Journal of Himalayan Earth Sciences Volume 56, No. 2, 2023 pp. 73-88

Palynostratigraphical and oceanic anoxic events investigation in the Lower Jurassic Black Shale, Indus Basin, Pakistan

Fahad Ali [1,2], Zhang Shiqi [1], Rafique Ahmad [2]*, Beenish Ali [2] and Hamid Iqbal [3]

[1]*School of Geoscience, China University of Petroleum, East China, Qingdao*

[2]*Department of Geology, Bacha Khan University, Charsadda, Pakistan*

[3]*Oil and Gas Training Institute, G & R Laboratory, OGDCL, Islamabad*

**Corresponding Author's Email: rafique.ahmad@bkuc.edu.pk*

Submitted date: 22/09/2023 Accepted date: 13/11/2023 Published online: 30/11/2023

Abstract

The stratigraphy of Lower Jurassic in the Indus Basin, Pakistan, portrays the siliciclastic and carbonate strata in studied sections. The representative stratigraphic sections were sampled to investigate using carbon and oxygen isotopes ($\delta^{13}C$ & $\delta^{18}O$), and palynology. Based on diagnostic palynomorphs from the Lower Jurassic, a single Hettigian-Pliensbachian assemblage biozone (HPABZ) is recognized. The oceanic anoxic event with a 2–3 ‰ negative shift in $\delta^{13}C$ & $\delta^{18}O$ across the Pliensbachian-Toarcian boundary is noted in the studied sections. The nature of the oceanic anoxic events are discussed and correlated with the established events worldwide.

Keywords: *Black shale; Jurassic; Palynology; Isotopes; Indus Basin, Pakistan.*

1. Introduction

Palynostratigraphy is widely used to establish reliable biostratigraphy and to determine depositional environments (Weerakoon et al., 2019). Palynomorphs serve as authentic proxies for precise and reliable paleo-reconstructions of paleoecology, paleogeography and paleoclimatology (Césari and Colombi, 2016; Lindström et al., 2016). However, in case of the Indus Basin very limited research has been done on the palynostratigraphy and stable isotope stratigraphy of the Jurassic strata in the studied area. The previous studies have addressed the sedimentological and stratigraphic aspects of Lower to Middle Jurassic succession based on lithofacies, microfacies and petrography (Fatmi, 1974; Akhtar, 1983; Mensink et al., 1988; Fatmi et al., 1990; Mertmann and Ahmad, 1994; Ali et al., 2018; 2019; Iqbal et al., 2019; Saboor et al., 2022; Ullah et al., 2022a). Only few reports of palynostratigraphy are available for this succession (Masood et al., 1997; Ali et al., 2018). The Jurassic (201–145 Myr ago) was a warm greenhouse period. Its warmest interval is represented by the late Early Jurassic Toarcian Stage, which is characterized by an unexpected ~7ºC increase globally at the beginning of Toarcian oceanic anoxic events (TOAE) in the mid-latitudes (Dera et al., 2011; Gradstein et al., 2012; Korte et al., 2015). Previous work on the high-resolution carbon-isotope data ($\delta^{13}C$) on Lower to Middle Jurassic periods, especially the Pliensbachian-Toarcian boundary (PL-TO) is scarce to non-existent in the Indus Basin exist as compared to the extensive studies elsewhere in the world (Hesselbo et al., 2000; Jenkyns et al., 2001, 2002; Katz et al., 2005; McElwain et al., 2005; Svensen et al., 2007; Littler et al., 2010; Kemp et al., 2011; Kemp and Izumi, 2014; Ali et al., 2018; 2022 a,b Izumi et al., 2018; Xu et al., 2018). The conventional stratigraphy and sedimentology of Indus Basin have been addressed in many of previous studies but no formal biostratigraphic framework and study of the anoxic events has been established yet in the Jurassic clastic and carbonate successions. In order to establish a reliable stratigraphy of any rock unit, it is significant to first put the same rock unit into a reliable biostratigraphic framework. The age of the Datta Formation is based on the law of superposition as no age related index fossil has been reported from it (Shah, 2009). The Shinawari Formation overlies the Datta Formation and contains some Toarcian ammonites, so the age assigned to the Datta Formation is based on stratigraphic assumptions (Shah, 2009). Therefore, this study is focused on establishing a reliable stratigraphic framework, augmented by stable isotope stratigraphic analysis, to demarcate age as well as the oceanic anoxic events in studied strata.

2. Geological Setting

After rifting from the Eastern Gondwana landmass, the Indian Plate started drifting north during the Early Cretaceous (c. 130 Ma), and collided with the Eurasian Plate giving rise to the Himalayas (Coward et al., 1986; Gibbons et al., 2013). The drifting of the Indian Plate squashed the Neo-Tehthys Ocean, present between India and Eurasia, causing intra-oceanic subduction which subsequently gave rise to the Kohistan Island Arc (Searle et al., 1987; Searle, 1991). The Kohistan Island Arc (KIA) is dominantly composed of plutonic, volcanic and metasedimentary rocks covering an area of about 36000 km^2. The KIA collided with the Karakoram Block during the Cretaceous along the suture zone known as Main Karakurram Thrust (MKT) (Windley, 1983). Later, in the Cenozoic (c. 55-50 Ma) the Indian Plate subducted below the Kohistan Island Arc and formed the Main Mantle Thrust (MMT), also known as the Indus Suture Zone (Tahirkheli, 1982). After the formation of MMT, the deformational stresses shifted southward and formed many regional thrusts, such as Main Boundary Thrust (MBT) and Salt Range Thrust (SRT). The Indus Basin is bounded by MBT in the north and Arabian Sea in the south and Chaman Transform Fault in the northwest. The Indus Basin preserves excellent sedimentary successions from Pre-Cambrian to Recent. The Pre-Cambrian and Paleozoic strata is only exposed in the Lower Indus Basin whereas the Mesozoic and Cenozoic rocks are exposed throughout the Indus Basin (Shah, 2009; Babar et al., 2018; Zahir et al., 2021; Ullah et al., 2022b; Sabba et al., 2023). The Indus Basin Jurassic sediments were deposited in the eastern part of the Tethys Ocean, representing the northwestern margin of the Indian Plate. The Jurassic sediments are represent by the clastic dominated Lower Jurassic Datta and Shirinab formations and the carbonate dominated Shinawari and Samana Suk formations and Chiltan Limestone (Ali et al., 2013, 2019) Fig. 1).

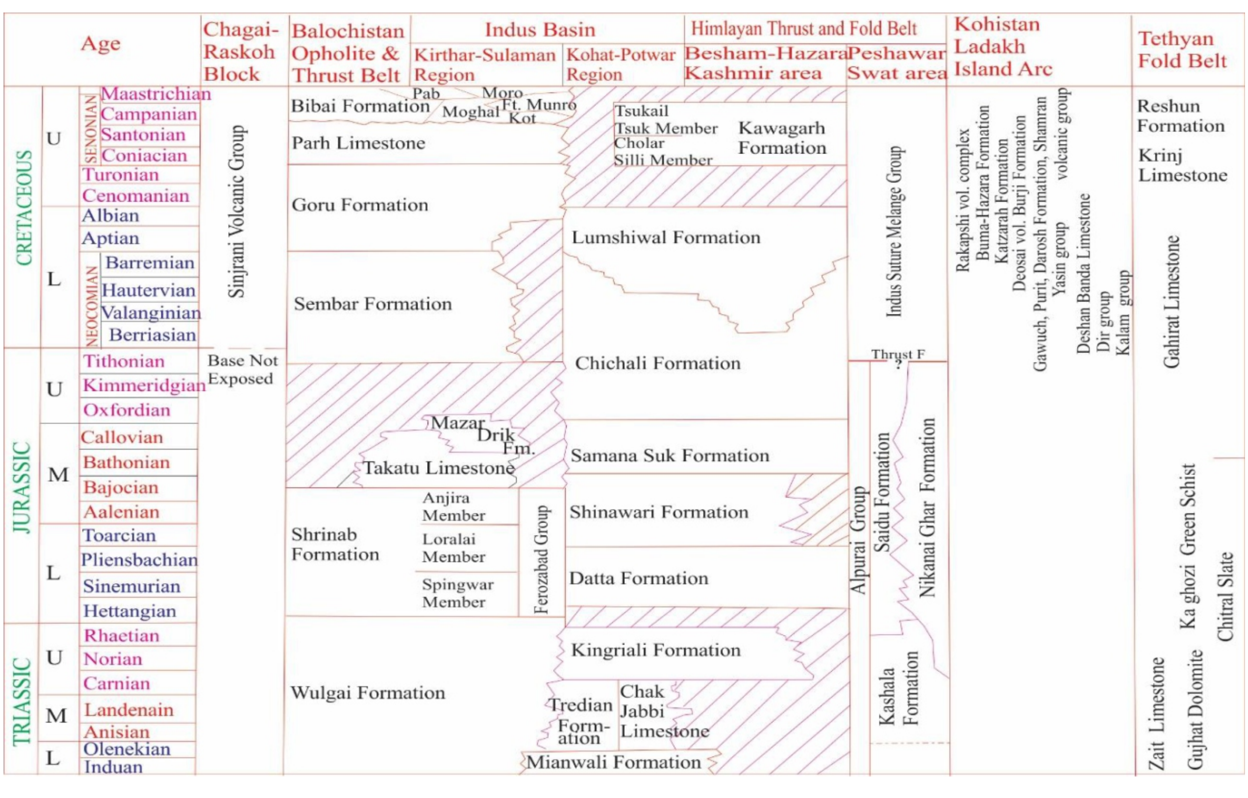

Fig. 1. Shows the Mesozoic stratigraphy of the Baluchistan Basin, Indus Basin and Kohistan-Ladakh Island Arc, Pakistan (modified after Bender and Raza, 1995).

3. Methods and Materials

A total of 29 fresh shale samples from outcrops of the Jurassic Datta and Shinawari formations from the following five sections 1. Kahi village; 2. Nammal Gorge Section; 3. Baroch Nala; 4. Chichali Nala; 5. Gula Khel Nala from Salt Ranges Pakistan were collected for this study (Fig. 2). The stratigraphic true thickness of the Datta and Shinawari formations were measured as per procedure described in previous published literature (Prothero and Schwab, 2004), and field photographs were taken (Fig. 3). Palynological slides were prepared from the dark shales by following the standard procedure of maceration (Wood et al., 1996; Ali et al., 2018). Transmitted light microscopy (i.e. Nikon SMZ-25) and polarizing microscope (i.e. Nikon OS-F12) were used for palynological analysis. The Datta Formation provided a good quantity and quality of terrestrial palynomorphs, with some marine content, in all studied samples.

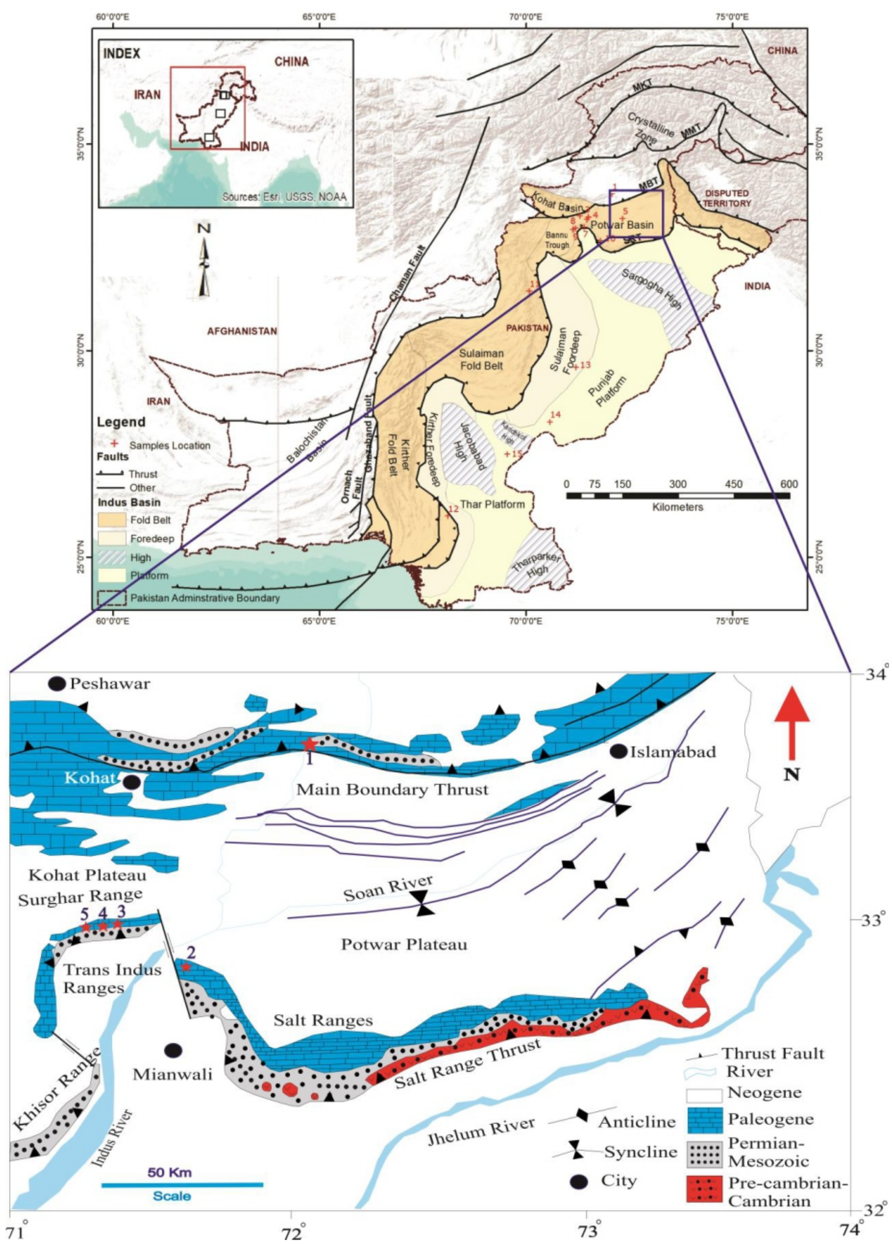

Fig. 2. Generalized geological map showing locations of the studied stratigraphic sections (denoted by steric and number) in the Indus Basin, Pakistan (used after Kazmi and Rana, 1982). 1. Kahi village; 2. Nammal Gorge Section; 3. Baroch Nala; 4. Chichali Nala; 5. Gula Khel Nala.

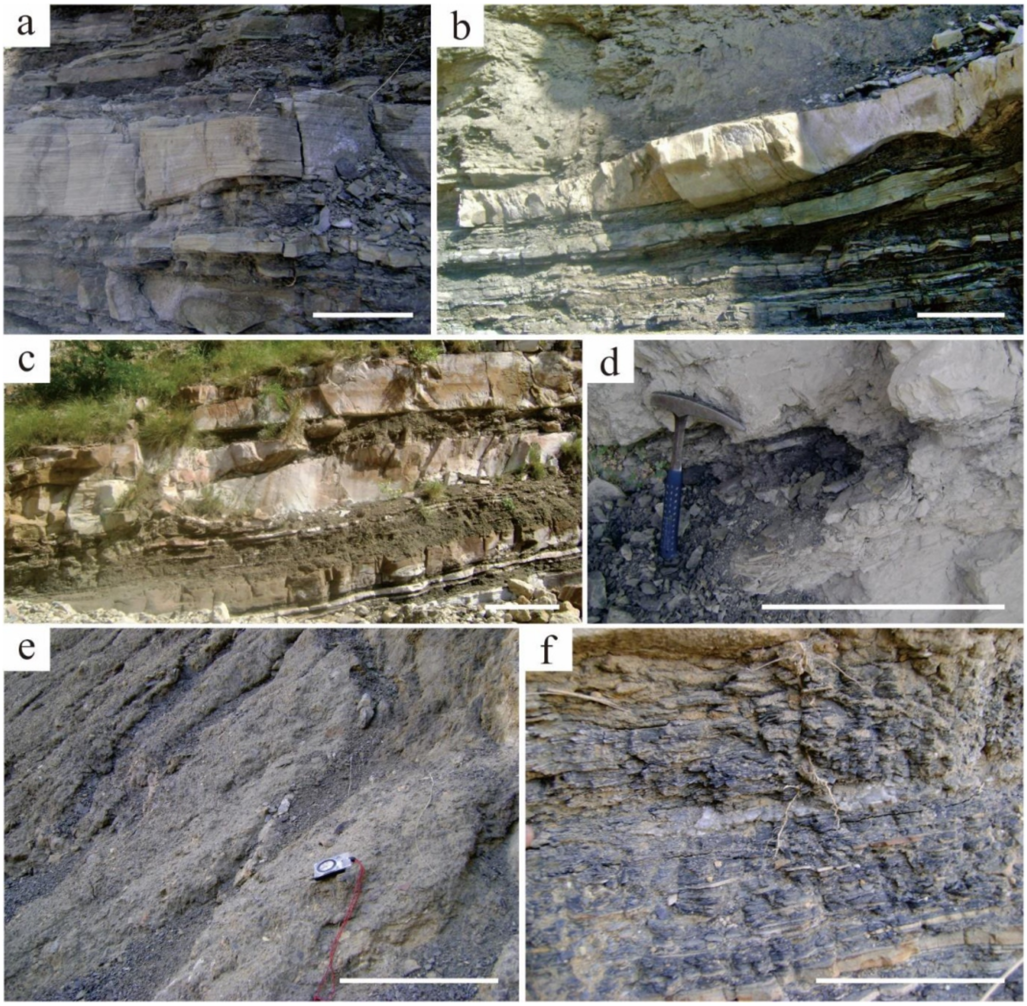

Fig. 3. Field photographs showing alternating beds of shale with minor limestone from the Jurassic Datta (a-c) and Shinawari (d-f) formations. (Scale: Length of the bar is 50cm)

The isotopic analysis for carbon and oxygen were carried out on a VG Isogas Prism III (Wolfson Laboratory, UK) and the Deltaplus Advantage (Thermo Fisher Scientific) was used in the current geological investigation. According to Ali et al. (2018), the PACS-2 standard was used for isotopic calibration, while Acetaniide was used for elemental composition. The standard deviation limit of each measurement for δ^{18} O is ±0.2‰ and for δ^{13} C is ±0.1‰ in the current study.

The total organic carbon is determined from the Total carbon analyzer (TOC). The TOC were measured as per the criteria described in Ali et al. (2022a). The TOC of all samples were measured in helium inert internal temperature. A 500 mg fine grained rock samples was subjected to 10% HCl (hydrochloric acid) to remove the inorganic carbon from the samples. In order to remove the effect of HCl the samples were washed with distilled water and subsequently placed in oven to remove the moisture. Further the specimens were placed in clay crucible and analyzed in the TOC analyzer (ELTRA HELIOSL).

4. Results

4.1 Lower Jurassic Palynostratigraphy

The Lower Jurassic palynostratigraphic taxa is represented by the following assemblage that includes the following stratigraphically significant taxa: *Calamospora tener, Vitreisporites pallidus, Artrisporites minimus, Chasmatosporites elegans, Chasmatosporites hians, Chasmatosporites major, Corrollina torosus, Corollina meyeriana, Cerebropollenites macroverrucosus, Alisporites pergrandis, Camptotriletes,* *cerebreformis, Classopollis* sp., *Dipterella oblatinoides, Marattisporites scabratus, Osmundacidites* sp., *Stereisporites compactus, Stereisporites congregatus, Stereisporites bujargiensis, Stereisporites psilatus and Stereisporites infragranulatus,* (Figs. 4-5 and Appendix . 1).

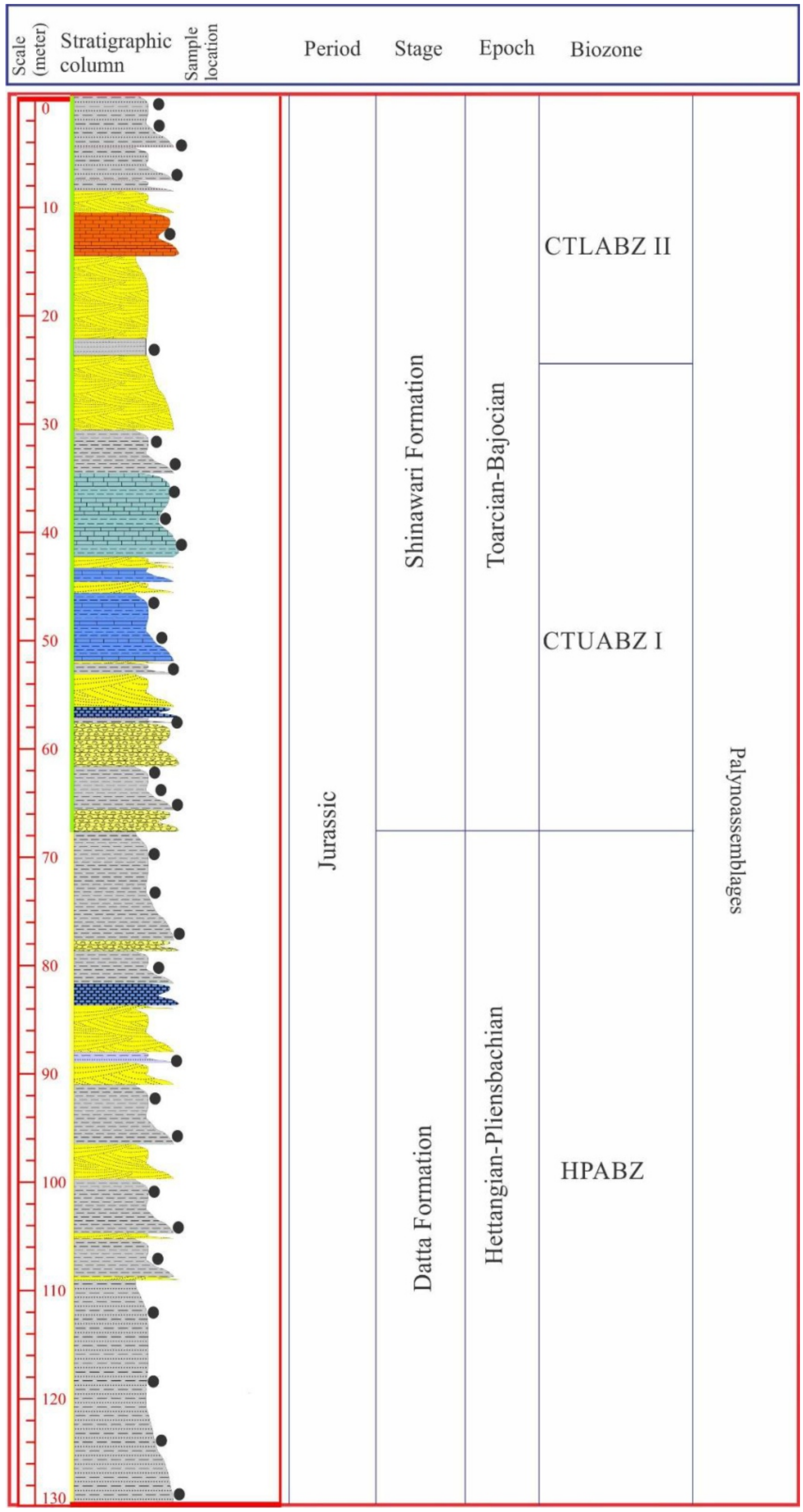

Fig. 4. Shows the stratigraphic column of the studied sections (Datta and Shinawari formations) and the assemblage biozones in the Indus Basin, Pakistan (the black circles represent sample locations).

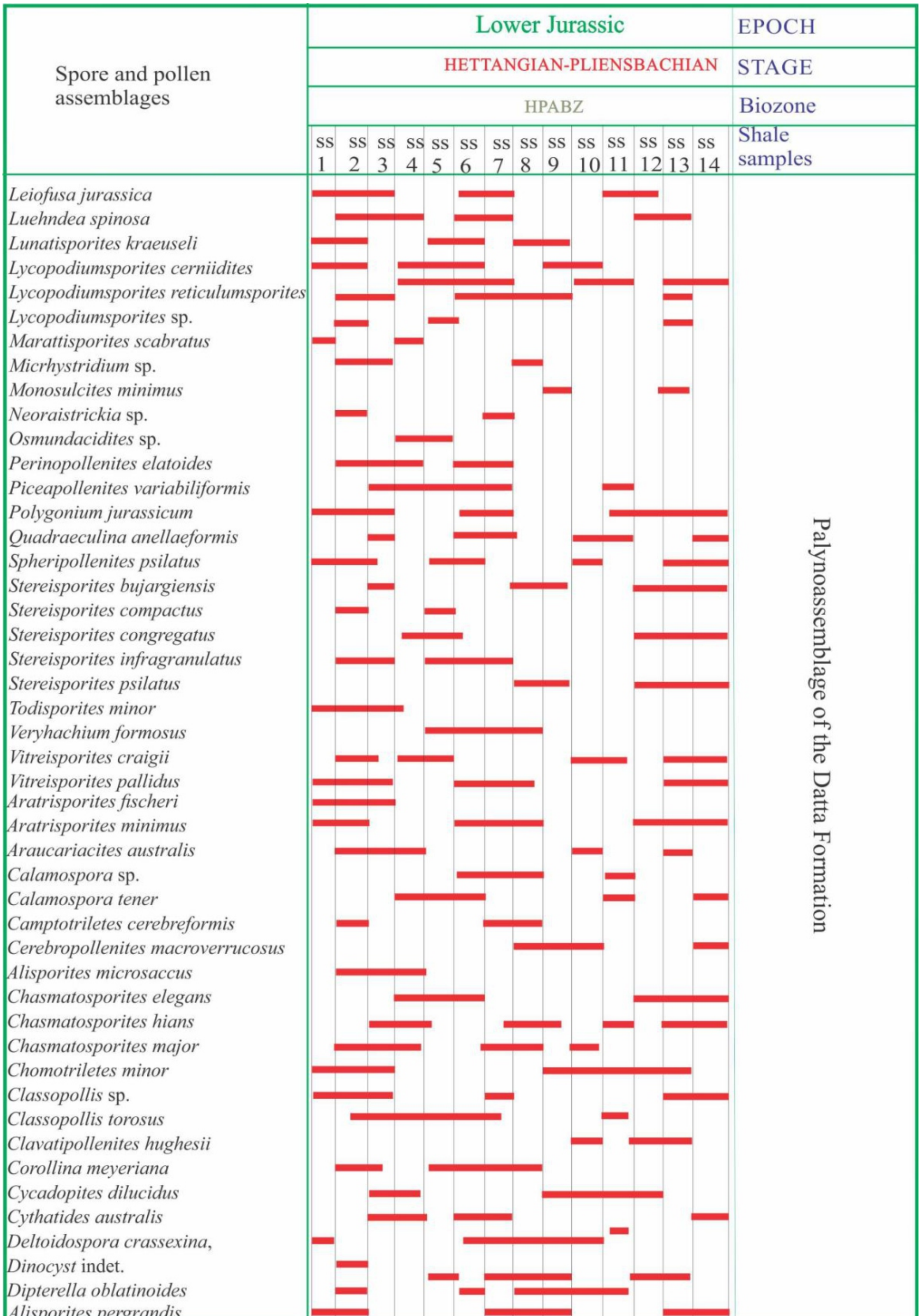

Fig. 5. Shows the range of different palyno-assemblage in the Lower Jurassic, Indus Basin, Pakistan.

Additional taxa include *Aratrisporites fischeri, Aratrisporites minimus, Araucariacites australis, Calamospora* sp., *Camptotriletes cerebreformis,* cf. *Alisporites microsaccus,* cf. *Chasmatosporites elegans, Chomotriletes minor, Corrollina* sp., *Clavatipollenites hughesii, Cycadopites dilucidus, Cyathidites australis, Deltoidospora crassexina, Dinocyst indet., Leiofusa jurassica, Luehndea spinosa, Lunatisporites kraeuseli, Lycopodiumsporites cerniidites, Lycopodiumsporites reticulumsporites, Lycopodiumsporites* sp., *Marattisporites* sp., *Micrhystridium* sp., *Monosulcites minimus, Neoraistrickia* sp., *Osmundacidites* sp., *Perinopollenites elatoides, Piceapollenites variabiliformis, Polygonium jurassicum, Pterospermella* sp., *Quadraeculina anellaeformis, Spheripollenites psilatus, Spheripollenites* sp., *Todisporites minor, Verrucosisporites* sp., *Veryhachium formosus, and Vitreisporites craigii* (Figs. 6-7).

Fig. 6. Palynomorphs from the Lower Jurassic of the Indus Basin. 1. *Piceapollenites* sp.; Figs. 2-3. *Neoraistrickia* sp.; Figs 4-6. *Lycopodiumsporites* sp.; 7-8. *Stereisporites infragranulatus*; Figs 9-10. *Stereisporites congregates*; 11-15. *Stereisporites bujargiensis;* 16-19. *Classopollis torosus;* 20. *Pterospermella* sp.; 21-25. *Marattisporites scabratus*; 26-29. *Camptotriletes cerebreformis;* 30-31. *Osmundacidites* sp.; 32-33. *Stereisporites psilatus;* 34. *Stereisporites compactus;* 35-36. *Stereisporites infragranulatus;* 37-39. *Stereisporites congregates;* 40-421 *Exesipollenites laevigatus;* 42-44. *eltoidospora crassexina;* 45. *Chomotriletes minor*; 46. *Spheripollenites psilatus*; 47. *Clavatipollenites hughesii;* 48-49 *Corollina meyeriana;* 50 *Perinopollenites elatoides;* 51. *Lycopodiumsporites reticulumsporites;* 52-53. *Cerebropollenites macroverrucosus*; 54-55. *Marattisporites* sp.; 56. *onosulcites minimus*; 57. *Lycopodiumsporites cerniidites*; 58-61. *Todisporites minor;* 62. *Calamospora sp.*; 63-64. *Calamospora tener;* 65-76. *Aratrisporites minimus*; 77-78. *Aratrisporites* sp; 79. *Vitreisporites craigii;* 80. *Veryhachium formosus;* 81. *Leiofusa jurassica;* 82-83 *Luehndea spinosa;* 84. *Micrhystridium* sp.

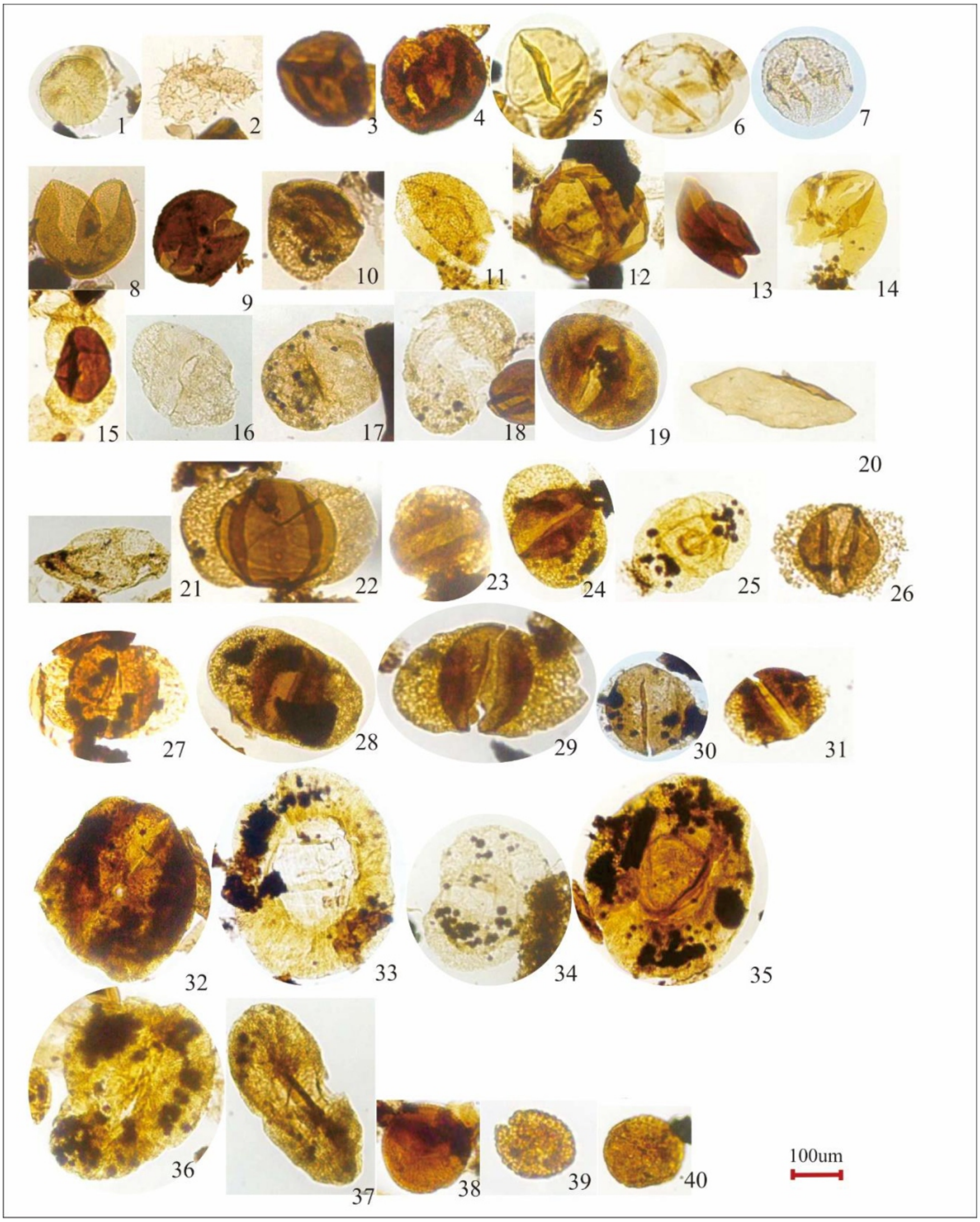

Fig. 7. Palynomorphs from the Lower Jurassic of the Indus Basin; 1. *Micrhystridium* sp.; 2. *Polygonium jurassicum;* 7. cf. *Chasmatosporites elegans;* 8-9. *Cythatides australis;* 10. cf. *Alisporites microsaccus;* 11. *Chasmatosporites major;* 12. *Araucariacites australis;* 13. *Spheripollenites* sp.; 14. *Cyclotriletes* sp.; 15. *Lunatisporites kraeuseli;* 16-19. *Vitreisporites pallidus;* 20. *Cycadopites dilucidus;* 21. *Dinocyst indet.;* 22-26. *Quadraeculina anellaeformis;* 27-28. *Alisporites pergrandis;* Fig. 29. *Verrucosisporites* sp.; 30-32. *Dipterella oblatinoides;* 33-34. *Chasmatosporites hians;* 35-36. *Aratrisporites fischeri;* 37. *Monosulcites minimus;* 38-40 *Corollina torosus.*

4.2 Bulk Carbon and Oxygen Isotopic Study

The $\delta^{13}C$ in the Datta Formation shows the minimum and maximum values of -2‰ to -3‰ negative carbon isotope excursion, with some samples have not recorded any experimental data in laboratory analysis. Furthermore, the Datta Formation show the minimum value of -0.95‰ and maximum value of -3.11‰ (Fig. 8).

4.3 Organic contents

The carbon contents is find out by the total organic content ranges from the 0.2-4.25%.

5. Discussion

5.1 Palynostratigraphic Frame work of Lower Jurassic

Dinoflagellates, spores, and pollens are utilized for stratigraphy of the Jurassic rocks all-around the globe (Pocock, 1978; Kotova, 1983; Hoelstad, 1985; Koppelhus and Nielsen, 1994; Tiwari and Tripathi, 1995; Burger, 1996; Dong et al., 1998; Tiwari, 1999; Tripathi, 2001; Koppelhus and Gregers, 2003; Ziaja, 2006; Atawy, 2009; Racey and Goodall, 2009; Barrón et al., 2010; Buthaina 2010; Schrank, 2010; Goryacheva, 2011; 2017 El Atfy et al., 2013; Peng et al., 2018). Based on the palynomorph assemblage encountered in the Datta Formation the Hettangian-Pliensbachian assemblage biozone (HPABZ) was identified.

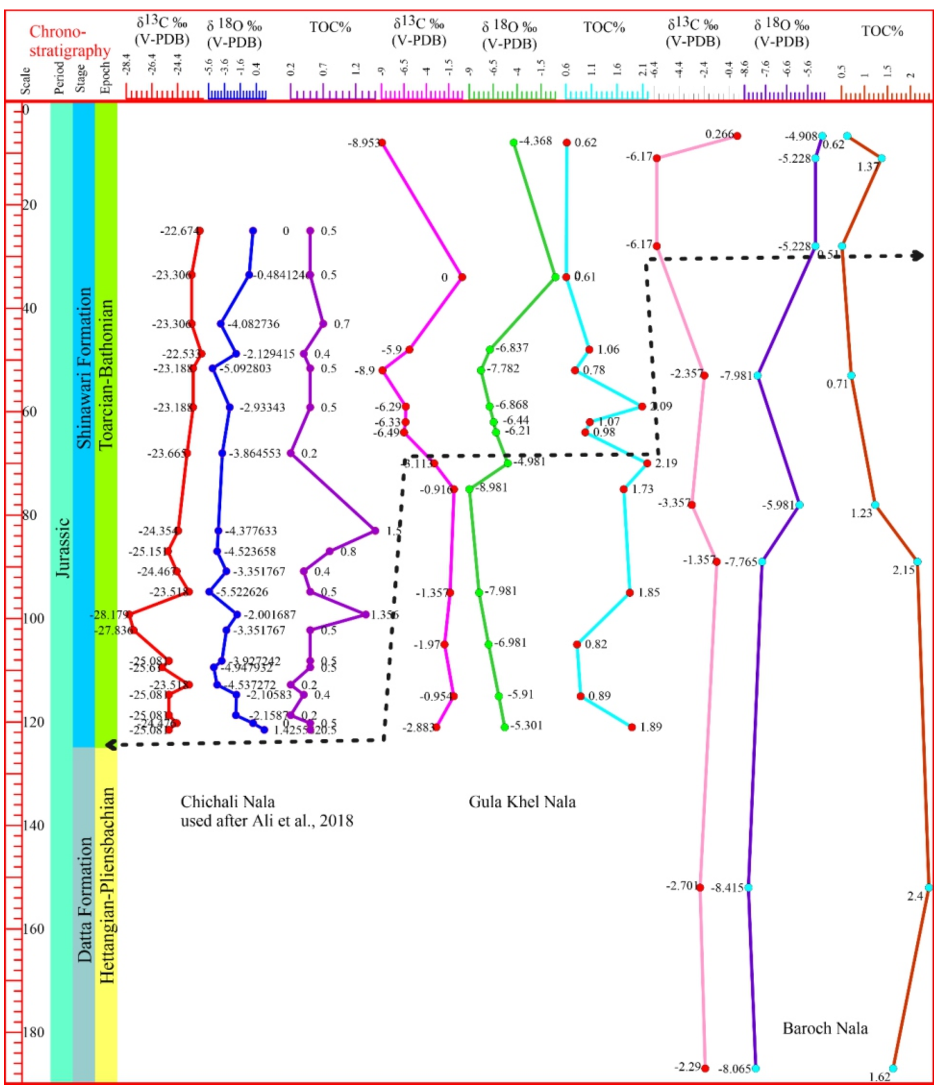

Fig. 8. Shows isotopic signals and TOC of Lower to middle Jurassic strata from Chichali Nala, Gula Khel Nala and Baroch Nala in the Indus Basin, Pakistan.

The presence of *Calamospora tener, Vitreisporites pallidus, Artrisporites minimus, Chasmatosporites* sp. such as *Chasmatosporites elegans, Chasmatosporites hians and Chasmatosporites major,* indicate Hettangian age (Schulz, 1967; Pocock, 1978; Pedersen and Lund, 1980; Lund and Pedersen, 1985; Dybkjær, 1991; Ziaja, 2006; Correia et al., 2018). The Sinemurian is represented by the *Corrollina torosus, Vitreisporites pallidus, Corollina meyeriana,* and *Cerebropollenites macroverrucosus* (Bujak and Williams, 1977). The Hettangian to Pliensbachian age is considered for Corrollina torosus biozone (Helby et al., 1987), whereas according to some other researchers a Pliensbachian age is suitable for the biozone represented by the *Chasmatosporites* (abundance of *C. hians* and *C.* sp.,) and at least showing the presence of *Corollina torosus*. Moreover, the *Alisporites pergrandis, Camptotriletes, cerebreformis, Chasmatosporites hians, Classopollis* sp., *Dipterella oblatinoides, Marattisporites scabratus, Osmundacidites* sp., *Stereisporites compactus, Stereisporites congregatus, Stereisporites bujargiensis, Stereisporites psilatus, Stereisporites infragranulatus, Vitreisporites pallidus* is similar to most of the Pliensbachian age Palynoassemblage 1 of Goryacheva (2017). So, based on the documented palynomorphs and the stratigraphic position in the Indus Basin, Pakistan, the lower Jurassic Datta Formation in the current study is marked as Hettangian to Pleinsbachian, while the Lower to Middle Jurassic Shinawari Formation is marked as Toarcian to Bajocain (Bender and Raza, 1995; Ali et al., 2018).

5.2 Anoxic Events

The TOAE was led by the PL-TO episode, with lesser $\delta^{13}C$ -2‰ to -3‰ negative carbon isotope excursion (Little and Benton, 1995; Pálfy and Smith, 2000; Hesselbo et al., 2007; Littler et al., 2010; Caruthers et al., 2013; Bodin et al., 2016; Percival et al., 2016). The Neotethys Tectonics of Hettangian-Pliensbachian strata in the current research is interpreted from the multi cyclic sequence representing the clastic and carbonates units (Fürsich et al., 1992). The large amplitude negative excursion in the bulk organic matter and the similar trend in the $\delta^{13}C$ of the bulk carbonate suggests that the Toarcian strata in the Chichali Nala Section correspond to the TOAE (Ali et al., 2018). Furthermore, the Datta Formation show the minimum value of -0.95‰ and maximum value of -3.11‰ having well defined Pliensbachian-Toarcian boundary showing 2-3 ‰ per mil shift in the studied strata. Furthermore, the Nammal Gorge Section has no deposition of the PL-TO strata and onward while in Kahi Village the PL-TO strata are represented by carbonate rocks. Beside pronounced negative excursion, some positive values which may be due to one or a combination of various factors such as an increase in sedimentation rates and organic matter accumulation, marine anoxia or diagenetic basin evolution (Brasier et al., 1994). The TOC values of the dark black shale vary from 0.2-4.25% and more or less correspond to the $\delta^{13}C$ excursion in the studied area. A similar correlation between TOC and the carbon isotope excursion is reported by the previous researchers (Ali et al., 2018).

The current research has two folds importance i.e. the stratigraphic information can be utilized by the oil and gas sectors for formations/lithologies identifications and other related process. While, the academia can get benefit from the established stratigraphy and anoxia for further geological research.

6. Conclusions

The following conclusions are drawn;

1. The palynostratigraphy of the Lower Jurassic is established in the Datta Formation and Hettigian-Pliensbachians assemblage (HPABZ) biozone is identified. The Hettangian age indicators species are *Chasmatosporites elegans, Chasmatosporites hians and Chasmatosporites major,* while the Sinemurian is represented by the *Corrollina torosus, Vitreisporites pallidus, Corollina meyeriana, and Cerebropollenites macroverrucosus* and Pliensbachian age is represented by the *Chasmatosporites.*

2. The Pliensbachian-Toarcian boundary is demarcated based on 2-3 ‰ shift in stable carbon and Oxygen isotopes in all the studied

sections except Nammal Gorge and Kahi village sections.

Authors' Contribution

Fahad Ali and Shiqi Zhang, proposed the main concept and involved in write up. Beenish Ali, assisted in establishing figure file. Rafique Ahamd, collected field data and formatting. Hamid Iqbal and Rafique Ahmad, did provision of relevant literature, and review and proof read of the manuscript.

ACKNOWLEDGMENTS

The current research is facilitated by the School of Geoscience, China University of Petroleum.

Conflict of interest: There is no conflict of interest among the authors.

References

Akhtar, M., 1983. Stratigraphy of Surghar Range: Geological Bullitien Punjab University, 18, 32-45.

Ali, F., Haneef, M., Anjum, M. N., Hanif, M., and Khan, S., 2013. Microfacies analysis and sequence stratigraphic modeling of the Samana Suk Formation, Chichali Nala, Trans Indus Ranges, Punjab, Pakistan: Journal of Himalayan Earth Sciences, 46(1), 41-53.

Ali, F., Ahmad, S., Khan, S., Hanif, M., and Qiang, J., 2018. Toarcian-Bathonian palynostratigraphy and anoxic event in Pakistan: An organic geochemical study: Stratigraphy, 15(3), 225-243.

Ali, F., Qiang, J., Ahmad, S., Khan, S., Hanif, M., and Jan, I. U., 2019. Sedimentological and Geochemical Analysis of the Middle Jurassic Shinawari Formation, Upper Indus Basin, Pakistan: Implications for Palaeoenvironmental and Hydrocarbon Assessment: Arabian Journal for Science and Engineering, 44, 6465–6487.

Ali, F., Zhang, S., Abbas, S., Hanif, M., Zhang, Y., and Mohibullah, M., 2022a. Discovery of the Lower-Middle Jurassic high potential source rocks based on the geochemical investigation from the Indus Basin, Pakistan: Journal of Petroleum Science and Engineering, 208, 109374.

Ali, F., Zhang, S., Hanif, M., Mohibullah, M., Zhang, Y., Usman, M., Wang, S., Liu, X., Ma, P., and Huang, D., 2022b. Geochemical investigation of low latitude black shale intervals of the Lower to Middle Jurassic succession, Indus Basin, Pakistan: Frontiers of Earth Science, 16(3), 568-586.

Atawy, S. A. M., 2009. Palynological investigation of some rock units from Palaeozoic Mesozoic of the Sheiba-1 Well: Western Desert, Egypt: Journal of Applied Sciences Research, 5, 122-136.

Babar, N., Mohibullah, M., Kasi, A. K., Ali, N., and Khan, A., 2018. Foraminiferal Biostratigraphy of the Eocene Kirthar Formation, western Sulaiman Fold-Thrust Belt, Balochistan, Pakistan: Journal of Himalayan Earth Science, 51(2), 66-77.

Barrón, E., Ureta, S., Goy, A., and Lassaletta, L., 2010. Palynology of the Toarcian–Aalenian Global Boundary Stratotype Section and Point (GSSP) at Fuentelsaz (Lower–Middle Jurassic, Iberian Range, Spain): Review of palaeobotany and palynology, 162(1), 11-28.

Bender, F.K., and Raza, H.A., 1995 Geology of Pakistan. Borntraeger, Berlin, Stuttgart.

Bodin, S., Krencker, F.-N., Kothe, T., Hoffmann, R., Mattioli, E., Heimhofer, U., and Kabiri, L., 2016. Perturbation of the carbon cycle during the late Pliensbachian–early Toarcian: New insight from high-resolution carbon isotope records in Morocco: Journal of African Earth Sciences, 116, 89-104.

Brasier, M., Corfield, R., Derry, L., Rozanov, A. Y., and Zhuravlev, A. Y., 1994. Multiple δ13C excursions spanning the Cambrian explosion to the Botomian crisis in Siberia: Geology, 22(5), 455-458.

Bujak, J. P., and Williams, G. L., 1977. Jurassic palynostratigraphy of offshore eastern Canada, Developments in Palaeontology and Stratigraphy, 6, 321-339.

Burger, D., 1996. Mesozoic palynomorphs from the north west shelf, offshore Western Australia: Palynology, 20(1), 49-103.

Buthaina S. Al-Jibouri, 2010. Palynostratigraphy of the lower clastic unit of Hussainiyat Formation (early Jurassic), western desert, Iraq Iraqi Bulletin of Geology and Mining 6.

Caruthers, A. H., Smith, P. L., and Gröcke, D. R., 2013. The Pliensbachian–Toarcian (Early Jurassic) extinction, a global multi-phased event: Palaeogeography, Palaeoclimatology, Palaeoecology, 386, 104-118.

Césari, S. N., and Colombi, C., 2016. Palynology of the Late Triassic Ischigualasto Formation, Argentina: paleoecological and paleogeographic implications: Palaeogeography, palaeoclimatology, palaeoecology, 449, 365-384.

Correia, V. F., Riding, J. B., Duarte, L. V., Fernandes, P., and Pereira, Z., 2018. The Early Jurassic palynostratigraphy of the Lusitanian Basin, western Portugal: Geobios, 51(6), 537-557.

Coward, M. P., Rex, D. C., Khan, M. A., Windley, B. F., Broughton, R. D., Luff, I. W., Petterson, M. G., and Pudsey, C. J., 1986. Collision tectonics in the NW Himalayas: Geological Society, London, Special Publications, 19(1), 203-219.

Dera, G., Brigaud, B., Monna, F., Laffont, R., Pucéat, E., Deconinck, J.-F., Pellenard, P., Joachimski, M. M., and Durlet, C., 2011. Climatic ups and downs in a disturbed Jurassic world: Geology, 39(3), 215-218.

Dong, W. Y., Qiu, J. D. X. Y. H., and Feng, S., 1998. Middle Jurassic Spore Pollen assemblages from Turpan Shanshan area, Xinjiang: Acta Botanica Sinica, 40(10), 969-976.

Dybkjær, K., 1991. Palynological zonation and palynofacies investigation of the Fjerritslev formation (Lower Jurassic—basal Middle Jurassic) in the danish subbasin: DGU, Danmarks Geologiske Undersøgelse Serie A, 30, 4-150.

El Atfy, H., Uhl, D., and Stribrny, B., 2013. Mesozoic (Late Jurassic) palynomorphs and charcoal from a sandstone pebble from Quaternary glacial deposits of the North Sea: Geological Journal, 48(4), 376-384.

Fatmi, A., Hyderi, I., and Anwar, M., 1990. Occurrence of the Lower Jurassic Ammonoid Genus Bouleiceras from the Surghar Range with a Revised Nomenclature of the Mesozoic Rocks of the Salt Range and Trans Indus Ranges (Upper Indus Basin): Geology Bulletin Punjab University, 25, 38-46.

Fatmi, A. N., 1974. Lithostratigraphic unites of the Kohat-Potwar province, Indus Basin, Pakistan: A Report of the Stratigraphic Comittee of Pakistan. Pakistan Geological Survey Memorial, 80 pages.

Fürsich, F., Oschmann, W., Singh, I., and Jaitly, A., 1992. Hardgrounds, reworked concretion levels and condensed horizons in the Jurassic of western India: their significance for basin analysis: Journal of the Geological Society, 149(3), 313-331.

Gibbons, A. D., Whittaker, J. M., and Müller, R. D., 2013. The breakup of East Gondwana: Assimilating constraints from Cretaceous ocean basins around India into a best-fit tectonic model: Journal of geophysical reserch 118(3), 808-822.

Goryacheva, A., 2011. Palynostratigraphy of the Lower-Middle Jurassic deposits, borehole section Vostok 4 (Southeast of West Siberia): Stratigraphy and Geological Correlation, 19(3), 268-288.

Goryacheva, A., 2017. Lower Jurassic palynostratigraphy of Eastern Siberia: Stratigraphy and Geological Correlation, 25(3), 265-295.

Gradstein, F. M., Ogg, J. G., Schmitz, M., and Ogg, G., 2012, The geologic time scale 2012, Ist Edition, elsevier.

Helby, R., Morgan, R., and Partridge, A., 1987. A palynological zonation of the Australian Mesozoic: Memoir of the Association of Australasian Palaeontologists, 4, 1-94.

Hesselbo, S. P., Gröcke, D. R., Jenkyns, H. C., Bjerrum, C. J., Farrimond, P., Bell, H. S. M., and Green, O. R., 2000. Massive dissociation of gas hydrate during a Jurassic oceanic anoxic event: Nature, 406(6794), 392-395.

Hesselbo, S. P., Jenkyns, H. C., Duarte, L. V., and Oliveira, L. C., 2007. Carbon-isotope record of the Early Jurassic (Toarcian) Oceanic Anoxic Event from fossil wood and marine carbonate (Lusitanian Basin, Portugal): Earth and Planetary Science Letters, 253, 455-470.

Hoelstad, T., 1985. Palynology of the

uppermost Lower to Middle Jurassic strata on Bornholm, Denmark: Bulletin of the Geological Society of Denmark, 34, 111-132.

Iqbal, S., Wagreich, M., Kuerschner, W. M., Gier, S., and Bibi, M., 2019. Hot-house climate during the Triassic/Jurassic transition: The evidence of climate change from the southern hemisphere (Salt Range, Pakistan): Global and planetary change, 172, 15-32.

Izumi, K., Kemp, D. B., Itamiya, S., and Inui, M., 2018. Sedimentary evidence for enhanced hydrological cycling in response to rapid carbon release during the early Toarcian oceanic anoxic event: Earth and Planetary Science Letters, 481, 162-170.

Jenkyns, H. C., Gröcke, D. R., and Hesselbo, S. P., 2001. Nitrogen isotope evidence for water mass denitrification during the early Toarcian (Jurassic) oceanic anoxic event: Paleoceanography and Paleoclimatology, 16(6), 593-603.

Jenkyns, H. C., Jones, C. E., GrÖcke, D. R., Hesselbo, S. P., and Parkinson, D. N., 2002. Chemostratigraphy of the Jurassic System: applications, limitations and implications for palaeoceanography: Journal of the Geological Society, 159(4), 351-378.

Katz, M. E., Wright, J. D., Miller, K. G., Cramer, B. S., Fennel, K., and Falkowski, P. G., 2005. Biological overprint of the geological carbon cycle: Marine Geology, 217(3), 323-338.

Kazmi, A.H., and Rana, R.A., 1982. Tectonic Map of Pakistan, Geological Survey of Pakistan.

Kemp, D. B., Coe, A. L., Cohen, A. S., and Weedon, G. P., 2011. Astronomical forcing and chronology of the early Toarcian (Early Jurassic) oceanic anoxic event in Yorkshire, UK: Paleoceanography, 26, doi:10.1029/2011PA002122

Kemp, D. B., and Izumi, K., 2014. Multiproxy geochemical analysis of a Panthalassic margin record of the early Toarcian oceanic anoxic event (Toyora area, Japan): Palaeogeography, Palaeoclimatology, Palaeoecology, 414, 332-341.

Koppelhus, E. B., and Nielsen, L. H., 1994. Palynostratigraphy and palaeoenvironments of the lower to middle Jurassic Bagå Formation of Bornholm, Denmark: Palynology, 18(1), 139-194.

Koppelhus Eva B., and Gregers, D., 2003. Palynostratigraphy and palaeoenvironments of the Rævekløft, Gule Horn and Ostreaelv Formations (Lower–Middle Jurassic), Neill Klinter Group, Jameson Land, East Greenland: Geological Survey of Denmark and Greenland Bulletin, 1, 723–775.

Kotova, I., 1983. Palynological study of Upper Jurassic and Lower Cretaceous sediments, site-511, Deep-Sea drilling project LEG-71 (Falkland Plateau): Initial Reports of the Deep Sea Drilling Project, 71, 879-906.

Lindström, S., Irmis, R. B., Whiteside, J. H., Smith, N. D., Nesbitt, S. J., and Turner, A. H., 2016. Palynology of the upper Chinle Formation in northern New Mexico, USA: implications for biostratigraphy and terrestrial ecosystem change during the Late Triassic (Norian–Rhaetian): Review of palaeobotany and palynology, 225, 106-131.

Little, C. T., and Benton, M. J., 1995. Early Jurassic mass extinction: a global long-term event: Geology, 23(6), 495-498.

Littler, K., Hesselbo, S. P., and Jenkyns, H. C., 2010. A carbon-isotope perturbation at the Pliensbachian–Toarcian boundary: evidence from the Lias Group, NE England: Geological Magazine, 147(2), 181-192.

Lund, J. J., and Pedersen, K. R., 1985. Palynology of the marine Jurassic formations in the Vardekløft ravine, Jameson Land, East Greenland: Geological Society of Denmark. Bulletin. 33(3), 371-400.

Masood K.R, Muntaha S.U, Qureshi K.A, and Siddique M., 1997. Early Jurassic palynology (Datta Formation), western Salt Range, Pakistan, with comments on depositional environment and organic thermal maturity. : Abstract, 3rd Pakistan Geol. Congress Peshawar,, 3rd, 42.

McElwain, J. C., Wade-Murphy, J., and Hesselbo, S. P., 2005. Changes in carbon dioxide during an oceanic anoxic event linked to intrusion into Gondwana coals: Nature, 435(7041), 479-82.

Mensink, V. H., Mertman, D., Bochum, and Ahmad, S., 1988. Facies development during the Jurassic of the Trans Indus Ranges, Pakistan,: Neues Jahrb Geological Paleontological memorial Germany, , 3, 153-166.

Mertmann, D., and Ahmad, S., 1994. Shinawari and Samana Suk Formationsof the Surghar and Salt ranges, Pakistan: Facies and depositional environments.Zeitschrift der Deutschen Geologischen Gesellschaft, 145, 305–317.

Pálfy, J., and Smith, P. L., 2000. Synchrony between Early Jurassic extinction, oceanic anoxic event, and the Karoo-Ferrar flood basalt volcanism: Geology, 28(8), 747-750.

Pedersen, K. R., and Lund, J. J., 1980. Palynology of the plant bearing Rhaetian to Hettangian, Kap Stewart Formation, Scoresby Sand, east Greenland. : Revision of Palaeobotony and Palynology, 31, 308 – 320. .

Peng, J., Li, J., Li, W., Slater, S. M., Zhu, H., and Vajda, V., 2018. The Triassic to Early Jurassic palynological record of the Tarim Basin, China: Palaeobiodiversity and Palaeoenvironments, 98(1), 7-28.

Percival, L. M., Cohen, A., Davies, M., Dickson, A., Hesselbo, S., Jenkyns, H., Leng, M., Mather, T., Storm, M., and Xu, W., 2016. Osmium isotope evidence for two pulses of increased continental weathering linked to Early Jurassic volcanism and climate change: Geology, 44(9), 759-762.

Pocock, S. A., 1978. Lowermost Jurassic spore-pollen assemblage from Canadian Arctic: Palaeobotanist, 25, 363-375.

Prothero, D. R., and Schwab, F., 2004, Sedimentary geology, Macmillan.557 pages

Racey, A., and Goodall, J. G., 2009. Palynology and stratigraphy of the Mesozoic Khorat Group red bed sequences from Thailand: Geological Society, London, Special Publications, 315(1), 69-83.

Sabba, M., Hanif, M., Mohibullah, M., Ullah, S., Ishaq, M., and Ghani, M., 2023. Planktonic foraminiferal biostratigraphy and palaeobiogeography of the Albian–Turonian succession from the Sulaiman Range, Pakistan: Geological Journal, 58(3), 1293-1323.

Saboor, A., Wang, C., Li, Y., Xi, C., Wang, L., Jafarian, A., Hanif, M., and Mohibullah, M., 2022. The physical and geochemical character of the post-depositional alterations in the Early-Middle Jurassic carbonates on the western margin of the Indian Plate: Implications for cement morphologies and dolomitization: Geological Journal, 57(9), 3781-3807.

Schrank, E., 2010. Pollen and spores from the Tendaguru Beds, Upper Jurassic and Lower Cretaceous of southeast Tanzania: palynostratigraphical and paleoecological implications: Palynology, 34(1), 3-42.

Schulz, E., 1967. Sporenpaläontologische Untersuchungen rätoliassischer Schichten im Zentralteil des Germanischen Beckens: Paläontologische Abhandlungen, Paläobotanik B, 2, 427-633.

Searle, M. P., 1991, Geology and tectonics of the Karakoram Mountains, John Wiley & Sons.

Searle, M. P., Windley, B. F., Coward, M. P., Cooper, D. J. W., Rex, A. J., Rex, D., Tingdong, L., Xuchang, X., Jan, M. Q., Thakur, V. C., and Kumar, S., 1987. The closing of Tethys and the tectonics of the Himalaya: Geological Society of America Bulletin, 98(6), 678-701.

Shah, S.M.I., 2009 Stratigraphy of Pakistan (Memoirs of the Geological Survey of Pakistan). The Geological Survey of Pakistan, 22.

Svensen, H., Planke, S., Chevallier, L., Malthe-Sørenssen, A., Corfu, F., and Jamtveit, B., 2007. Hydrothermal venting of greenhouse gases triggering Early Jurassic global warming: Earth and Planetary Science Letters, 256(3-4), 554-566.

Tahirkheli, R.A.K., 1982. Geology of Hindu Kush, Himalayas and Karakoram in Pakistan. Geological Bulletin of University of Peshawar, 15, 51 p.

Tiwari, R., 1999. Paradigm of FAD, LAD and DOD of some miospore taxa in Late

Permian and Early Triassic successions on the Indian Peninsula: Journal of the Paleontological Society of India, 44, 69-89.
Tiwari, R., and Tripathi, A., 1995. Palynological assemblages and absolute age relationship of intertrappean beds in the Rajmahal Basin, India: Cretaceous Research, 16(1), 53-72.
Tripathi, A., 2001. Permian, Jurassic and early Cretaceous palynofloral assemblages from subsurface sedimentary rocks in Chuperbhita coalfield, Rajmahal basin, India: Review of palaeobotany and palynology, 113(4), 237-259.
Ullah, S., Ali, N., Latif, K., Iqbal, S., Tahir, M., Hussain, H. S., Turab, S. A., Mumtaz, A., and Mohibullah, M., 2022a. Paleoenvironments and sequence stratigraphy of the Early Jurassic Datta Formation, Chichali Nala, Surghar Range, Pakistan: Himalayan Geology, 43(1A), 111-121.
Ullah, S., Jan, I. U., Hanif, M., Latif, K., Mohibullah, M., Sabba, M., Anees, A., Ashraf, U., and Vo Thanh, H., 2022b. Paleoenvironmental and bio-sequence stratigraphic analysis of the cretaceous pelagic carbonates of eastern tethys, sulaiman range, Pakistan: Minerals, 12(8), 946.
Weerakoon, W. P., Aggarwal, N., Jha, N., Jayasena, H., Joshi, H., Yakandawala, D., Chandrajith, R., Perera, K. G. S., and Ratnayake, N. P., 2019. Reconstruction of the Upper Gondwana palaeoclimates based on palynostratigraphy, palynofacies and sedimentology of the Jurassic sequences in the Tabbowa Basin, Sri Lanka: Journal of Asian Earth Sciences, 172, 264-278.
Windley, B.F., 1983. Metamorphism and tectonics of the Himalaya. Journal of Geological Society London, 140, 849–865
Wood, G., Gabriel, A., and Lawson, J., 1996. Palynological techniques—processing and microscopy: Palynology: principles and applications, 1, 29-50.
Xu, W., Ruhl, M., Jenkyns, H. C., Leng, M. J., Huggett, J. M., Minisini, D., Ullmann, C. V., Riding, J. B., Weijers, J. W., and Storm, M. S., 2018. Evolution of the Toarcian (Early Jurassic) carbon-cycle and global climatic controls on local sedimentary processes (Cardigan Bay Basin, UK): Earth and Planetary Science Letters, 484, 396-411.
Zahir, M., Awais, M., Ghani, M., Mohibullah, M., Hersi, O., Jan, I. U., Ahmad, S., and Iqbal, H., 2021. Reservoir Quality Assessment of the Upper Permian Chhidru Formation, Salt and Surghar Ranges, Pakistan: Acta Geologica Sinica-English Edition, 95(6), 2120-2137.
Ziaja, J., 2006. Lower Jurassic spores and pollen grains from Odrowąż, Mesozoic margin of the Holy Cross Mountains, Poland: Acta Palaeobotanica, 46(1), 3-83

Appendices

Alisporites pergrandis, (Bolch.) Iljina
Aratrisporites fischeri, (Klaus) Playford and Dettmann, 1965
Aratrisporites minimus, (Schulz 1967)
Araucariacitesaustralis, (Cookson 1947)
Calamosporatener, (Leschik 1955) Mädler 1964
Camptotriletescerebreformis, (Naum. ex Jarosh)
Cerebropollenitesmacroverrucosus, (Thiergart) Schulz 1967
cf. *Alisporitesmicrosaccus,* (Couper1958) Pocock 1962
cf. *Chasmatosporiteselegans,* (Nilsson 1958)
Chasmatosporiteshians, (Nilsson 1958)
Chasmatosporites major, (Nilsson 1958) *Pocock&Jansonius* 1969
Chomotriletes minor, (Kedves) Pocock 1970
Classopollistorosus, (Reissinger 1950) Couper 1958
Clavatipolleniteshughesii, (Couper 1958)
Corollinameyeriana, (Klaus 1960) *Venkatachala&Goczån* 1964
Cycadopitesdilucidus, (Bolch.) Iljina
Cythatidesaustralis, (Couper 1953)
Deltoidosporacrassexina, (Nilsson 1958) Lund 1977
Dipterellaoblatinoides, (Maljavkina 1949)
Leiofusajurassica, (Schulz 1967)
Luehndeaspinosa, (Morgenroth 1970)
Lunatisporiteskraeuseli, (Leschik 1955)
Lycopodiumsporitescerniidites, (Ross 1949) *Delcourt & Sprumont* 1955
Lycopodiumsporitesreticulumsporites, (Rouse 1959) Dettmann 1963
Marattisporitesscabratus, (Couper 1958)
Monosulcitesminimus, (Cookson 1947)Couper 1953
Perinopolleniteselatoides, (Couper 1958)
Piceapollenitesvariabiliformis, (Bolch.) Petr.,
Polygoniumjurassicum, (Bucefalo Palliani et al., 1996)
Quadraeculinaanellaeformis, (Maljavkina1949)
Spheripollenitespsilatus, (Couper 1958)
Stereisporitesbujargiensis, (Bolch.) Schulz1967
Stereisporitescompactus, (Bolch.) Iljina
Stereisporitescongregatus, (Bolch.) Schulz1967
Stereisporitesinfragranulatus, (Schulz 1967)
Stereisporitespsilatus, (Ross) Pflug 1953
Todisporites minor, (Couper 1958)
Veryhachiumformosus, (Stockmans & Williere 1960)
Vitreisporitespallidus, (Reissinger 1950)