383, figures 71-93 (see synonymy therein)

Diagnosis

The guard of the specimens is slightly hastate. A narrow and somewhat deep alveolar groove is preserved that reaches into the stem region. The guard is strongly compressed therefore resembles an oval in cross section (Fig 4: B6a-b).

Geographic distribution: *H. aff. arkelli* has been reported from Upper Jurassic (Tithonian) rocks in Indonesia *(*Mutterlose 1986).

Age in Pakistan: Tithonian

Species *Hibolithes cf. pilleti* Pictet (1868) (Fig 5: B7a-b)

Synonymy

1868 *Belemnites Pilleti* Pictet, pp. 219-220, pi. 36, figs. 7,8-9(?).
1879 *Belemnites Pilleti* Pictet-Vacek, p. 670.
1880 *Belemnites Pilleti* Pictet-Favre, pp. 18-19, pi. I, figs. 12-13(7).
1897 *Belemnites* nov. spec.-Abel, p. 346.
1890 *Belemnites Pilleti* Pictet-Toucas, pp. 573,590.
1995 *Pseudohibolites pilleti* Pictet-Riegraf, p. 104

Diagnosis

The outline of the guard is subhastate. The grooves are not preserved. The transverse section is circular at the stem and apical regions and depressed at the alveolar region. The flanks of the specimens are plano-convex (Fig 5: B7a-b)

Geographic distribution: It has been reported from France, southeast Spain, and Switzerland in Berriasian strata (Janssen 1997).

Age in Pakistan: Tithonian

4.1.2. Genus *NEOHIBOLITES* Stolley (1911)

Species *Neohibolites ewaldi* Strombeck, 1861 (Fig 5: B8a-b)

Synonymy

1847 *Belemnites semicanaliculatus* Blainville; d'Orbigny, p. 23, pl. IX, fig. 7-8
1861 *Belemnites Ewaldi* v. Strombeck, p. 34
1911 *Neohibolites clava* Stolley, p. 37, pl. I, fig. 21; pl. II, fig. 1-12
1911 *Neohibolites inflexus* Stolley, p. 42, pl. I, fig. 30; pl. II, fig. 13-26

1955 Neohibolites ewaldi (v. Strombeck); Swinnerton, p. 64, pl. XVI, fig. 8-26, pl. XVII, fig. 1-14
1987 Neohibolites ewaldi (v. Strombeck); Doyle, p. 312, pl. 43, fig. 1-5

Diagnosis

These are medium sized belemnite with hastate to subhastate shape. The apex is moderately acute. The outline is symetrical. The cross section of the stem and apical region is circular. The apical line is ortholineate and the species is doppellinien (having double lateral lines). The alveolar groove is short and deep (Fig 5: B8a-b).

Geographic distribution: It has been recorded from southern France, Germany, southern Mozambique, and the United Kingdom in Upper Jurassic–Lower Cretaceous strata (Gradstein and Ludden 1992).

Age in Pakistan: Kimmeridgian–Valanginian

4.1.3. Genus *BELEMNOPSIS* Bayle and Zeiller (1878)

Species *Belemnite bessinus* d' Orbigny (1842) (Fig 5: B9a-b)

Diagnosis

The shape of the guard is sub hastate to cylindrical, and the cross section is slightly compressed to quadratic. A groove is present along the stem region almost up to the apex. (Fig 5: B9a-b).

Geographic distribution: It has been reported from the Mediterranean Province, where it is found in Toarcian to Oxfordian age. In the Indo-Pacific Province (India, South America, Madagascar, New Zealand, Antarctica, Australia, and Indonesia), it has been found in Bathonian to Hauterivian age (Gradstein and Ludden 1992).

Age in Pakistan: Kimmeridgian–Valanginian

Species *Belemnopsis jonkeri* cf. Stolley (1929) (Fig 5: B10a-b)

Diagnosis

It is a large-sized, partially preserved belemnite. The shape of the guard is subhastate, and the outline is elongated to symmetrical. The transverse section is slightly depressed. The alveolar region is missing, and a groove is preserved along the length of the stem (Fig 5: B10a-b)

Geographic distribution: This species was first reported from Kimmeridgian rocks in Indonesia (Stolley 1929). It has also been reported from the East Indies in Berriasian to Valanginian strata (Gradstein and Ludden 1992).

Age in Pakistan: Berriasian–Valanginian

Species *Belemnopsis moluccana* Boehm (1907) (Fig 5: B11a-b)

Diagnosis

It is a large-sized belemnite. The outline is subhastate to slightly cylindrical and symmetrical. The transverse section is circular at the stem and apical regions and becomes slightly depressed at the alveolar region. A ventral alveolar groove is present along the stem (Fig 5: B11a-b).

Geographic distribution: This species has been reported from the eastern Indian Ocean in Lower Cretaceous (Berriasian) strata (Gradstein and Ludden 1992).

Age in Pakistan: Kimmeridgian–Berriasian

4.1.4. Genus *CASTELLANIBELUS* Combemorel (1972)

Species *Belemnite orbignyamus* Duval-Jouve (1841) (Fig 5: B12a-b)

Description: The shape of the guard is cylindrical, and the cross section is slightly compressed to quadratic. A groove is present along the stem region almost up to the apex. The ventral surface is flat, so the apical line is ventrally placed (Fig 5: B12a-b).

Geographic distribution: It is found in the Tethyan Realm in Tithonian–Velanginian age (Gradstein and Ludden 1992).

Age in Pakistan: Tithonian–Velanginian

4.2. Biostratigraphy

The Chichali Formation contains ammonoids (*Perisphinctes, Prososphinctes virguluiodes, P. (Arisphinctes) orientalis, Aulacosphinctes, Himalayites)* and belemnites, including *Belemnopsis gerardi* and *Hibolithes,* and is of Oxfordian to Hauterivian age (Spath 1930; Fatmi 1969, 1972, 1977; Shah 2009). The regional distribution of the ammonoid fauna indicates an Oxfordian to Valanginian age of the lower and middle parts of the Chichali Formation, while the upper part may represent the Hauterivian age (Fatmi 1969, 1972, 1977). In this study, we have recorded four belemnite genera and twelve species: *Hibolithes hastatus* Montfort (1808), *Hibolithes jaculoides* Swinnerton (1937), *Hibolithes longior* Schwetzoff (1913), *Hibolithes marwiki marwiki* Stevens (1965), *Hibolithes aff. verbeeki* Kruizinga (1921), *Hibolithes aff. arkelli* Stevens (1965), *Hibolithes cf. pilleti* Pictet (1868), *Neohibolites ewaldi* Strombeck (1861), *Belemnite bessinus* d' Orbigny (1842), *Belemnopsis jonkeri* cf. Stolley (1929), *Belemnopsis moluccana* Boehm (1907), and *Belemnite orbignyamus* Duval-Jouve (1841).

Based on belemnite species, the Chichali Formation is divided into four local biozones, which are calibrated against the ammonoid fauna (Spath 1930; Fatmi 1969, 1972, 1977) and the dinoflagellate biozones (Khan 2013). The details of these biozones are listed below.

4.2.1. Hibolithes pilleti/Hibolithes jaculoides/Hibolithes hastatus assemblage biozone

This biozone is defined by the simultaneous first occurrence (FO) of *H. pilleti*, *H. jaculoides*, and *H. hastatus* in the lower part of the Chichali Formation. It is correlated with ammonoid fauna (*Aspidoceras sp., Physodoceras sp., Katroliceras cf. pottingeri*, and *Pachysphinctea robustus*) of Kimmeridgian age (Spath 1930; Fatmi 1969, 1972, 1977) and with the dinoflagellate Oppel Zone A of Kimmeridgian age (Khan 2013).

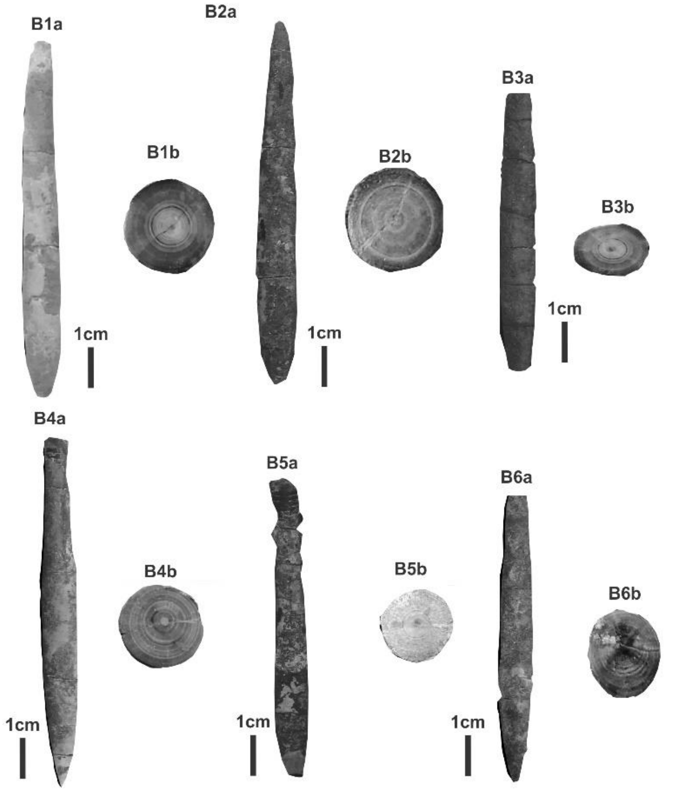

Fig 4. The figure shows *Hibolithes hastatus* Montfort (1808) (B1a-b); *Hibolithes jaculoides* Swinnerton (1937) (B2a-b); *Hibolithes longior* Schwetzoff (1913) (B3a-b); *Hibolithes marwicki* Stevens (1965) (B4a-b); *Hibolithes aff. Verbeeki* Kruizinga (1921) (B5a-b); *Hibolithes aff. arkelli* Stevens (1965) (B6a-b).

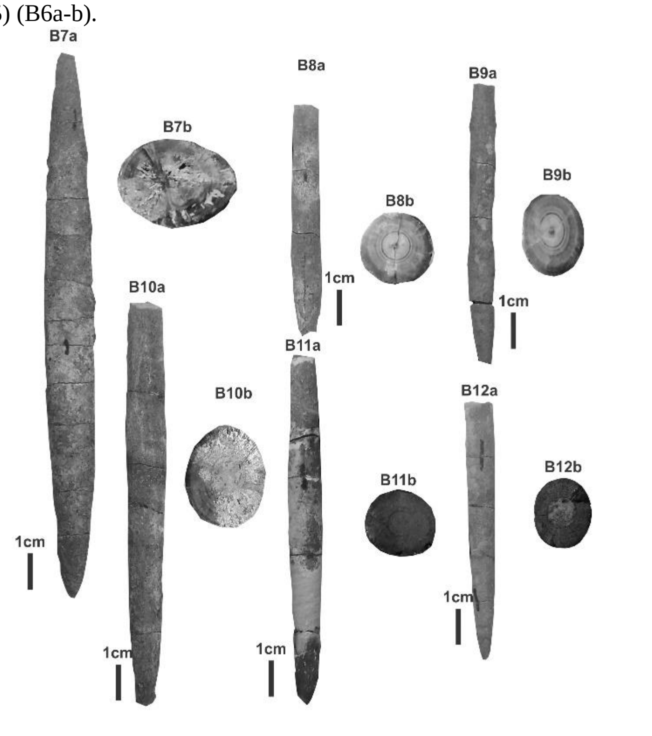

Fig 5. The figure shows *Hibolithes cf. pilleti* Pictet (1868) (B7a-b); *Neohibolites ewaldi* Strombeck (1861) (B8a-b); *Belemnite bessinus* d' Orbigny (1842) (B9a-b); *Belemnopsis jonkeri* Stolley (1929) (B10a-b); *Belemnopsis moluccana* Boehm (1907) (B11a-b); *Belemnite orbignyamus* Duval-Jouve (1841) (B12a-b)

Based on this comparison, we assign a Kimmeridgian age to this biozone (Fig 6).

***4.2.2. Hibolithes marwicki /Hibolithes arkelli* taxon range biozone**

The distribution of *H. marwicki marwicki* and *H. arkelli* define this biozone in the lower-middle part of the Chichali Formation. This biozones is correlated with the ammonoid fauna of Tithonian age that includes *Aulacosphinctoides sp.*, *Virgatosphinctes sp.*, *Hildoglochioceras sp.*, *Pronicerasindicum sp.*, *Blanfordiceras sp.*, *Pterolytocerasexoticum sp.*, *Spiticeras multiforme sp.*, and *Protacanthodiscus sp.* (Spath 1930; Fatmi 1969, 1972, 1977). Thus, the age of this biozone is Tithonian (Fig 6).

4.2.3. Belemnopsis malucana taxon biozone

This biozone is defined by the last occurrence (LO) of *Belemnopsis malucana* in the middle part of the Chichali Formation. It is correlated with the ammonoid fauna, including *Subthurmannia balsseri*, *Neohoploceras*, and *Spiticeras*, of Berriasian age (Spath 1930; Fatmi 1969, 1972, 1977). Based on this comparison, we assign a Berriasian age to this biozone (Fig 6).

***4.2.4. Neohibolites ewaldi/Hibolithes longior/Belemnopsis jonkeri* assemblage biozone**

The LO of *N. ewaldi/H. longior* and *B. jonkeri* defines this biozone, which has been recorded in the upper-middle part of the Chichali Formation. It correlates with the ammonoid fauna that includes *Rogersitesshinki*, *Olcostephanusmaidani*, *Neocomites*, and *Thurmanniceras sarasinella* (Spath 1930; Fatmi 1969, 1972, 1977) and the dinoflagellate Oppel Zone B, representing a Velanginian age (Khan 2013). Based on this correlation, we assign a Valanginian age to this biozone (Fig 6).

Although the upper part of Chichali Formation in the Chichali Nala section did not reveal any age-diagnostic occurrences of fauna and flora, however; in other parts of the Indus Basin, a Hauterivian-aged fauna including rhynchonellid and terebratulid brachiopods, foraminifera, and some vertebrate fossil remains have been found. Thus, the upper part may represent the Hauterivian age (Fatmi 1969, 1972, 1977; Shah 2009).

5. Discussion

5.1. Migration pathways of Belemnites

The biostratigraphic range of the belemnite species in the study area corresponds to a Kimmeridgian–Velanginian age, and their biostratigraphic ranges in the Indo-Pacific and Mediterranean Provinces within the Tethyan and Boreal Realms were gathered from the literature to construct a global biostratigraphic framework (Fig 7). We used the global biostratigraphic range distribution data as a key to describe the migration pathways and paleobiogeographic distributions of the following belemnite species in the Tethyan and Boreal Realms.

H. hastatus has been reported from the Mediterranean Province (Sicily, Southern Italy), where it ranges from Late Callovian to Middle Oxfordian age (Mariotti et al. 2013). This species has also reported from Oxfordian age in France and Germany (d' Orbigny 1842; Fig 7).

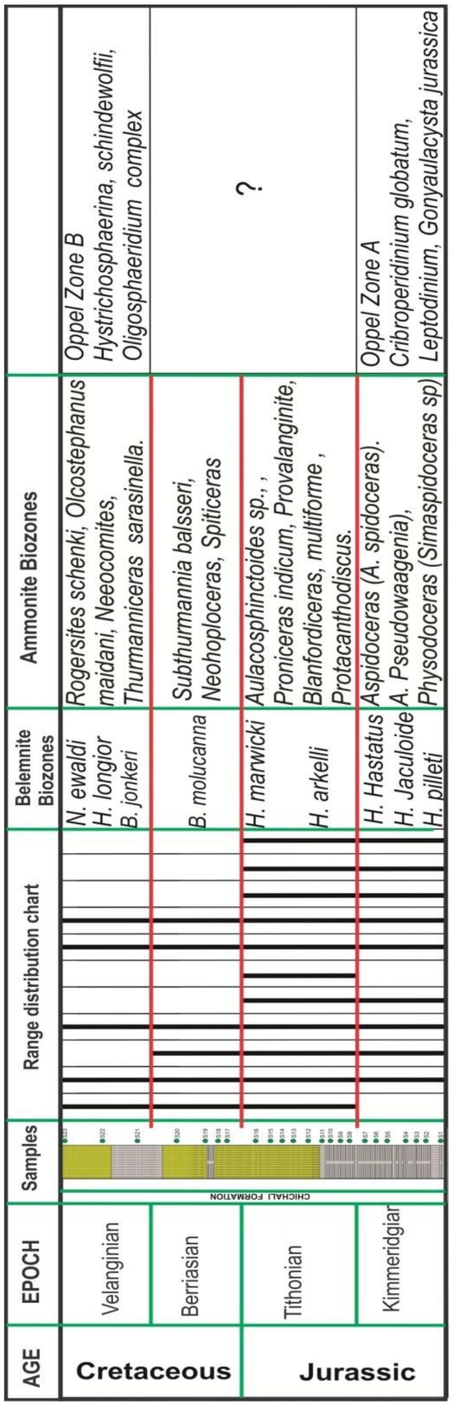

Fig 6. The Belemnite biostratigraphy of the Chichali Formation and its calibration against the ammonoid fauna (Spath 1930; Fatmi 1969, 1972, 1977) and the dinoflegellate biozonation (after Khan 2013) in the study area.

Furthermore, Favre (1876) suggested that *H. hastatus* is the most widespread species in the Callovian and Oxfordian age of Switzerland. In Poland, *H. hastatus*is found in Bathonian to Oxfordian age units. Pugaczewska (1961) and Riegraf (1981) also reported it from the Mediterranean Province (France, England, Austria, Portugal, Spain, Algeria, Cascasus, and Arabia), the Indo-Pacific Province (India and Madagascar), and the Boreal Realm (Russia). *H. hastatus* represents Kimmeridgian age in Pakistan (Khan 2013). Riegraf (1981) reported *H. hastatus* from southwest Germany in Oxfordian to Tithonian age units (Fig 7). The global biostratigraphic and paleobiogeographic distribution of *H. hastatus* suggests that it simultaneously evolved in the Mediterranean Province (Spain) and the Boreal Realm (Russia) in the Middle Jurassic (Bathonian) and later migrated within the Mediterranean Province (Germany and France) and to the Indo-Pacific Province (Pakistan) in the Kimmeridgian (Fig 7).

H. jaculoides has been reported from Russia, northwestern Europe, Kongsoya, and the Arctic in the Boreal Realm and from the Mediterranean Province in Germany in Valanginian to Hauterivian age (Stevens 1965, Mutterlose 1978). In the Tethyan Indo-Pacific Province, it is recorded in Kimmeridgian to Tithonian age in Pakistan (Fig 7). Thus; we conclude that *H. jaculoides* migrated from the Indo-Pacific Province to the Mediterranean Province and the Boreal Realm (Fig 7).

H. cf pilleti has been reported from the Mediterranean Province in France, Spain, and Switzerland in Berriasian strata (Favre 1876; Pugaczewska 1961; Riegraf 1981; Mutterlose 1986; Doyle and Kelly 1988; Challinor 1991; Doyle and Mariotti 1991; Gradstein and Ludden 1992; Janssen 1997; Peter and Mutterlose 2009; Mariotti et al. 2013; Fig 7). In the Indo-Pacific Province (Pakistan), it occurs in Kimmeridgian–Tithonian time. These data confirm that *H. cf pilleti* first evolved in the Indo-Pacific Province and then migrated to the Mediterranean Province (Fig 7).

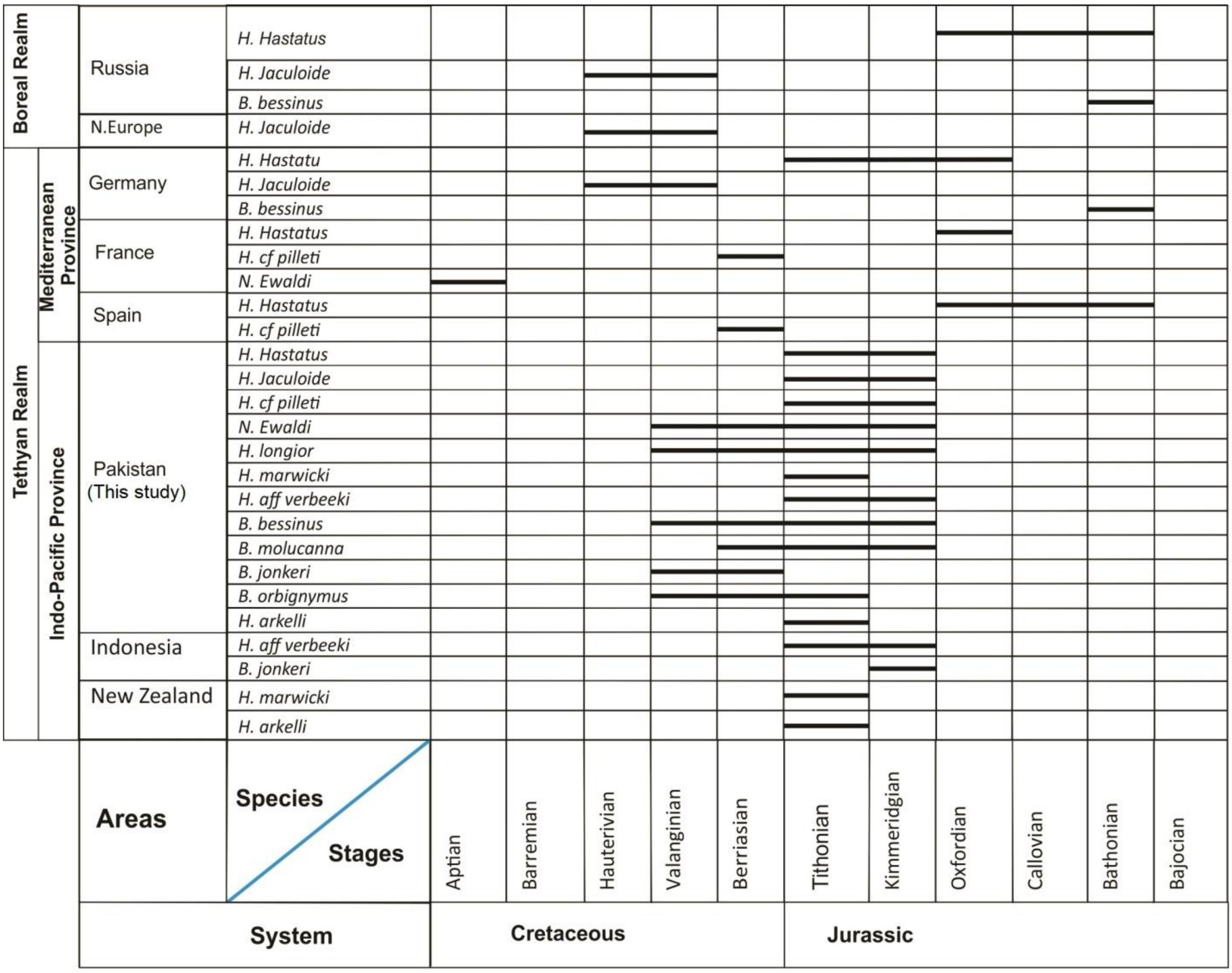

Fig 7. Global biostratigraphic framework of belemnites in the Tethyan Realm (Indo-Pacific Province and Mediterranean Province) and Boreal Realm. This chart is compiled from the integration of current study and the available published literature (Favre 1876; Pugaczewska 1961; Riegraf 1981; Mutterlose 1986; Doyle and Kelly 1988; Challinor 1991; Doyle and Mariotti 1991; Gradstein and Ludden 1992; Janssen 1997; Peter and Mutterlose 2009; Mariotti et al. 2013 and Khan 2013).

H.longior has been recorded in Valanginian–Hauterivian age in the Mediterranean Province. In the Indo-Pacific Province (Pakistan), it has been reported from Kimmeridgian–Valanginian time (Fig 7). This comparison reveals that *H. longior* migrated from the Indo-Pacific Province to the Mediterranean Province (Fig 7).

H. marwicki resembles *H. lagoicus* and *H. compressus*, species which have been reported from New Zealand and assigned a Tithonian age (Mutterlose 1986). It has also been reported from Pakistan in Tithonian time (Fig 7). From this comparison, we conclude that *H. marwicki* was restricted only to the Indo-Pacific Province in the Tithonian period (Fig 7). Similarly, *H. aff. Verbeeki* has been reported only from the Indo-Pacific Province, Somaliland, and Indonesia, where it was found in Kimmeridgian and Tithonian age units, thus showing a simultaneous evolution within the Indo-Pacific Province (Fig 7; Mutterlose 1986). The presence of *H. arkelli* in New Zealand (Mutterlose 1986) and Pakistan (this study) in Tithonian rocks suggests that it simultaneously originated within the regions of the Indo-Pacific Province (Fig 7).

Neohibolites ewaldi has been reported from the Mediterranean Province (southern France, Germany, southern Mozambique, Yorkshire, and Kent) in Aptian time (Fig 7; Doyle and Mariotti 1991). It represents Kimmeridgian–Valanginian strata in Pakistan (Khan 2013). The regional biostratigraphic distribution of *N. ewaldi* suggests that it first evolved in the Indo-Pacific Province and then migrated to the Mediterranean Province (Fig 7).

The occurrence of the genus *Belemnopsis* was noted in Toarcian to Oxfordian age units of the Mediterranean Province (central and southern Europe) and Bathonian to Hauterivian time of the Indo-Pacific Province (India, South America, Madagascar, New Zealand, Antarctica, Australia, Indonesia, and Pakistan; Gradstein and Ludden 1992). In general, this pattern suggests a migration from the Mediterranean Province to the Indo-Pacific Province within the Tethyan Realm. The species *Belemnopsis bessinus* d' Orbigny has been reported from Bathonian strata of France, Germany, Switzerland, and Russia (Pugaczewska 1965). This species has also been reported from Poland in the Bathonian Clays and from the Indo-Pacific Province (Pakistan) in Kimmeridgian strata (Fig 7). Thus, we conclude that *B. bessinus* simultaneously originated in the Mediterranean Province (Tethyan Realm) and the BorealRealm (Russia) in the Bathonian age and then migrated into the Indo-Pacific Province (Pakistan) in the Kimmeridgian age (Fig 7).

Belemnopsis molucanna has been reported from Berriasian period in the Indo-Pacific Province (Gradstien and Ludden 1992) and Pakistan (this study). Therefore, it is assumed that *B. moluccana* simultaneously evolved within the regions of the Indo-Pacific Province (Fig 7).

Belemnopsis jonkeri has been reported from Kimmeridgian time in Indonesia (Stolley 1929) and from Berriasian to Valanginian time in the Indo-Pacific Province (Gradstien and Ludden 1992). In Pakistan, it has been reported from Kimmeridgian–Velanginian period. This regional comparison (Fig 7) suggests that *B. jonkeri* first originated in the Indo-Pacific Province (Indonesia) within Kimmeridgian age, and then an in situ migration within the Indo-Pacific Province (East India, Pakistan) took place within Berriasian to Valanginian age. *Belemnite orbignymus* represents Tithonian–Valanginian strata in the Tethyan Realm (Janssen 1997, 2003), and suggests a simultaneous evolution.

5.2. Diversity, Abundance, and Paleobiogeographic distribution

Species may migrate into or out of a region as the geographic conditions change. The belemnite fauna from the Indo-Pacific region is conspecific with the Mediterranean Province and Boreal Realm, so it provides a basis for deciphering a paleobiogeographic distribution of different species within Upper Jurassic–Lower Cretaceous strata.

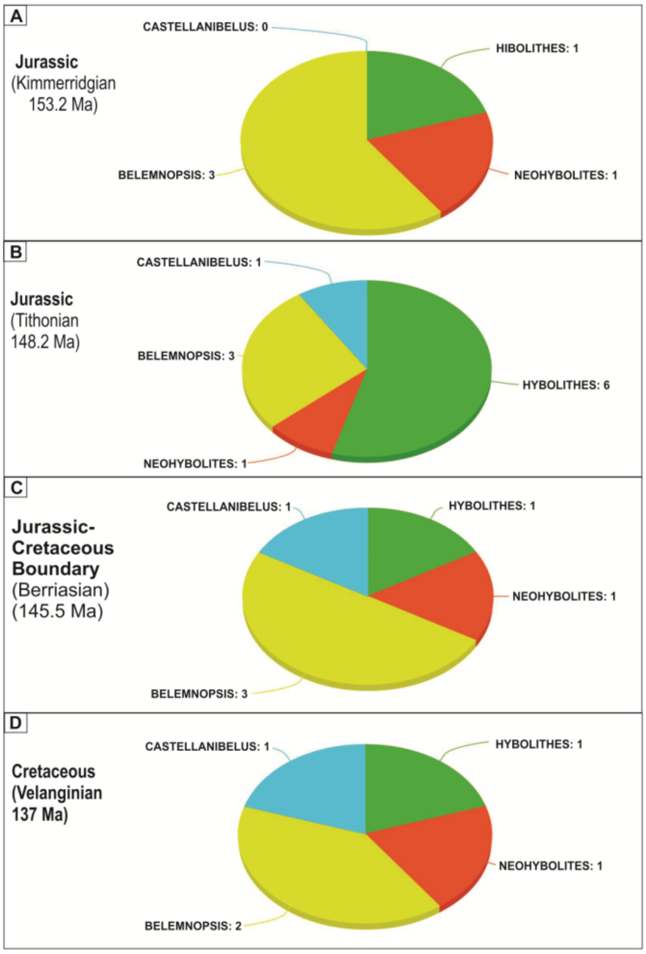

Fig 8. The belemnite species diversity chart reflects the variation in abundance of the genera and species in the Upper Jurassic (Kimmeridgian-Tithonian) Lower Cretaceous (Berriasian-Valanginian) deposits of the Chichali Formation.

In this study, four belemnite genera (i.e. *Hibolithes, Belemnopsis, Castellanibelus,* and *Neohibolites*) were identified, and the migration pathways of twelve belemnite species were plotted on Jurassic and Cretaceous paleogeographic maps after Scotese (2014). The details of the species that show a migration are discussed in their respective biozones as follows.

In the *Hibolithes pilleti/Hibolithes jaculoides/Hibolithes hastatus* biozone, representing the Kimmeridgian age, four species of *Hibolithes,* one species of *Neohibolites,* and three species of *Belemnopsis* were noted (Fig 8). Among these species, only *B. besinus* and *H. hastatus* migrated from the Boreal to the Tethyan Realm and also from the Mediterranean Province to the Indo-Pacific Province, disclosing the existence of a close oceanic connection between the provinces in the Upper Jursssic (Kimmeridgian; Fig 9). We can only speculate about the high species diversity of belemnite fauna during the Kimmeridgian (153.2 Ma), which could be related to the eustatic sea level rise of about 80m, indicating a maximum flooding surface as predicted by Scotese (2014) in his Jurassic paleogeographic maps (Fig 9).

In the *Hibolithes marwicki/Hibolithes arkelli* biozone, which represents Tithonian strata (c. 148.2 Ma), the highest level of species diversity was observed in the study area (Fig 8), and it could be linked to the highstand systems tract with a 40-m eustatic sea level rise as predicted by Scotese (2014) in his Jurassic paleogeographic maps (Fig 9). During the Tithonian period, *H. hastatus* showed a migration from the Boreal Realm and the Mediterranean Province into the Indo-Pacific Province of the Tethyan Realm, pointing towards the existence of a connection between the shallow-water routes (Figs 8, 9).

At the Tithonian–Berriasian (c. 143 Ma) boundary, the *Belemnopsis malucana* biozone records six species in the study area (Figs 8, 10), a single species in the Mediterranean Province, and no species in the Boreal Realm. In the Berriasian period, *H. pelliti* was the only one that showed a migration from the Indo-Pacific to the Mediterranean Province (Fig 10). During the Berriasian period, the eustatic sea level was comparable to the present-day sea level, as shown in the Cretaceous paleogeographic maps of Scotese (2014; Fig 10).

The Neohibolites ewaldi/Hibolithes longior/Belemnopsis jonkeri biozone represents a Velanginian (c. 137 Ma) distribution of a single species each of *Hibolithes, Neohibolites*, *Castillanibelus* and two species of *Belemnopsis* (Figs 8, 10). *H. jaculoides* was the only one that migrated from the Indo-Pacific to the Mediterranean Province and Boreal Realm during the Velanginian period (Fig 10). The highstand systems tract having up to 40-m eustatic rise, similar to the Tithonian rise as shown in the Cretaceous paleogeographic maps of Scotese (2014), might have distributed these species in both the Boreal and Tethyan Realms.

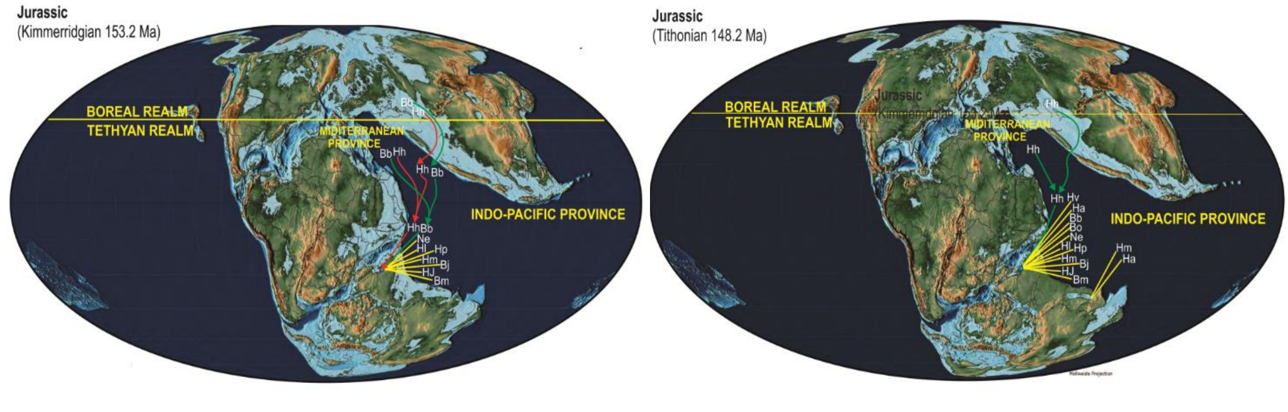

Fig 9. The Jurassic Paleobiogeographic map is modified after Scotese (2014), which shows the migration pathways of different belemnite species during the Late Jurassic (Kimmeridgian-Tithonian) ages in the Tethyan (Indo-Pacific-Mediterranean Provinces) and Boreal Realms. The symbols refer to the following species, i.e. Hh=*Hibolite hastatus,* Hm= *Hibolithes longior*, Hv=*Hibolithes aff. Verbeeki,* Ha=*Hibolithes arkelli,* Hm=Hibolithes marwicki, Hj=*Hibolithes jaculoids,* Hp=*Hibolithes pellet,* Bj=*Belemnopsis jonkeri,* Bm=*Belemnopsis molluccana,* Bb=*Belemnite bessinus.*

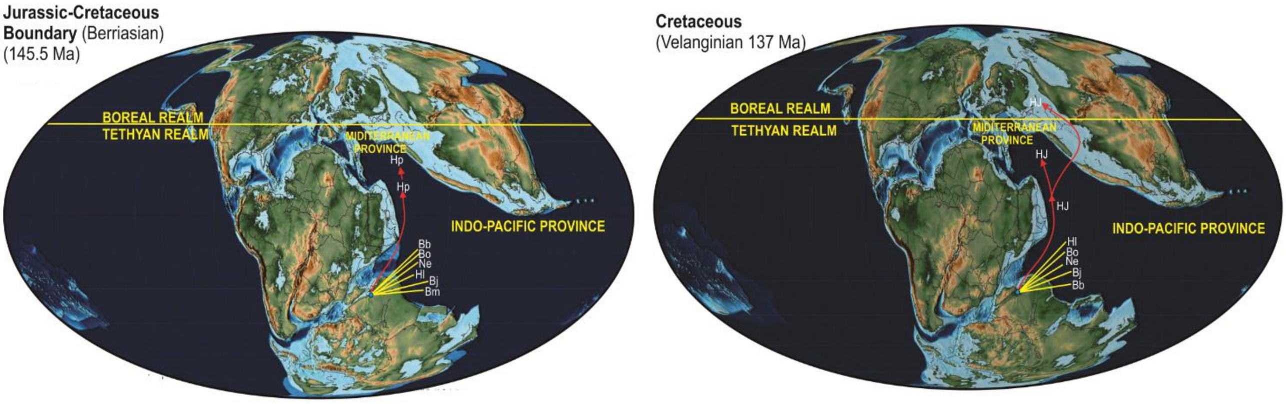

Fig 10. The Cretaceous Paleobiogeographic map is modified after Scotese (2014), which shows the migration pathways of different belemnite species during the Early Cretaceous (Berriasian-Valanginian ages) in the Tethyan (Indo-Pacific-Mediterranean Provinces) and Boreal Realms. The symbols refer the foloowing species: i.e. Hl=*Hibolite longier,* Hj=*Hibolithes jaculoids,* Hp=*Hibolithes pellet,* Bj=*Belemnopsis jonkeri,* Bb=*Belemnite bessinus.*

6. Conclusion

The global biostratigraphic framework and migration pathways of the belemnite species within the Late Jurassic (Kimmeridgian–Tithonian) Epoch of the Tethyan Realm confirm the existence of a close oceanic connection between the Indo-Pacific and Mediterranean Provinces. Similarly, on the basis of the coexistence of Tethyan-derived belemnite species within the Early Cretaceous (Berriasian–Valanginian) Epoch of the Boreal Realm, it is concluded that Russia, northwestern Europe, southern Germany, France, Spain, India-Pakistan, Indonesia, and New Zealand were closely linked by shallow water routes within the Tethyan and Boreal Realms.

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