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Mesozoic Oceanic Anoxic Events: Records from India and future scope

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ABSTRACT

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This paper presents an assessment of the Mesozoic Oceanic Anoxic Event (OAE) studies carried out from India. It provides a summary of the research work pursued on biostratigraphic, isotopic and organic geochemical proxies for establishing Oceanic Anoxic Events (OAEs) from the Mesozoic sedimentary sequences of the Indian subcontinent. From Indian sedimentary basins, studies are available on OAE 1a, OAE 1b, OAE 1d, OAE 2 and OAE 3. From the Cauvery Basin records of OAE 1b, OAE 1d, OAE 2 and OAE 3 are available. From the Spiti Valley, records are present only of OAE 2 (Chikkim Formation) and the possibilities of late Valanginian Weissert Event (W–OAE). Latest Hauterivian Faraoni Event (F–OAE) and OAE 1a are expected to be present in the Giumal Formation. Nonetheless, the Black shale from Rudramata Shale, Jhuran Formation from Kutch Basin indicate possible late Jurassic OAE based on the character of sedimentary facies and organic geochemical results. There is also the possibility of OAE 1a and OAE 1b in the Ukra and Upper member of the Bhuj Formation. This paper aims to provide a comprehensive introduction on global and regional OAEs records from Indian subcontinent and a significant window on available knowledge of these events in India and supply significant attention for the future research possibilities from the Indian landmass.

Key–words—Oceanic Anoxic Event, Mesozoic, Black Shale, Spiti Himalaya, India.

INTRODUCTION

THE Mesozoic Era (time span approx. 186 Ma) is an important and remarkable time period in the Earth's history as it witnessed the rifting of the Pangaea Supercontinent and the opening–spreading of the Atlantic and Indian oceans. Mesozoic Era brackets the time interval sandwiched between two extreme events of biodiversity crisis, i.e. the end Permian mass extinction (~ 252 Ma) marking the base of the Triassic Period (start of the Mesozoic Era) and the Cretaceous–Paleogene mass extinction (around 66 Ma) marking the end of the Cretaceous Period (end of Mesozoic Era). Each extinction event records major change in atmosphere and ocean composition and its impact on bio–diversity (extinction–adoptation–radiation) and it provides crucial information in understanding of anthropogenic climate change.

During the Mesozoic time, the global oceans experienced many catastrophic events that affected the major chemical compositions in oceans and the atmosphere. The CO_2 increase in the atmosphere affects the composition of the ocean and atmosphere, which is reflected in the sedimentary basin as changes in sediment dynamics–pattern, palaeo–redox, pH of the ocean, nutrient supply, etc. These events are recognised as deposits of dark colored laminated shale, highly rich in organic carbon content and sulphides (Jenkyns, 2010). These events are known as Oceanic Anoxic Events (OAEs) and are widely documented from a single isolated basin to quasi–global scale and from shallow coastal zones to the deepest parts of the open ocean (Jenkyns, 2010; Schlanger & Jenkyns, 1976).

In pelagic and neritic habitats, during periods of extreme greenhouse temperature, three global OAEs (Toarcian–OAE, OAE 1a and OAE 2) are marked by a carbonate crisis (Weissert *et al.*, 1998; Cobianchi & Picotti, 2001; Herrle & Mutterlose, 2003). In comparison with current populations, the excess CO_2 released from volcanoes during OAE prevented biocalcification in reef communities (Langdon *et al.*, 2000), along with planktonic foraminifers (Barker & Elderfield, 2002) and calcareous nannoplankton (Riebesell *et al.*, 2000). After surplus CO_2 was drawn down by accelerated weathering and burial of organic matter, carbonate sedimentation restarted and possibly the rate of nutrient delivery also slowed down.

OAEs affected nannofossil productivity in different ways. Certain OAEs have led to speciation events whereas others have caused extinction events. The Toarcian OAE and OAE 1a events, show similar nannofossil evolutionary trends, are preceded by a speciation event and do not exhibit extinctions. Conversely, nannofossil assemblages during OAE 2 are characterised by a turnover, in which new species emerge after a set of species vanished. Therefore, calcareous nannoplankton benefitted from the environmental changes that occurred during the Aptian and Toarcian, which in turn encouraged diversification. Perhaps nannofloras suffered from far more harsh conditions during OAE 2.

The concept of the oceanic anoxic event was first introduced by Schlanger and Jenkyns (1976) and Jenkyns (1980). A total of nine episodes of global and regional OAEs were recorded during the Mesozoic Era (Leckie *et al.,* 2002; Erba, 2004; Jenkyns, 2010). The intense effect of climate change on global oceans has been studied from the geochemical signatures in carbon–rich dark black shale sequences deposited under an anoxic condition and representing a reducing environment (Schlanger & Jenkyns, 1976). These OAE events were recognised as intervals in the geological timescale which lasted for about a few 100−1000 years (Jenkyns, 2010).

During an extensive volcanic eruption, high concentrations of carbon dioxide released in the atmosphere and caused extreme warming effect. Due to the warm environment, the solubility of oxygen in ocean water dropped and caused enhanced stratification (Hesselbo *et al.,* 2000; Beerling *et al.,* 2002; Leckie *et al.,* 2002). This long–term intense warming also caused huge continental weathering (Jenkyns, 2003, 2010). The long–term depletion of oxygen in the ocean and high concentration of carbon dioxide, caused the extinction of calcareous micro–organisms in the oceans which

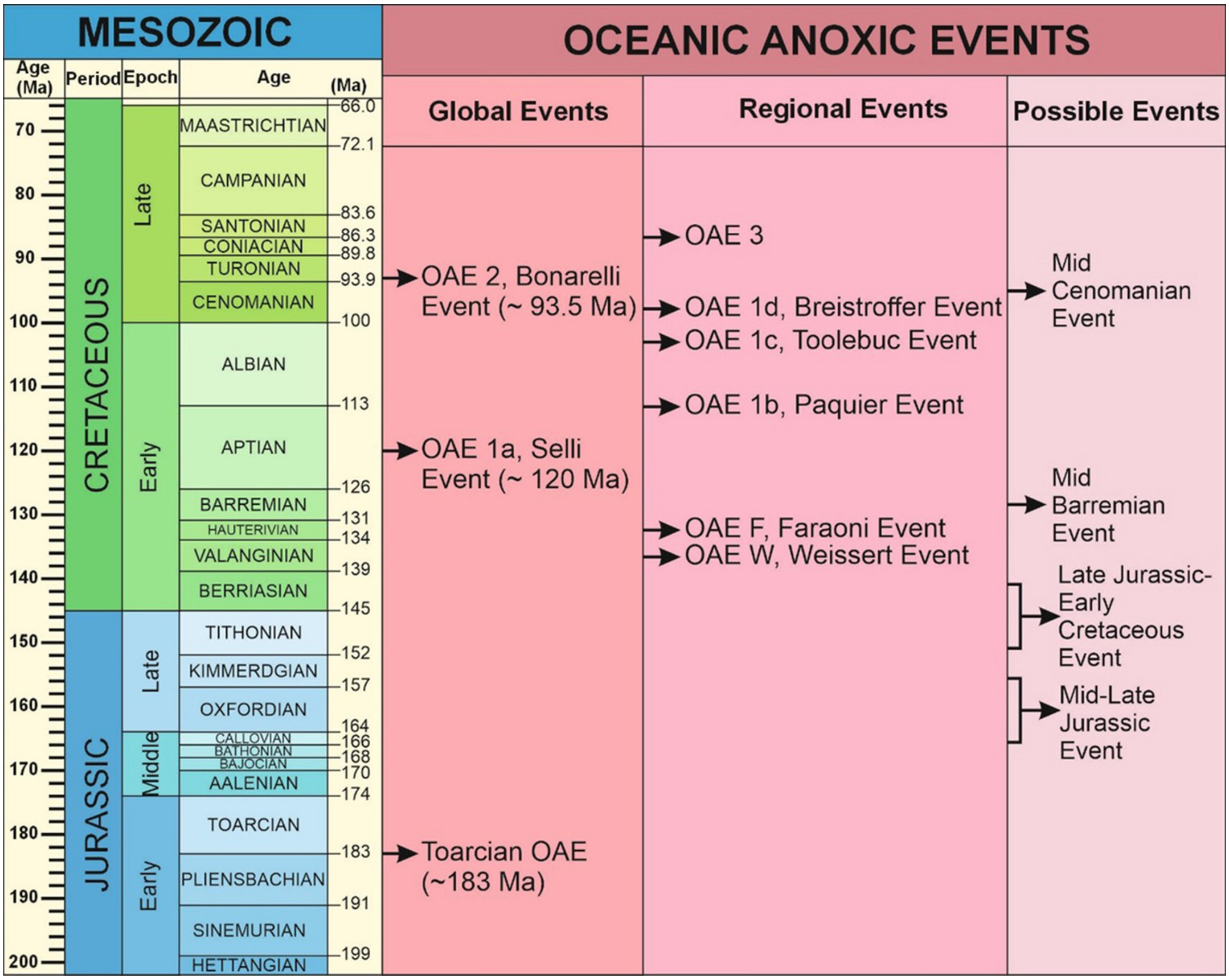


Fig. 1—Mesozoic Oceanic Anoxic Events plotted against geological time scale.

led to mass extinction events of calcareous phytoplanktons and zooplanktons in the geological past, such as during K/Pg boundary (Keller *et al.*, 2011 and references cited therein). Hence, a better understanding of the past catastrophe with the future prediction of climate and oceans could be achieved from OAE studies (Arthur & Schlanger, 1979; Jenkyns, 1999; Bottjer *et al.,* 2001; Huber *et al.,* 2002; Takashima *et al.,* 2006; Bralower, 2008).

Several studies have demonstrated plenty of evidence of global and regional OAE events in the Mesozoic sediments (Leckie *et al.,* 2002; Erba, 2004; Jenkyns, 2010). Early Toarcian (Posidonienschiefer event, T–OAE, ~ 183 Ma); early Aptian (Selli event, OAE 1a, ~ 120 Ma); early Albian (Paquier event, OAE 1b, ~ 111 Ma) and Cenomanian–Turonian (Bonarelli event, C/T OAE, OAE 2, ~ 93 Ma) events are well studied. These events are first recognised in the Vocontian Trough of southeast France (Bréhéret, 1985). Some other events are recognised from the Tethyan realm (OAE 1c, OAE 1d) Toolebuc event, late Albian Breistroffer event, (Arthur *et al.,* 1990), the late Cretaceous Valanginian Weissert event (W–OAE) and latest Hauterivian Faraoni Event (F–OAE) also demonstrated from the various Tethyan and Atlantic domain regions (Lini *et al.* 992; Erba *et al.,* 2004; Bornemann & Mutterlose, 2008; Brassell, 2009; Rodríguez–Tovar & Uchman, 2017) and Coniacian–Santonian (OAE 3) (Arthur *et al.,* 1990; Wagner *et al.,* 2004). In addition, the late Jurassic anoxic event (Nozaki *et al.,* 2013; Arora *et al.,* 2015; Carmeille *et al.,* 2020; Rogov *et al.,* 2020) and an Oxfordian–Kimmeridgian OAE (Martinez & Dera, 2015) also identified (Fig. 1).

During the Mesozoic time three global OAE's (i). Toarcian OAE or Jenkyns Event, (ii). OAE 1a or Selli Event, (iii). OAE 2 or Bonarelli Event and six regional OAEs (W–OAE or Weissert Event, F–OAE or Faraoni Event, OAE 1b or Paquier Event, OAE 1c or Toolebuc Event, OAE 1d or Breistroffer Event and OAE 3 Coniacian–Santonian) are recorded. The global OAEs are associated with warm conditions due to the high carbon dioxide levels related to the various volcanic activities. T–OAE has been attributed to the warming due to the excessive carbon input into the atmosphere potentially caused by volcanism from the Karoo–Ferrar Large Igneous Province, the thermogenic emission of ^{12}C via intrusion of Karoo–Ferrar sills in Gondwanan coal deposits (McElwain & Hesselbo, 2005; Svensen *et al.*, 2007) and/or the dissociation of methane gas hydrates (Hesselbo *et al.*, 2000, 2007; Kemp *et al.*, 2005).

OAE 1a has been attributed to the warm conditions resulting from the increased CO_2 levels in the atmosphere, which could possibly resulting from the volcanic activity on the Ontong Java Plateau (OJP) in the Mid–Pacific. Studies also suggest that volcanic activity in the Songliao Basin and northeast Asia possibly played an important role (Wang *et al.*, 2016a).

OAE 2 was linked to the high global temperatures associated with large igneous province (LIP) emplacements (Leckie *et al.*, 2002) and elevated volcanic degassing (Arthur *et al.*, 1985; Larson, 1991; Huber *et al.*, 1995; Kuroda *et al.*, 2007; Jones *et al.*, 2021) increased atmospheric CO_2 concentrations (Forster *et al.*, 2007; Sinninghe–Damsté *et al.*, 2010; O'Brien *et al.*, 2017; Robinson *et al.*, 2019).

Regional OAEs are comparatively less studied for the causative mechanisms. While the role of volcanic activity is not established for all regional OAEs, sea level changes and climate change could have played a key role in the formation of regional OAEs.

The present study contributes to the synthesis of various studies made on Oceanic anoxic events (OAEs) recognised from the Indian sedimentary records. The OAEs recorded from the Indian basins are OAE 1b (Paquier event); OAE 2 (Bonarelli event); OAE 1d (Breistroffer event) and OAE 3 (Coniacian–Santonian). The study also demonstrates the possible time slices and sediment succession from where OAE studies can be pursued from Indian sub–continent.

INDIAN MESOZOIC SEQUENCES AND OAE RECORDS

In India, Mesozoic sequences are well developed and sought great attention from stratigraphers and the palaeontologists worldwide (Medlicott, 1872; Matley, 1921; Brookfield & Westermann, 1982; Jadoul *et al.,* 1990; Oloriz & Tintori, 1990; Garzanti, 1992; Premoli Silva *et al.,* 1992; Cariou *et al.,* 1996; Fürsich, 1998; Whatley & Bajpai, 2000; Hart *et al.,* 2001; Whatley *et al.,* 2002; Bertle & Suttner, 2005; Alberti *et al.,* 2013; Lukeneder *et al.,* 2013; Krishna, 2017; Chopparapu & Rajanikanth, 2018; Fürsich *et al.,* 2018). The Indian sequences are exposed in the northern (Laddakh, Spiti, Uttarakhand); western (Jaisalmer, Kutch); eastern (Rajmahal Basin and Assam–Arakan); central (Narmada–Son, Satpura and Rewa basins); and southern parts (Cauvery, Krishna–Godavari, Palar, Mahanadi and Pranhita–Godavari basins) (Krishna, 2017; Chopparapu & Rajanikanth, 2018). However, the marine exposures comprising OAEs can only be found in Ladakh and Spiti Himalaya, Kutch, Jaisalmer and Cauvery basins (Fig. 2). The areas from which OAE studies are available and the possible areas for these studies are discussed below and compiled in Fig. 3.

Cauvery Basin

The Cauvery Basin is a pericratonic rift basin along the eastern continental margin of the Peninsular India (Rangaraju *et al.,* 1993; Madhavaraju *et al.,* 2015). It comprises more than 6000 m thick well–preserved sediments ranging from Cretaceous to Paleocene. The sediments were deposited during two phases–(1) syn–rift phase which predominantly contains fluvial and lacustrine deposits and (2) post–rift

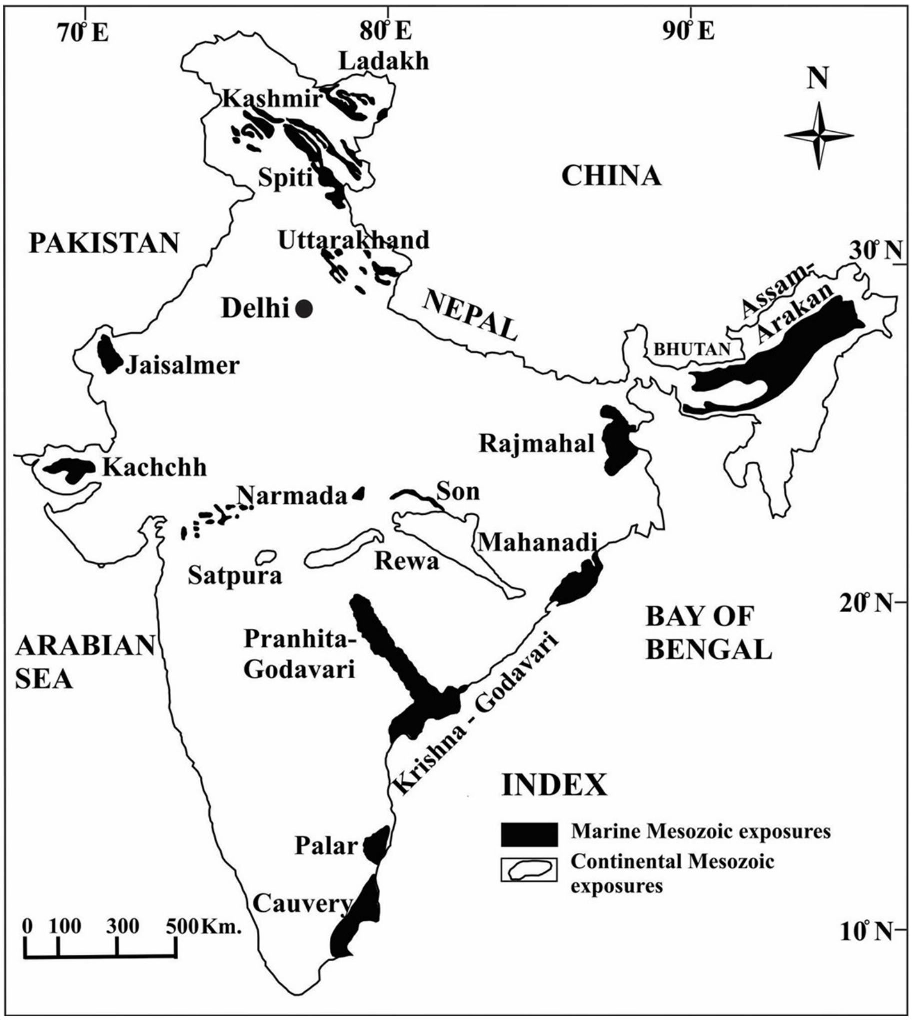


Fig. 2—Marine and continental Mesozoic exposures in India (Modified after Krishna, 2017; Chopparapo & Rajanikanth, 2018).

phase consisting of shelf carbonates and marine shale (Reddy *et al.,* 2013). Post–rift phase sediments are well exposed in the Ariyalur area (Madhavaraju *et al.,* 2015). The Cretaceous and the early Paleogene sediments are exposed in disconnected outcrops (Govindan, 2017); dipping towards east from bounding nonconformity with Archean charnockitic crystalline basement (Sundaram *et al.,* 2001), mainly exposed in three areas: in Ariyalur, Vriddhachalum and Pondicherry districts. The complete succession is well represented in the Ariyalur area. A total thickness of 2.5 km of the Cretaceous sediments is well preserved in the Ariyalur area (Sundaram *et al.,* 2001). Blanford (1862) classified the Cretaceous sedimentary rocks of the Ariyalur area and divided them into three groups, the Uttatur, Trichinopoly and Ariyalur groups. The Uttatur Group overlies the Archean basement. It comprises terrestrial, paralic and shallow marine strata (Sundaram *et al.,* 2001). Nagendra and Reddy (2017) divided the Uttatur Group into three formations–Terani, Dalmiapuram and Karai formations (Fig. 4).

The Trichinopoly Group comprises Garudamangalam Formation, which is further divided into three members–Kulakkalnattam Sandstone, Anaipadi Sandstone and Saturbugan Sandstone members (Fig. 4).

The Ariyalur Group is divided into three formations–Sillakkudi, Kallankurichchi and Kallamedu. The Sillakkudi Formation is further divided into three members–Kilpavalur Grainstone, Sillakkudi Sandstone and Kaller Conglomerate. The Kallankurichchi Formation comprises Kallankurichchi Limestone Mb. The Kallamedu Formation is divided into two members–Ottakovil Sandstone and Kallamedu Sandstone (Reddy *et al.,* 2013) (Fig. 4).

In the Uttatur Group, the Terani Formation (Berriasian–Aptian) comprises fluvial and marine sediment deposits during the first marine worldwide transgression in late Aptian to early Albian during the Cretaceous Period (Blanford, 1862; Sundaram *et al.,*2001; Reddy *et al.,* 2013; Govindan, 2017; Nagendra & Reddy, 2017). It comprises bedded sandstone containing local boulder conglomerates with bleached,

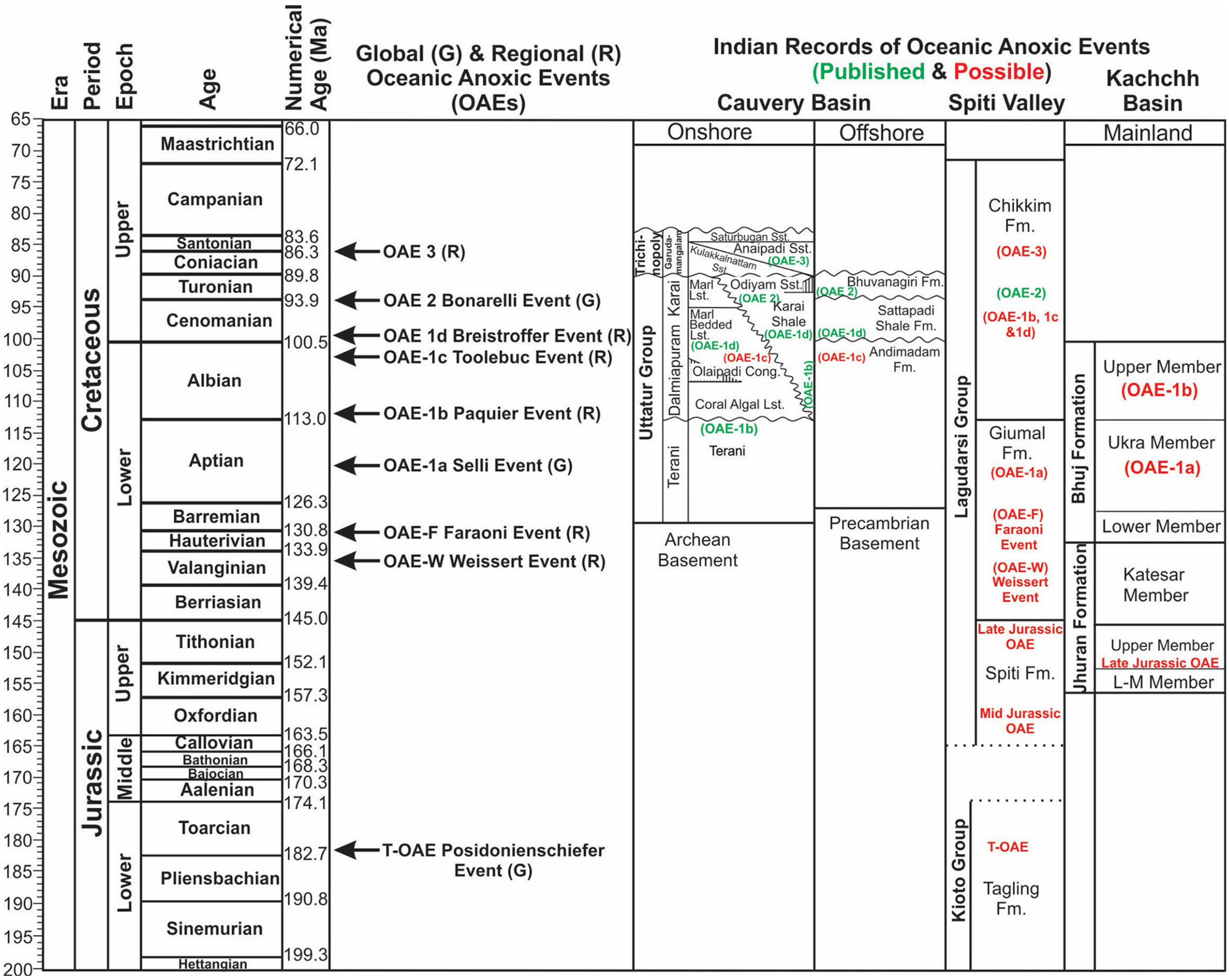


Fig. 3—Established Global and Regional Oceanic Anoxic events (OAEs) and records from Indian basins (Published events–green colour; Possible events–red colour).

kaolinitic claystone and micaseous shale, which is interbedded with siltstone and sandstone of 0.5 m and well–cemented with calcareous material.

It is overlain by the Dalmiapuram Formation (Albian to middle Turonian) comprising grey, fossiliferous, poorly lithified shale, calcareous mudstone, irregularly bedded to massive, fine–grained coralline micritic and algal limestone, coquinite and calcareous sandstone with rounded quartzite pebbles locally grading to beds of granule and pebble conglomerate. The internal facies mosaic of this unit is complex, but in the type section, limestone interbedded with calcareous mudstone overlies a thick unit (>30 m) of grey shale (Sundaram *et al.,* 2001).

The Karai Shale Formation time equivalent of Dalmiapuram Formation consists of ammonites, belemnites and worm tubes (Madhavaraju *et al.,* 2015). Lithologically, it contains grey–brown, gypsiferous, glauconitic mudstone and marl which is black and gypsum free when freshly deposited, with sporadic thin, interbeds of siltstone, calcareous sandstone and coquinite particularly in its upper part. Sporadic calcareous, sideritic and phosphatic concretions and concretionary horizons occur in some intervals. Scattered macrofossils, predominantly molluscs, are typical of the Formation (Sundaram *et al.,* 2001).

The Garudamangalam Formation (Coniacian–Santonian) of Trichinopoly Group unconformably overlies the Karai Shale Formation and comprises burrows in sandstone. Cross laminations are preserved in the upper portion indicating the presence of the fluvial system and a sea level drop in the Basin (Nagendra & Reddy, 2017). This Formation is devoid of foraminifera but contains nannoplanktons and ammonite fossils (Reddy *et al.,* 2013). The Sillakkudi Formation (Campanian) overlies the Garudamangalam Formation. It comprises glauconite pellets and calcareous nodules (Rasheed

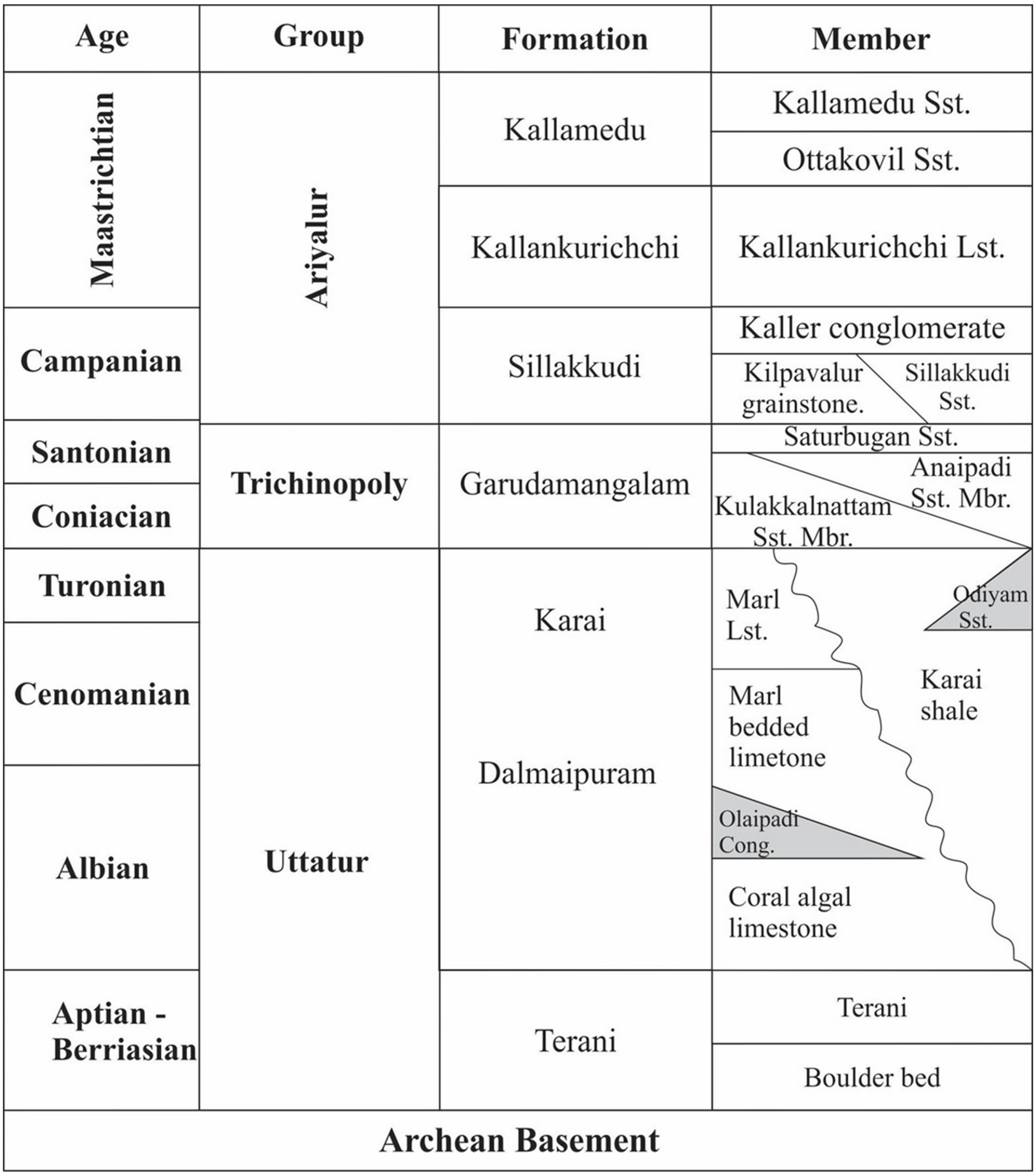


Fig. 4—Mesozoic stratigraphy of the Cauvery Basin (modified after Nagendra & Reddy, 2017).

& Ravindran, 1978). The Kallankurchchi Formation (early Maastrichtian) overlies the Sillakkudi Formation and consists of limestone beds dominated by the benthic foraminifera. The Kallamedu Formation (late Maastrichtian) comprises ferruginous limestone, a lower arenaceous limestone and Gryphaea limestone overlies the Kallankurchchi Formation (Reddy *et al.,* 2013, Nagendra & Reddy, 2017).

OAE records

A number of significant OAE events have been demarcated from the Cauvery Basin. The OAE 1b has been marked at the Aptian–Albian boundary from the organic–rich shale deposits of the Terani Formation (Nagendra & Reddy, 2017). The OAE 2 (Cenomanian–Turonian) and OAE 3 (Coniacian–Santonian) has recorded from the Karai Shale Formation and Garudamangalam Formation respectively (Fig. 3). Later on, Bansal *et al.* (2019) provided more precise age of the OAE by ^{40}Ar / ^{39}Ar study from the glauconite occurred at the lower part of the Karai Shale Formation. The age, ranging from 100.3 ± 0.7 to 92.6 ± 0.6 Ma correlates to the OAE 1d and OAE 2. Govindan (2017) and Nagendra and Reddy (2017) recorded OAE 1c, OAE 1d and OAE 2 from the Andimandam, Sattapadi Shale and Bhuvanagiri formations from the organic-rich shale containing up to 6% TOC.

Madhavaraju *et al.* (2015) carried out the petrographic, carbon and oxygen isotopic studies from the Dalmiapuram Formation exposed in the Vadugarpettai. He reported the positive shift of 0.8% in carbon isotopic values from the lower portion of the Coral algal Limestone. The shift coincided with the initiation of OAE 1d. The carbon isotopic value increases in the middle portion of the limestone coincided with the upper limit of the OAE 1d.

Tewari *et al.* (1996) correlated the significant evolution of the Planktonic foraminifera assemblages and planktonic/benthonic (p/b) ratio with the OAE 1d and the OAE 2.

Spiti Valley

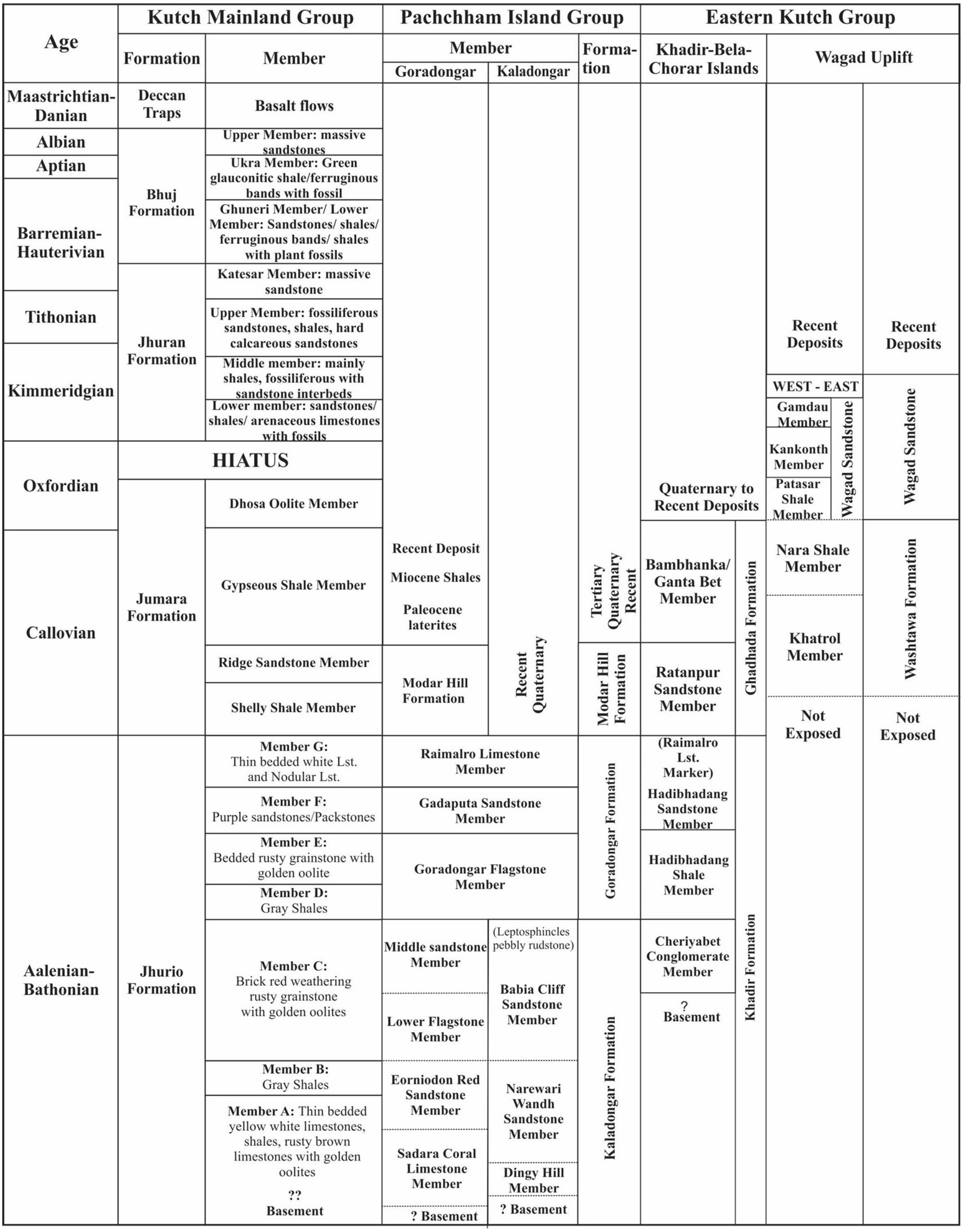
The Spiti valley is considered as the deformed remnants of the northern continental margin of the Indian subcontinent. It consists of dominant limestone, shale, siltstone and dolomite. The sequence of 12,000 meters of Paleozoic–Mesozoic sediments is well preserved in this synclinoria basin in the Tethyan Himalaya. The succession was first referenced by Gerard (1827); subsequently worked by Hayden (1904, 1908) and Diener (1912). Further, detailed work was done by many workers (Srikantia, 1981; Bagati, 1990; Gaetani & Garzanti, 1991; Bhargava & Bassi, 1998; Srikantia & Bhargava, 1998; Myrow *et al.,* 2003). The detailed lithostratigraphic framework of the Spiti Valley was proposed by Bhargava (2008). The Mesozoic Tethys sediments were classified into Tamba Kurkur Group, Sanglung Group, Nimoloksa Group, Kioto Group and Lagudarsi Group; lies disconformably in ascending order shown in Fig. 5.

OAE records

Pandey and Pathak (2015) carried out a preliminary study on ammonoids from the early Cretaceous Giumal Formation of the Spiti Valley, Himachal Pradesh. They suggested Berriasian to early Aptian age to the Giumal Formation based on the ammonoids and also, showed the presence of all the stages from Berriasian to early Aptian in the Giumal Formation. The age range of Giumal Formation and the presence of dark grey to black shale layers in between sandstone beds enhances the possibility of the presence of the late Valanginian Weissert Event (W–OAE), the latest Hauterivian Faraoni Event (F–OAE) and OAE 1a in the Giumal Formation succession. The area has potential for the study of early Cretaceous OAEs.

Group	Formation	Lithology	Age
Lagudarsi	Chikkim	Limestone, Shale	Albian-Campanian/Early Maastrichtian
	Giumal	Sandstone	Berriasian-Aptian
	Spiti	Shale	Callovian-Tithonian
Unconformity			
Kioto	Tangling	Limestone, Dolomite	Late Triassic-Early Jurassic
	Para	Limestone, Dolomite	Late Rhaetian
Nimoloksa	Nunuluka	Sandstone, Siltstone, Limestone	Late Norian-Early Rhaetian
	Alaror	Shale, Siltstone, Limestone	Late Norian
	Hangrang	Limestone, Dolomite	Middle Norian
	Rangrik	Shale, Sandstone, Limestone	Early-Middle Norian
Sanglung	Rongtong	Dolomite, Limestone	Middle-Late Carnian
	Rama	Shale, Sandstone, Limestone	Early-Middle Carnian
Tamba Kurkur	Chomule	Limestone	Ladinic-Early Carnian
	Kaga	Shale, Sandstone, Limestone	Ladinian
	Mikin	Limestone	Induan-Anisian
Unconformity			

Fig. 5—Mesozoic stratigraphy of Spiti Valley, Himachal Pradesh (modified after Cariou *et al.*, 1996; Bertle & Suttner, 2005; Pathak, 2007; Bhargava, 2008; Lukeneder *et al.*, 2013; Pandey & Pathak, 2015).



Age	Kutch Mainland Group		Pachchham Island Group			Eastern Kutch Group		Wagad Uplift		
	Formation	Member	Member: Goradongar	Member: Kaladongar	Formation	Khadir-Bela-Chorar Islands				
Maastrichtian-Danian	Deccan Traps	Basalt flows	Recent Deposit Miocene Shales Paleocene laterites	Recent Quaternary	Tertiary Quaternary Recent	Quaternary to Recent Deposits		Recent Deposits		Recent Deposits
Albian	Bhuj Formation	Upper Member: massive sandstones								
Aptian		Ukra Member: Green glauconitic shale/ferruginous bands with fossil								
Barremian-Hauterivian		Ghuneri Member/ Lower Member: Sandstones/ shales/ ferruginous bands/ shales with plant fossils								
	Jhuran Formation	Katesar Member: massive sandstone								
Tithonian		Upper Member: fossiliferous sandstones, shales, hard calcareous sandstones								
Kimmeridgian		Middle member: mainly shales, fossiliferous with sandstone interbeds						WEST - EAST		
		Lower member: sandstones/ shales/ arenaceous limestones with fossils						Gamdau Member	Wagad Sandstone	Wagad Sandstone
Oxfordian	HIATUS	HIATUS						Kankonth Member		
	Jumara Formation	Dhosa Oolite Member						Patasar Shale Member		
Callovian		Gypseous Shale Member				Bambhanka/ Ganta Bet Member	Ghadhada Formation	Nara Shale Member		Washtawa Formation
		Ridge Sandstone Member	Modar Hill Formation		Modar Hill Formation	Ratanpur Sandstone Member		Khatrol Member		
		Shelly Shale Member						Not Exposed		Not Exposed
Aalenian-Bathonian	Jhurio Formation	Member G: Thin bedded white Lst. and Nodular Lst.	Raimalro Limestone Member		Goradongar Formation	(Raimalro Lst. Marker) Hadibhadang Sandstone Member	Khadir Formation			
		Member F: Purple sandstones/Packstones	Gadaputa Sandstone Member							
		Member E: Bedded rusty grainstone with golden oolite	Goradongar Flagstone Member			Hadibhadang Shale Member				
		Member D: Gray Shales								
		Member C: Brick red weathering rusty grainstone with golden oolites	Middle sandstone Member	(Leptosphincles pebbly rudstone)	Kaladongar Formation	Cheriyabet Conglomerate Member				
			Lower Flagstone Member	Babia Cliff Sandstone Member		? Basement				
		Member B: Gray Shales	Eorniodon Red Sandstone Member	Narewari Wandh Sandstone Member						
		Member A: Thin bedded yellow white limestones, shales, rusty brown limestones with golden oolites ?? Basement	Sadara Coral Limestone Member	Dingy Hill Member						
			? Basement	? Basement						

Fig. 6—Mesozoic stratigraphy of Kutch Basin (modified after Biswas, 2016).

Bertle and Suttner (2005) carried out a detailed biostratigraphy of the Chikkim Formation based on planktonic foraminifera. They have given an age ranging from late Albian to early Maastrichtian? to the Chikkim Formation. The age of the Lower Chikkim Formation ranges from late Albian to Santonian and contains Cenomanian age sediments also, which is evidenced by the presence of FO of *Rotalipora globotruncanoides*. In the upper portion of the Lower Chikkim Formation, the presence of single thin pinkish coloured bed, suggests a change towards an oxygenated water column and presence of possible OAE 2, documented by the occurrence of *Whiteinella archaeocretacea* Zone (Bertle & Suttner, 2005).

Kutch Basin

The Kutch Basin is a pericratonic rift basin in the western continental margin of India, Gujarat. It comprises more than 25,000 m of synrift middle Jurassic to early Cretaceous sediments and post–rift late Paleocene to Pliocene and Quaternary sediments distributed in the northern, eastern and the southern part of the basin (Biswas, 2016). The Mesozoic rocks are exposed in the uplifted areas especially islands (Wagad, Pachchham, Khadir, etc.) and Kachchh mainland whereas the low–lying areas of Kachchh mainland are enclosed by Tertiary to recent marine and fluvio–deltaic sediments. Biswas (2016) classified Mesozoic successions of Kutch Basin into three lithostratigraphic Groups–Mainland Group, Pachchham Group and Eastern Kutch Group. The mainland sequences are divided into four formations–Jhurio, Jumara, Jhuran and Bhuj in ascending chronological order shown in Fig. 6.

The Pachchham Group is divided into two formations–Lower Kaladongar and Upper Goradongar formations. They are exposed in the northern Kaladongar and southern Goradongar hill ranges. The Eastern Kutch Group is divided into four formations–Khadir, Ghadhada, Washtawa and Wagad Sandstone which are exposed in the disconnected rock units outcroped in the Khadir, Bela, Chorar 'Island' and Wagad Highland. The middle Jurassic to late Jurassic sediments were deposited in the marine transgressive phase during the syn rifting stage whereas, the late Cretaceous to recent sediments deposited after post–rift stage, which indicates a deltaic to marginal shelf depositional environment.

OAE records

The sedimentary facies and organic geochemical analysis carried out by Arora *et al.* (2015) on the organic rich black shale of the Middle Member (Rudramata Shale) of the Jhuran Formation. They divided lower portion of the Rudramata Shale into five lithofacies–

Facies A: black shale,

Facies B: black shale with siltstone inter–bedding,

Facies C: shale and siltstone alternations with minor sandstones,

Facies D: siltstone–sandstone alternations, and

Facies E: plane laminated and hummocky cross–stratified sandstone.

The Total Carbon Content (TOC), Oxygen Index (OI), Hydrogen Index (HI), T_{max} and trace elemental composition study records show significant variations. The TOC content decreases from Facies A (av. TOC–3.4%) to Facies D (av. 0.6%). The black shale of Facies A and B have high TOC values and indicates deposition in possibly oxygen minimized zone developed at that time. Also, a significant shift recorded in the Ni/Co ratio and V/(V+Ni) ratio plot represents an anoxic and sulfidic condition in the depositional setting, whereas, the V/Cr ratio plot represents anoxic condition that might be due to the diagenetic redistribution of the elements. The presence of the pyrite framboids of size ranging from 7 to 20 µm also correlated with an anoxic and sulfidic conditions within the depositional setting. These suggest sub–oxic to anoxic conditions prevailed during the late Jurassic and it could be the signature of the late Jurassic Oceanic Anoxic Event.

Pandey and Pathak (2016) discussed the presence of OAE 1a in the Ukra Member (early Cretaceous) of Bhuj Formation, Kutch Basin.

DISCUSSION

Apart from the globally recorded oceanic anoxic events (Three: T–OAE, OAE 1a and OAE 2) several regional or local anoxic events are also reported from different parts of the world (Jenkyns, 2010; Leckie *et al.,* 2002; Erba, 2004) (Table 1).

Leckie *et al.* (2002) have given an overview of additional possible oceanic anoxic events. These additional possible anoxic events are recorded from the black shale units deposited worldwide during the late Aptian (~116 Ma), latest Aptian–early Albian (OAE 1b; ~113–109 Ma), late Albian (OAE 1c and OAE 1d; ~102 and ~99.2 Ma, respectively), mid Cenomanian (~96 Ma), an event in the late Aptian, between OAE 1a and OAE 1b (Arthur *et al.,* 1990; Weissert & Lini, 1991; Bralower *et al.,* 1993, 1999; Bréhéret, 1994; Erbacher *et al.,*1996; Weissert *et al.,* 1998; Wilson & Norris, 2001). The multiple black shales of OAE 1b are mostly restricted to Mexico and the North Atlantic basin (western Tethys) and the Mediterranean (eastern Tethys) region (Arthur & Premoli Silva, 1982; Bréhéret *et al.,* 1986; Premoli Silva *et al.,* 1989; Bralower *et al.,* 1993, 1999). OAE 1b time interval is linked with cooling and sea level fall in the latest Aptian and following sea level rise during the early Albian (Weissert & Lini, 1991; Weissert *et al.,* 1998). OAE 1c (lower upper Albian) has been identified in central Italy, the U.S. western interior and Australia (Pratt & King, 1986; Coccioni & Galeotti, 1993; Haig & Lynch, 1993; Bralower *et al.,* 1993; Erbacher *et al.,* 1996). Conversely, OAE 1d is

Table 1—Global, Regional and Possible Oceanic Anoxic Events and their records from the different regions of the world**.**

Sl. No.	**Oceanic Anoxic Events**	**Records**
Global Oceanic Anoxic Events		
1.	OAE 2, Bonarelli Event (~ 93.5 Ma)	**Western Tethys, Southern Tethys**, **USA, North African Continental margin, Canadian Arctic, Alaska, Mexico, Japan** (Tewari *et al.*, 1996; Bertle & Suttner, 2005; Govindan, 2017; Nagendra & Reddy, 2017; Boulila *et al*., 2020; Sooraj *et al*., 2024)
2.	OAE 1a Selli Event (~120 Ma)	**Northern Tethys** (Zhang *et al*., 2021 and references therein) **Western Tethys** (Midtkandal *et al*., 2016; Giraud *et al*., 2018; Tedeschi *et al*., 2020; Castro *et al*., 2021; Giraldo–Gomez *et al*., 2022) **Southern Tethys** (Lowrie *et al*., 1980; Coccioni *et al*., 1987, 1990; Erba, 1994; Baudin *et al*., 1998; Erba & Larson, 1998; van Breugel *et al*., 2007; Bottini *et al*., 2012; Li *et al*., 2016; Karakitsios *et al*., 2018; Talbi *et al*., 2021) **Pacific** (Thiede *et al*., 1981; Sliter, 1989; van Breugel *et al*., 2007; Bottini *et al*., 2012; Erba *et al*., 2015; Matsumoto, 2024)
3.	Toarcian OAE (Jenkyns Event) (~183 Ma)	**Arctic** (Suan *et al*., 2011 and references therein) **Panthalassic Ocean** (Kemp *et al*., 2019, 2022; Chen *et al*., 2023 and references therein) **Northern Tethys** (Nie *et al*., 2023; Huang *et al*., 2024; Jin *et al*., 2020 and references therein) **Western Tethys** (Mattioli *et al*., 2009; Peti & Thibault, 2017; Satolli *et al*., 2018; Boulila *et al*., 2019; Müller *et al*., 2020; Chen *et al*., 2021; Fernández–Martínez *et al*., 2021; Galasso *et al*., 2021; Reolid *et al*., 2021) **Southern Tethys** (Han *et al*., 2022; Kemp *et al*., 2022 and references therein)
Regional Oceanic Anoxic Events		
1.	OAE 3	**Boreal** (Jenkyns *et al*., 1994; Jarvis *et al*., 2006; Pugh *et al*., 2014; Thibault *et al*., 2016; Eldrett *et al*., 2021; Grasby *et al*., 2024) **Northern Tethys** (Chamberlain *et al*., 2013; Wang *et al*., 2016b; Jones *et al*., 2018 and references therein) **Western Tethys** (Arthur & Fischer, 1977; Jenkyns *et al*., 1994; Stoll & Schrag; 2000; Wagreich & Krenmayr, 2005; Lamolda & Paul, 2007; Locklair *et al*., 2011; Frijia *et al*., 2015) **Southern Tethys** (Clark & Jenkyns, 1999; Tur & Wagreich, 2005; Li *et al*., 2006; Wendler *et al*., 2011; Petrizzo *et al*., 2017; Huber *et al*., 2018; MacLeod *et al*., 2020; Mansour *et al*., 2020b) **Eastern Tethys** (Navidtalab *et al*., 2016; Razmjooei *et al*., 2020 and references therein) **Pacific** (Perez–Infante *et al*., 1996; Alberdi–Genolet & Tocco, 1999; Rey *et al*., 2004; Takashima *et al*., 2010; Ando *et al*., 2013; Machado *et al*., 2016; Tessin *et al*., 2019) **Atlantic** (Huber *et al*., 2002; Bottcher *et al*., 2006; Beckmann *et al*., 2008; Sachse *et al*., 2012, 2014; Aquit *et al*., 2017; Junium *et al*., 2018; Luft de Souza *et al*., 2018)
2.	OAE 1d, Breistroffer Event	**Boreal** (Mitchell *et al*., 1996; Bornemann *et al*., 2017, 2023 and references therein) **Northern Tethys** (Melinte–Dobrinescu *et al*., 2015 and references therein) **Western Tethys** (Gale *et al*., 1996; Erbacher & Thurow, 1997; Stoll & Schrag, 2000; Strasser *et al*., 2001; Bornemann *et al*., 2005; Reichelt, 2005; Sprovieri *et al*., 2013; Gambacorta *et al*., 2015; Giorgioni *et al*., 2015; Bąk *et al*., 2016; Gyawali *et al*., 2017; Bottini & Erba, 2018)

		Southern Tethys (Govindan, 2017; Nagendra & Reddy, 2017; Yao *et al*., 2018; Mansour *et al*., 2020a; Madhavaraju *et al*., 2021) **Eastern Tethys** (Vahrenkamp, 2013; Zhang *et al*., 2016; Wohlwend *et al*., 2016; Hennhoefer *et al*., 2018; Navidtalab *et al*., 2019) **Atlantic** (Wilson & Norris, 2001; Nederbragt *et al*., 2001; Watkins *et al*., 2005; Petrizzo *et al*., 2008; Ando *et al.,* 2010; Rodríguez–Cuicas *et al*., 2020) **Pacific** (Takashima *et al*., 2004; Robinson *et al*., 2008; Navarro–Ramirez *et al*., 2015; Rodríguez–Cuicas *et al*., 2019, 2020) **Western Interior Seaway (North America)** (Gröcke *et al*., 2006; Gröcke & Joeckel, 2008; Scott *et al*., 2013; Richey *et al*., 2018) **Indian Ocean** (Madhavaraju *et al*., 2015 and references therein)
3.	OAE 1c, Toolebuc Event	**Boreal** (Strasser *et al*., 2001; Wójcik–Tabol & Ślączka, 2015 and references therein) **Southern Tethys** (Coccioni & Galeotti, 1993; Tewari *et al*. 1996; Galeotti *et al*., 2003; Luciani *et al*., 2004; Govindan, 2017; Nagendra & Reddy, 2017; Madhavaraju *et al*., 2021) **Pacific** (Meyers *et al*., 2006; Scott *et al*., 2020 and references therein) **Austral** (Bralower *et al*., 1993; Haig & Lynch, 1993; Alibrahim, 2016 and references therein)
4.	OAE 1b, Paquier Event	**Boreal** (Herrle *et al*., 2015; Bodin *et al*., 2023 and references therein) **Northern Tethys** (Ando & Kakegawa, 2007; Suarez *et al*., 2018; Gavrilov *et al*., 2019 and references therein) **Western Tethys** (Breheret & Crumiere, 1989; Strasser *et al*., 2001; Grocke, 2002; Heimhofer *et al*., 2003; Mutterlose *et al*., 2003; Herrle *et al*., 2004; Follmi *et al*., 2007; Millan *et al*., 2014) **Southern Tethys** (Coccioni *et al*., 2014; Li *et al*., 2016; Ben Chaabane *et al*., 2019) **Atlantic** (Bralower *et al*., 1999; Erbacher *et al*., 2001; Wagner *et al*., 2008; Huber & Leckie, 2011; McAnena *et al*., 2013; Peybernes *et al*., 2013; Phelps *et al*., 2015; Caetano–Filho *et al.,* 2017; Huber *et al*., 2018; Matsumoto *et al*., 2023) **Pacific** (Price, 2003; Robinson *et al*., 2004; Ludvigson *et al.,* 2015; Navarro–Ramirez *et al*., 2015; Matsumoto *et al*., 2020)
5.	F–OAE, Faraoni Event	**Western Tethys** (Baudin, 2005; Baudin & Riquier, 2014; Rodríguez–Tovar & Uchman, 2017) **Southern Tethys** (Ammar & Layeb, 2021) **Atlantic** (Stein *et al*., 1989) **South Africa** (Brown *et al*., 1996) **North Sea** (Mutterlose & Ruffell, 1999) **Pacific** (Baudin *et al*., 1995; Jenkyns, 1995) **Argentina** (Tyson *et al*., 2005; Guler *et al*., 2013)
6.	W–OAE, Weissert Event	**Southern Tethys** (Bottini *et al*., 2018; Ammar & Layeb, 2021) **Western Tethys** (Moller *et al*., 2020) **Atlantic** (Moller *et al*., 2020)
Possible Oceanic Anoxic Events		
1.	Mid Cenomanian Event	**Western Tethys** (Coccioni & Galeotti, 2003)
2.	Mid Barremian Event	**Southern Tethys** (Talbi *et al*., 2021)
3.	Late Jurassic–early Cretaceous Event	**Boreal sea** (Rogov *et al*., 2020) **Panthalassic Ocean** (Nozaki *et al*., 2013) **Southern Tethys** (Arora *et al*., 2015) **Northern Tethys** (Carmeille *et al*., 2020)
4.	Middle–late Jurassic Event	**Western Tethys** (Martinez & Dera, 2015)

widely preserved as a black shale across Tethys with patchy occurrences in the South Atlantic, southern Indian and eastern Pacific Ocean basins; it is primarily linked with marine organic matter enrichment due to increased primary productivity (Bréhéret & Delamette, 1989; Bréhéret, 1994; Erbacher *et al.,* 1996; Wilson & Norris, 2001). The cause of the OAE 1d is explained from the ODP Site 1052. The Cyclic black shales in the uppermost Albian sequence are correlative to OAE 1d and correspond to an interval manifested by the collapse of upper water column stratification, which was caused by the intensification of mixing during winters and reduced stratification during summers (Petrizzo *et al.*, 2008).

The global and regional OAE records from India are very limited. Only one global Oceanic Anoxic Event, OAE 2 is recorded from the Indian successions. It is recorded from the two areas, (i). Chikkim Formation, Spiti Valley, (ii). Karai Shale Formation and Bhuvanagiri Formation, Cauvery Basin. In India the published records on regional OAEs (OAE 1b, OAE 1d and OAE 3) are available only from the Cretaceous successions of Cauvery Basin.

Possible OAEs and possible horizons in India

Possible OAE occurs in the mid–Cenomanian of the Tethys where it is associated with a positive carbon excursion (~1%), deposition of marine organic matter and an extinction event in the radiolarian (Erbacher *et al.,* 1996; Stoll & Schrag, 2000; Coccioni & Galeotti, 2003).

Within the same time period, benthic calcareous micro–organisms exhibit a steady reduction in both species diversity and faunal density (Coccioni *et al.*, 1995).

Apart from the above OAE, a Mid Barremian anoxic event (Talbi *et al.*, 2021), a late Jurassic–early Cretaceous anoxic event (Nozaki *et al.*, 2013; Arora *et al.*, 2015; Carmeille *et al.*, 2020; Rogov *et al*., 2020) and a Middle–late Jurassic OAE event (Martinez & Dera, 2015;) are also possible. To ascertain their regional or global extent, more studies are needed from the suitable successions around the world.

In Indian sedimentary sequences, the marine Mesozoic black shale, dark grey or glauconitic deposits falling in the additional possible OAEs time slice are mainly deposited in Spiti, Kutch and Cauvery basins. From the Kutch Basin, Pandey and Pathak (2016) showed the possible presence of the early Aptian sediments based on the ammonoid genera *Deshayesites* and *Australiceras* in the Ukra Mb. of the Bhuj Formation. These ammonoids were recorded from the green shales which is characteristic deposit of OAE in Shallower depths. For ascertaining the presence of OAE 1a in the Ukra Mb., geochemical studies and other marine fossil group studies are required from the green shales, which is key lithology to show the presence of OAE in an extreme marginal location. OAE 1b can be demarcated in Upper Mb. of the Bhuj Formation due to its age range and marine nature of deposits (Darji & Solanki, 2017). Predominantly, Rudramata shale Member of Jhuran Formation contains dark grey to black shales, which could be a possible horizon to study the late Jurassic OAE (Arora *et al.*, 2015) (Fig. 3).

The Tagling Formation (Lias) of Kioto Group, Spiti Valley mainly contains limestone with black shaley bands and ranges in age from late Triassic to early Jurassic. In this view the possibility of T–OAE in Tagling Formation could not be denied. The Spiti Formation (Callovian–Tithonian) mainly comprises black shale and remarks the presence of late Jurassic OAE. The overlying Giumal Formation (Berriasian–Aptian) mainly comprises sandstone with intercalations of black shales and these black shales can give signatures of Weissert event, Faraoni event and OAE 1a. Also, OAE 1b, OAE 1c, OAE 1d, OAE 2 and OAE 3 can be traced out in the Chikkim Formation (Cenomanian–early Maastrichtian) (Fig. 3).

From the Cauvery Basin, OAE 1b, OAE 1d, OAE 2 and OAE 3 have already been studied but the possibility of OAE 1c from Onshore and Offshore organic rich shaley successions are still present and can be distinguished in the Karai Formation (Albian to middle Turonian) of Uttatur Group on Onshore and from Andimadam Formation on Offshore. Still detailed study of the previously recorded oceanic anoxic events from the Cauvery Basin is required (Fig. 3).

CONCLUSION

In the last few years, in India, researches on oceanic anoxic events have been carried out by utilizing detailed biostratigraphy, stable isotopic studies, organic geochemistry and sedimentary facies studies of the geochemically significant organic–rich laminated black shales from the Mesozoic successions exposed in different basins. However, the integrated approach for OAE characterisation from the individual section is lacking. The purpose of this review paper is to provide a comprehensive introduction to Oceanic Anoxic Events and records of OAEs from the varied parts of India and find out the probable horizons from which these studies can be taken up in future. The review highlights the potentiality of the various regions from where the increasing number of studies would offer a much better understanding of the OAEs from Indian basins. The holistic approach for establishing OAE events from Indian sections is totally lacking. A few studies have been taken from the Cauvery Basin up to some extent, but from the other areas, the OAE studies are in a nascent stage. It is an author's hope that this comprehensively presented work will pave the ground for more research on OAEs from Indian sediments.

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