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Palaeoclimate reconstructions of the Middle Jurassic of Kachchh (western India): an integrated approach based on palaeoecological, oxygen isotopic, and clay mineralogical data

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Abstract

The Middle Jurassic sedimentary succession of the Kachchh Basin shows significant changes in lithology, faunal content and diversity across the Bathonian–Callovian boundary. The change in lithology from predominantly carbonates in the Middle and Late Bathonian to siliciclastics in the Callovian is accompanied by a drop in species diversity from high to moderate. Characteristic faunal elements of the Bathonian (corals, sponges, the bivalves *Eligmus* and members of the Opinae) are absent or rare in the Callovian. In contrast, Callovian sediments contain comparatively high proportions of nuculid bivalves. The clay mineral assemblage reveals prominent variations in the smectite vs. kaolinite abundance, especially during the Bathonian to Callovian transition. From the Bajocian to the Middle Bathonian, smectite becomes the dominant clay mineral and is nearly exclusively present in the Late Bathonian. Towards the Middle Callovian, its content gradually decreases and kaolinite becomes the dominant clay mineral. Illite generally is only a minor component throughout the Middle Jurassic. Based on these results, the Bajocian to Middle Bathonian time interval is interpreted to represent subtropical climatic conditions with seasonal droughts and a moderate supply of terrigenous clastics to the basin. The Late Bathonian was a period with a semi-arid climate, hot seasonal droughts and a minor input of terrigenous clastics. The increase in kaolinite contents in the Callovian suggests a subtropical humid climate with less prominent seasonal droughts and a higher input of siliclastics into the basin accompanied by a higher nutrient influx. Oxygen isotope ratios measured on Bathonian to early Callovian brachiopod shells give palaeotemperatures of 19–24 °C. Callovian to Oxfordian paleotemperatures calculated from oxygen isotopes measured on belemnite rostra range from 11 to 21 °C. The lower palaeotemperatures estimated from the oxygen isotopic composition of belemnite calcite are explained by assuming that the belemnites spent most of their life span in colder regions of the Malagassy Gulf and migrated into the warmer subtropical waters of the Kachchh Basin. Combining these various lines of evidence, the changes in lithology and faunal composition

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taking place in the Kachchh Basin during the Middle Jurassic appear to reflect largely a change towards increasing humidity rather than a distinct decrease in water temperature.

Keywords: Jurassic; India; Kachchh Basin; Palaeoclimate; Oxygen isotopes; Palaeoecology; Clay mineralogy

1. Introduction

Palaeoenvironmental reconstructions of ancient sedimentary successions commonly use a number of independent parameters such as lithology, sedimentary structures and sequences, fossil content, mineralogy, and geochemistry. Physical sedimentological parameters are preferentially used for environmental reconstruction (e.g., Reineck and Singh, 1980; Reading, 1996; Miall 1997; Einsele 2000). The palaeoecological interpretation of fossils yields additional evidence on depositional environments and palaeoclimate (e.g., Bosence and Allison, 1995; Brenchley and Harper, 1998). Oxygen isotope ratios of marine skeletons, especially those composed of low-magnesium calcite, are useful for palaeotemperature reconstruction, and clay minerals may indicate the palaeoclimate in the source area (Chamley, 1989). A combination of these various approaches can lead to a sound reconstruction of the palaeoclimate of a given stratigraphic unit.

The Kachchh Basin is located at the western margin of the Indian plate and has a well-developed succession of Jurassic sediments. Marine sedimentation in the Kachchh Basin started in the early Middle Jurassic in response to the opening of the Arabian Sea. As a result, marine waters of the Tethys inundated the Kachchh Basin and the Malagassy Gulf, which opened between Africa and Madagascar-India. The Middle Jurassic (Middle Bathonian to Callovian) sediments deposited in the Kachchh Basin represent one of the thickest sequences of this time span and contain a rich benthic and nektonic fauna belonging to the so-called Ethiopian faunal province (e.g. Hallam, 1975; Liu et al., 1998). The understanding of the sedimentary and climatic history of the Jurassic sequence of the Kachchh Basin is a key to understanding the evolution of the Malagassy Gulf, the opening of the Arabian Sea, and of the western Indian Ocean.

In the present paper, the palaeoclimatic relevance of the benthic macrofauna of the Bathonian–Callovian succession is discussed. In addition, oxygen isotope ratios measured on brachiopod and belemnite calcite are used to calculate palaeotemperatures for the shallow seas of the Kachchh Basin. Clay minerals have been used to interpret weathering conditions and palaeoclimate in the source area. An attempt has been made to integrate these investigations into a palaeoclimate model for the Kachchh Basin during the Bathonian–Callovian time interval.

2. Geological setting

The Kachchh Basin is a small sedimentary basin situated at the eastern margin of a southerly extension of the Neotethys, the so-called Malagassy Gulf, at a palaeo-latitude during the Middle Jurassic of around 33° S (Dercourt et al., 2000) (Fig. 1). The basin originated in the Late Triassic as an E-W directed rift basin, situated at the western margin of the Indian craton (e.g. Biswas, 1991). After a phase of terrestrial sedimentation in the Late Triassic and Early Jurassic, the basin was inundated by the sea in Bajocian times or even earlier (the oldest index fossil, the Upper Bajocian ammonite *Leptosphinctes*, being underlain by more than 300 m of so far undated mixed marine-terrestrial sediments (Fürsich et al., 2001). Lower Middle Jurassic (Bajocian–Middle Bathonian) sediments of the Jhurio Formation range from fluvial and coastal plain sediments to nearshore coarse-grained siliciclastics in landward sections and are carbonate-dominated in offshore areas. Carbonates are the characteristic deposits of the Upper Bathonian Patcham Formation in most of the sections, which extended from high energy coastal areas to open shelf settings well below storm wave base. These

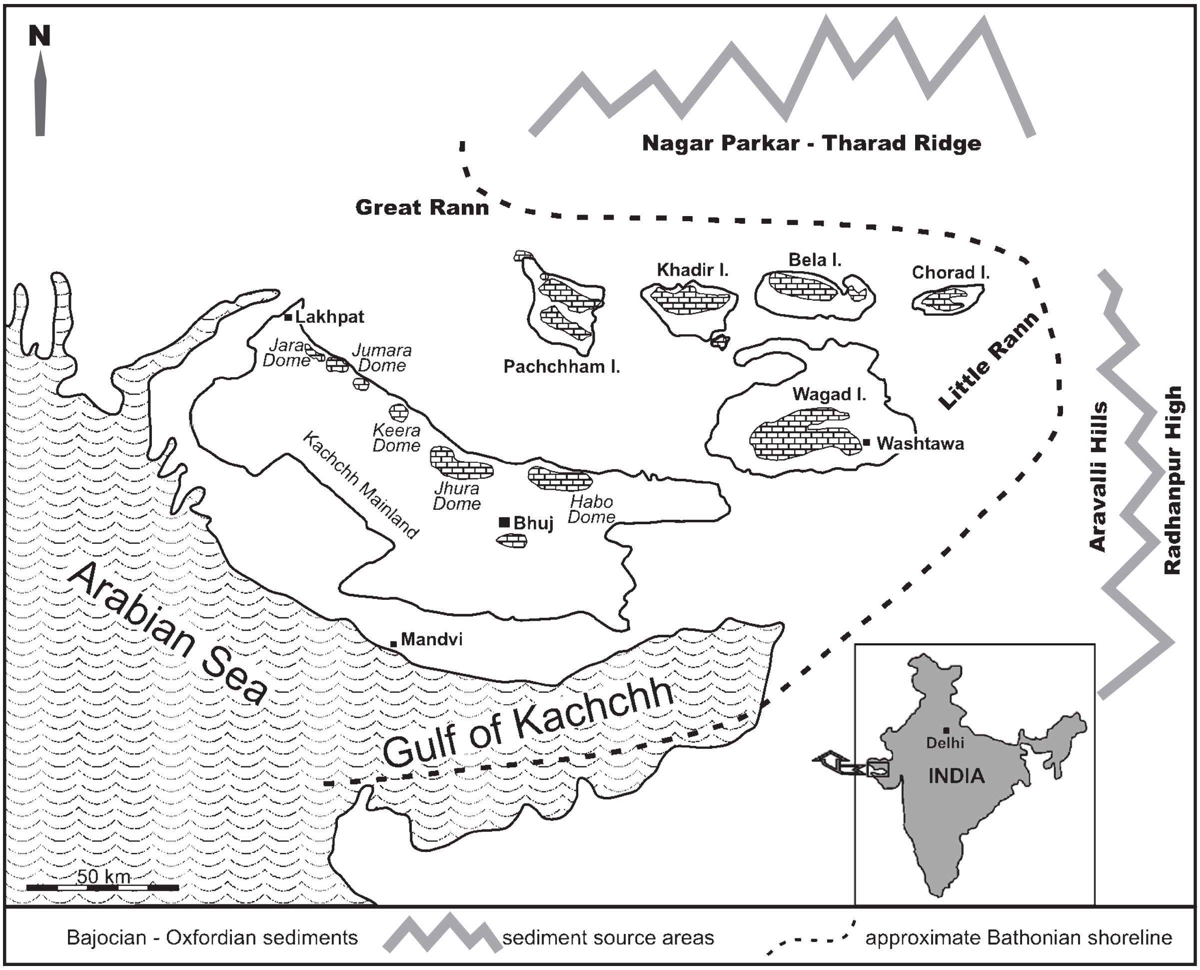


Fig. 1. Locality map and shape of the Kachchh Basin during the Middle Jurassic.

carbonate sediments are believed to have been deposited on a ramp (Fürsich et al., 2001, 2004). Sedimentation during the Callovian was essentially terrigenous clastic (Chari Formation). In more offshore areas towards the basin centre, silt- to silty clay-dominated sediments were deposited around mid-shelf depths. These deposits show occasional intercalations of sandstone bodies, which have been interpreted as indicating phases of shallowing (Fürsich et al., 2001). Sea-level was highest during the Oxfordian and resulted in the deposition of the Dhosa Oolite, a characteristic marker horizon in most areas of the Kachchh Basin (Fürsich et al., 1992; Singh, 1989). Post-Oxfordian deposits of the Kachchh Basin are essentially sandy sediments which gradually filled the basin until the Albian.

The predominance of carbonates during the late Middle and Late Bathonian (upper part of the Jhurio Formation and Patcham Formation; Fig. 2) does not coincide with a general shift to more offshore environments, because the carbonates extend from nearshore, shallow water environments to mid-shelf areas of the basin centre (Fürsich et al., 2004). A more likely explanation for widespread carbonate deposition during this time interval is a reduced input of terrigenous clastic sediments into the basin from the hinterland due to tectonic

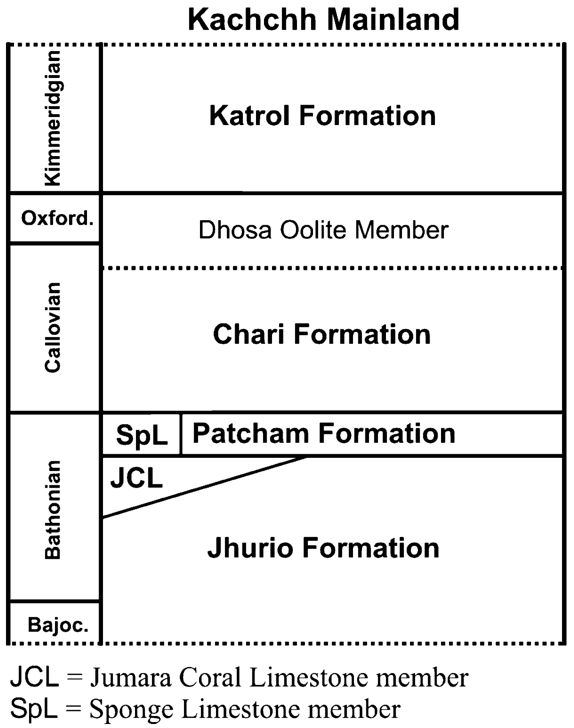


Fig. 2. Main lithostratigraphic units of the Middle and lower Upper Jurassic rock succession of Kachchh Mainland.

quiescence and a low relief and/or due to an increasing aridity.

3. Sections and field sampling

For the present investigations samples of belemnites and brachiopods were collected mainly from two sections, namely the Jumara Dome section and the Jhura Dome section. Some additional samples were obtained from the Jara Dome section (Fig. 1). A short description of these sections is given below. The lithostratigraphic units are shown in Fig. 2.

3.1. Jumara Dome section

The Middle Bathonian to Oxfordian succession is about 430 m thick, whereby the lower part is represented by carbonate deposits, while the upper part is made up of argillaceous-silty sediments with few intercalations of sandstones. The succession starts with 17 m of well-bedded micritic limestones and marls of the Jumara Coral Limestone member of the Jhurio Formation, characterised by highly diverse coral meadows (Fürsich et al., 1994b). A several metres thick marker bed consisting of a sandy echinoderm packstone separates this unit from the Sponge Limestone member of the Patcham Formation. This is an approximately 32 m thick package of well-bedded marly wackestones rich in siliceous sponges and brachiopods (Mehl and Fürsich, 1997). The following Chari Formation (Callovian) is composed of 370 m of fine-grained siliciclastics, except for two intercalations of coarsening-upward sandstone bodies, thoroughly bioturbated by *Zoophycos*. The succession of argillaceous silt is repeatedly interrupted by levels with reworked and bored concretions which indicate breaks in sedimentation (Fürsich et al., 1992). The 4–5 m thick Dhosa Oolite member (Oxfordian) at the top of the Chari Formation is characterised by ferruginous ooids, concentrations of fossils and numerous features of highly discontinuous sedimentation such as hardgrounds, winnowed burrow networks and reworked concretions (Singh, 1989; Fürsich et al., 1992). The Jumara section occupies a position close to the centre of the Kachchh Basin (e.g., Biswas, 1980; Fig. 1).

3.2. Jhura Dome section

The Middle to lower Upper Jurassic succession of the Jhura Dome is about 550 m thick. It occupies an intermediate position along an onshore–offshore transect. The exposed part of the Jhurio Formation is much thicker (212 m) than at the Jumara Dome and most likely not only comprises the Bajocian and Bathonian but also parts of the Aalenian. It is a mixed succession of nodular wackestones, well-bedded packstones, marly silts, and bioclastic ferruginous oolites (grainstones and rudstones). The Patcham Formation is represented, as at the Jumara Dome, by the Sponge Limestone member. The overlying Chari Formation (355 m) is more sandy in nature than at the Jumara Dome with seven intercalations of sandstone bodies between the argillaceous to silty bulk sediment. The trace fossil assemblage (e.g. *Ophiomorpha*) and primary sedimentary structures such as large-scale trough cross-stratification mostly in the sandstone units indicate shallower depositional environments than equivalent horizons at the Jumara Dome (Fürsich et al., 2001). The Dhosa Oolite member is similar in nature to that of the Jumara Dome, rich in ferruginous ooids and exhibiting signs of condensation (Fürsich et al., 1992).

3.3. Jara Dome section

Four additional fossil samples for isotopic studies were collected from the Jara Dome section which, during the Jurassic, occupied a yet farther offshore

Table 1
Carbon and oxygen isotopes of Bathonian–Oxfordian non-luminescent brachiopod and bivalve shells and belemnite rostra from the Kachchh Basin

Sample	Position (m)	Stratigraphic level	Locality	$\delta^{13}C$ (‰ V-PDB)	$\delta^{18}O$ (‰ V-PDB)	Temperature (°C)
Jh 9b bel	530	Chari Fm	Jhura Dome	1.80	0.26	11.0
Jh 9a bel	530	Chari Fm	Jhura Dome	0.61	−0.86	15.4
Jh 8b bel	525	Chari Fm	Jhura Dome	0.59	−1.09	16.4
Jh 8a bel	525	Chari Fm	Jhura Dome	0.65	−1.66	18.8
Jh 7 bel	497	Chari Fm	Jhura Dome	1.02	−1.02	16.1
Jh 6 bel	487	Chari Fm	Jhura Dome	1.09	−1.47	18.0
Jm 13c bel	382	Chari Fm	Jumara Dome	0.47	−0.88	15.5
Jm 13b bel	382	Chari Fm	Jumara Dome	0.19	−0.91	15.6
Jm 13a bel	382	Chari Fm	Jumara Dome	0.29	−1.34	17.4
Jm 12c bel	318	Chari Fm	Jumara Dome	0.50	−0.94	15.8
Jm 12b bel	318	Chari Fm	Jumara Dome	0.35	−1.10	16.4
Jm 12a bel	318	Chari Fm	Jumara Dome	0.14	−1.11	16.5
Jm 11 bel	312	Chari Fm	Jumara Dome	0.47	−0.35	13.4
Jm 10 bel	297	Chari Fm	Jumara Dome	−0.46	−2.09	20.6
Jh 5 bel	296	Chari Fm	Jhura Dome	0.27	−1.00	16.0
Jm 9 bel	292	Chari Fm	Jumara Dome	0.12	−0.95	15.8
Jm 8 bel	273	Chari Fm	Jumara Dome	0.54	−1.95	20.1
Jm 7b bel	265	Chari Fm	Jumara Dome	0.69	−0.95	15.8
Jm 7a bel	265	Chari Fm	Jumara Dome	−0.08	−1.07	16.3
Jm 6b bel	263	Chari Fm	Jumara Dome	0.93	−0.68	14.7
Jm 6a bel	263	Chari Fm	Jumara Dome	0.05	−1.47	18.0
Ja 3 bel	257	Chari Fm	Jara Dome	0.37	−1.35	17.5
Jm 5c bel	254	Chari Fm	Jumara Dome	0.06	−0.73	14.9
Jm 5b bel	254	Chari Fm	Jumara Dome	0.81	−0.73	14.9
Jm 5a bel	254	Chari Fm	Jumara Dome	0.17	−0.92	15.7
Ja 2 brach	252	Chari Fm	Jara Dome	1.82	−2.33	21.7
Jm 4b bel	245	Chari Fm	Jumara Dome	−0.20	−0.91	15.6
Jm 4a bel	245	Chari Fm	Jumara Dome	0.19	−1.46	17.9
Jm 3 biv	243	Chari Fm	Jumara Dome	1.67	−1.97	20.1
Jm 2c bel	233	Chari Fm	Jumara Dome	1.65	−0.59	14.3
Jm 2b bel	233	Chari Fm	Jumara Dome	1.76	−0.92	15.7
Jm 2a bel	233	Chari Fm	Jumara Dome	0.80	−1.69	18.9
Ja 1c bel	231	Chari Fm	Jara Dome	0.26	−1.54	18.3
Ja 1b bel	231	Chari Fm	Jara Dome	0.14	−1.21	16.9
Ja 1a bel	231	Chari Fm	Jara Dome	−0.05	−1.07	16.3
Jm 1b bel	221	Chari Fm	Jumara Dome	0.81	−0.95	15.8
Jm 1a bel	221	Chari Fm	Jumara Dome	0.54	−1.04	16.2
Jh 4 brach	167	Chari Fm	Jhura Dome	0.01	−2.04	20.4
Jh 3b brach	141	Patcham Fm	Jhura Dome	0.44	−2.17	21.0
Jh 3a brach	141	Patcham Fm	Jhura Dome	0.48	−2.37	21.9
Jh 2 brach	125	Patcham Fm	Jhura Dome	0.47	−2.86	24.2
Jh 1 brach	90	Patcham Fm	Jhura Dome	1.12	−1.84	19.6

Palaeotemperatures calculated using the equation given by Anderson and Arthur (1983) and assuming an ice-free Jurassic world ($\delta^{18}O_{sea}=-1$‰ V-SMOW; bel=belemnite; brach=brachiopod; biv=bivalve.

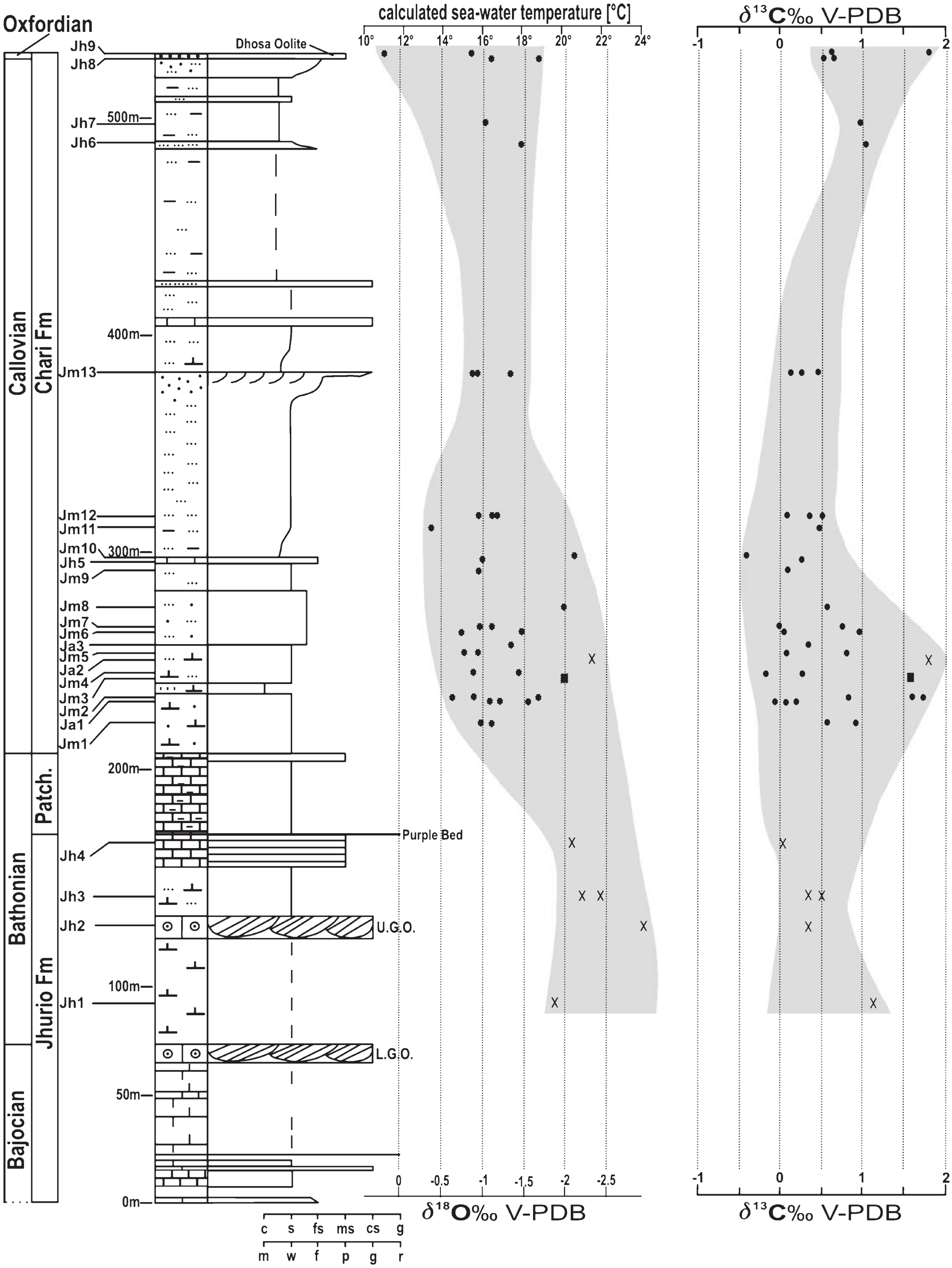


Fig. 3. $\delta^{18}O$, $\delta^{13}C$ values and palaeotemperatures of the Bajocian–Oxfordian rock succession of Kachchh Mainland. Oxf.: Oxfordian; c: clay; s: silt; fs: fine sand; ms: medium sand; cs: coarse sand; g: gravel; m: mudstone; w: wackestone; f: floatstone; p: packstone; g: grainstone; r: rudstone. For key see Fig. 4.

position than the Jumara Dome. At the Jara Dome, the section starts in the lower Chari Formation. Most of the section comprises argillaceous silt with levels of ferruginous concretions and several horizons at which the concretions were reworked, bored and encrusted. The intercalated sandstones are fine-grained and highly bioturbated by *Zoophycos*. The Dhosa Oolite member exhibits highly complex features of non-sedimentation, erosion, and synsedimentary cementation (Fürsich et al., 1992).

Oxygen isotope studies are generally carried out on skeletons that are composed of low Mg-calcite (LMC), as LMC is the stable polymorph of calcium carbonate and least prone to diagenetic alteration.

The basic aim was to collect and analyse belemnites and brachiopods from the same bed. It was presumed that belemnites, having a nektonic mode of life, would give surface water palaeotemperatures, and brachiopods, living on the sea floor, would give sea bottom palaeotemperatures. However, this plan of sampling could not be followed successfully, because the distribution of the two groups of organisms was too uneven to allow sampling at regular intervals. In most samples, belemnites did not co-occur with brachiopods. Moreover no belemnites were present in pre-Callovian sediments. Due to the uneven distribution, brachiopods and belemnites were collected from occasional fossil-rich bands, at irregular intervals.

Sampling for clay mineral studies was mainly done in the Jhura Dome section (31 samples). This section has a relatively high percentage of terrigenous clastics also in the lower part of the section. In the Jumara Dome section five samples were collected from different stratigraphic levels to compare them with those from the Jhura Dome. Mostly fine-grained layers consisting of mudstone, siltstone, marl, or calcareous mudstone were sampled. Twenty-one samples are from the Chari Formation, 10 from the Patcham Formation, and six from the Jhurio Formation (Table 2).

4. Methodology

4.1. Stable Isotopes

Belemnite rostra and brachiopod shells were carefully cleaned removing any matrix adhering to them. All belemnites and brachiopods were investigated using cathodoluminescence microscopy in order to test for diagenetic recrystallisation. Many of the fossil hard parts were luminescent and had to be rejected as only non-luminescent shells were accepted for stable isotope analysis. Thirty-two non-luminescent skeletons are from the Chari Formation (8 from the Jhura Dome, 19 from the Jumara Dome, and 5 from the Jara Dome). Four specimen are from the Jhurio Formation of the Jhura Dome (Table 1). Six analyses were carried out on brachiopod shells, 29 on belemnite rostra, and one on an oyster shell (*Bilobissa alimena*). Carbonate powders were collected using a microdrill. Since the brachiopod shells were in many cases too thin to be sampled, only a limited number of the large collection of fossils could be used for the isotope study.

Carbon and oxygen isotopes were measured on carbonate powders using an on-line carbonate preparation system (Carbo-Kiel I) connected to a ThermoFinnigan 252 mass-spectrometer at the Institute of Geology and Mineralogy, University of Erlangen-Nürnberg. All isotopic values were reported in the standard δ-notation in per mil relative to V-PDB. Reproducibility of the isotope measurements was controlled by replicate analyses of NBS19 and laboratory standards and was better than ±0.06‰ (1σ) for both carbon and oxygen isotopes.

4.2. Clay mineralogy

Samples for clay mineral studies were gently ground to fine powder and sieved through a 63 μm sieve. The finer fraction was used for separation of the clay fraction (<2 μm) in small settling tubes using

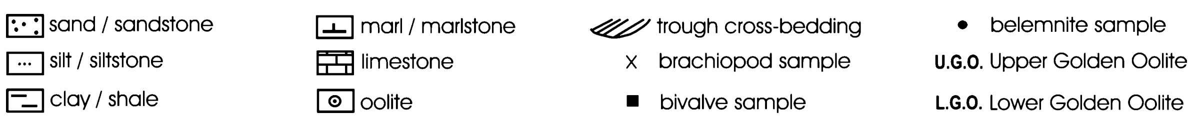


Fig. 4. Key to Figs. 3 and 5.

Stoke's Law. No acid treatment of the sample was done, as often unstable chlorite may be dissolved in the process. Oriented clay fraction (<2 μm) slides were made for clay mineral identification. A Siemens X-ray diffractometer with CuKα radiation, graphite secondary monochromator, a step size of 0.02° 2θ, and a counting time of 2 s/step was used. Measurements for natural, Mg-saturated, glycolated, and heated (350–550 °C) samples of oriented clay mineral slides were carried out between 2° and 32° 2θ. Semi-quantitative estimation of clay minerals was done on the Mg-saturated, glycolated samples, using the software Winfit and following the procedures of Moore and Reynolds (1989).

Table 2
Clay mineral composition of sediment samples from the Bajocian–Oxfordian rock succession of the Kachchh Mainland

Sample	Formation	Smectite	Illite	Kaolinite	Smectite (%)	Illite (%)	Kaolinite (%)	Smectite/Kaolinite
Jhura Dome								
328	Chari	430	157	1954	17	6	77	18
256	Chari	326	23	189	61	4	35	63
327	Chari	147	78	532	19	10	70	22
326	Chari	1592	242	591	66	10	24	73
250	Chari	96	28	234	27	8	65	29
325	Chari	1017	104	1402	40	4	56	42
246	Chari	61	31	254	18	9	73	19
323	Chari	138	19	94	55	8	37	59
245	Chari	1140	72	404	71	4	25	74
320	Chari	18	83	912	2	8	90	2
240	Chari	0	99	169	0	37	63	0
315	Chari	10	76	1546	1	5	95	1
243	Chari	299	6	209	58	1	41	59
237	Chari	45	104	1187	3	8	89	4
157	Chari	577	106	481	50	9	41	55
150	Chari	211	41	218	45	9	46	49
236	Chari	1715	171	534	71	7	22	76
232	Chari	1194	35	286	79	2	19	81
230	Chari	475	33	132	74	5	21	78
228	Patcham	258	14	57	78	4	17	82
227	Patcham	892	33	74	89	3	7	92
226	Patcham	561	21	6	95	4	1	99
225	Patcham	1178	30	12	97	2	1	99
224	Patcham	1624	43	6	97	3	0	100
223	Patcham	1318	39	28	95	3	2	98
216	Patcham	1963	36	60	95	2	3	97
215	Patcham	170	3	14	91	2	7	92
214	Patcham	315	16	2	95	5	1	99
212	Patcham	1283	14	25	97	1	2	98
207	Jhurio	337	6	31	90	2	8	92
209	Jhurio	803	15	46	93	2	5	95
205	Jhurio	1061	50	209	80	4	16	84
206	Jhurio	786	41	352	67	3	30	69
165	Jhurio	105	47	202	30	13	57	34
161	Jhurio	75	79	199	21	22	56	27
Jumara Dome								
274	Chari	1417	43	282	81	2	16	83
277	Chari	1455	136	20	90	8	1	99
278	Patcham	1646	62	29	95	4	2	98
311	Patcham	837	31	27	94	3	3	97
89	Jhurio	167	19	233	40	5	56	42

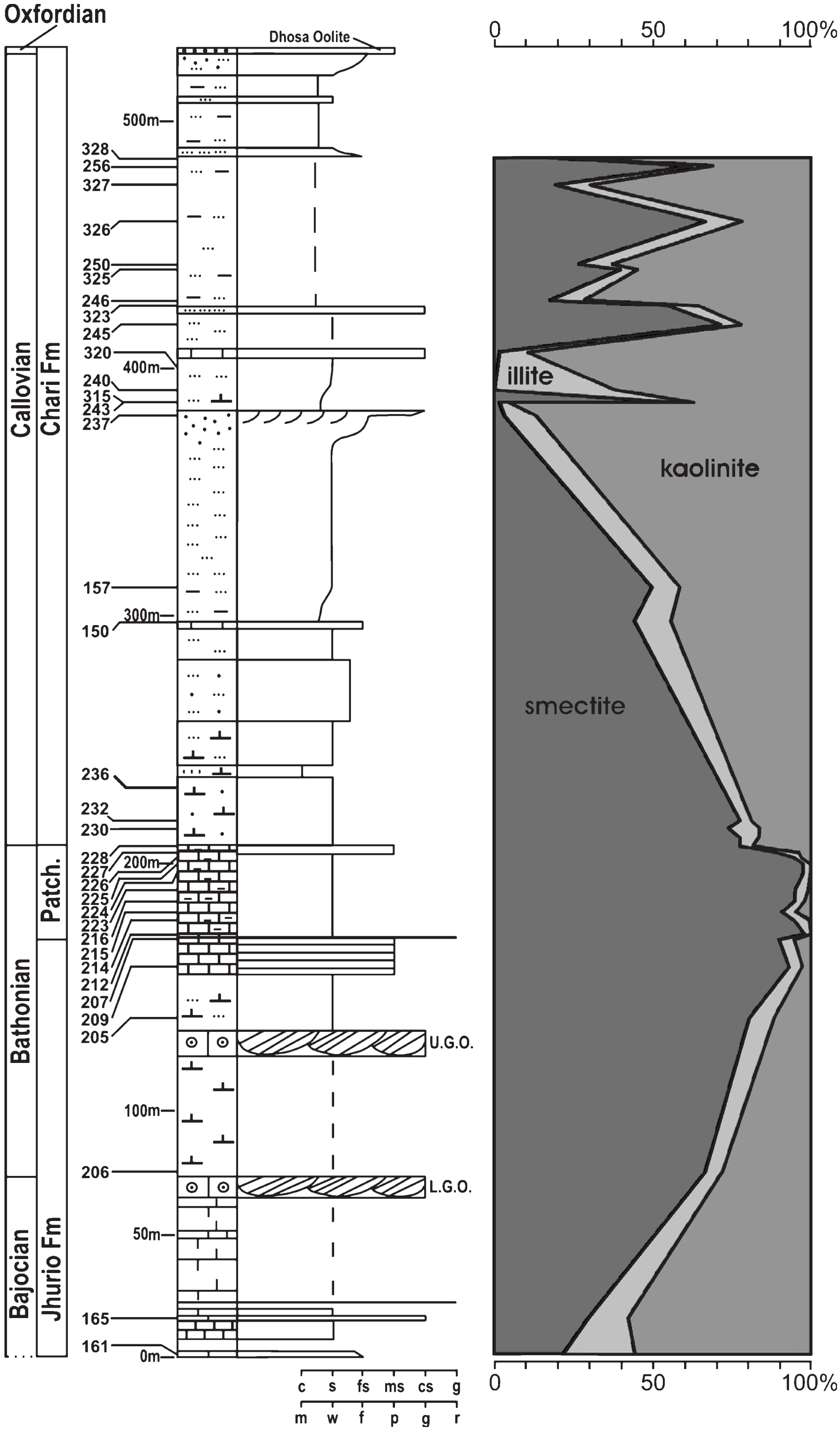


Fig. 5. Clay mineralogical composition of the Bajocian–Oxfordian rock succession of Kachchh Mainland. c: clay; s: silt; fs: fine sand; ms: medium sand; cs: coarse sand; g: gravel; m: mudstone; w: wackestone; f: floatstone; p: packstone; g: grainstone; r: rudstone. For key see Fig. 4.

5. Results

5.1. Stable isotopes

Most of the investigated brachiopod samples are from different stratigraphic levels of the upper Jhurio Formation, one brachiopod and one bivalve specimen are from the lower part of the Chari Formation. None of the numerous samples from the Patcham Formation proved suitable for stable isotope analysis. The belemnites are from different stratigraphic levels of the Chari Formation.

The oxygen and carbon isotope values of brachiopods and belemnites are given in Table 1 and shown in Figs. 3 and 4. The carbon isotope values of the brachiopods from the Jhurio Formation range from 0‰ to +1.1‰ with an average δ^{13}C value of +0.5‰. The brachiopod shell from the Chari Formation has a carbon isotope value of +1.8‰. The oxygen isotope ratios of the brachiopods from the Jhurio Formation range from −2.8‰ to −1.8‰ with an average value of −2.3‰. The specimen from the Chari Formation shows a δ^{18}O value of −2.3‰. The belemnite rostra have δ^{18}O and δ^{13}C values ranging from −2.1‰ to −0.4‰ and −0.5‰ to +1.8‰, respectively. Average δ^{18}O and δ^{13}C values are -1.1 ± 0.4‰ (±1 s.d.) and $+0.5\pm0.5$‰, respectively.

5.2. Clay minerals

The relative proportions of clay minerals of all samples are given in Table 2, along with smectite–kaolinite ratios. The data is plotted along with lithology for the Jumara Dome and Jhura Dome sections to establish stratigraphic trends and to assess the reasons for the changes in the clay mineral composition (Fig. 5). Examples of diffractograms are given in Fig. 6.

Only three clay mineral groups, namely smectite, kaolinite and illite, are present in the studied samples showing prominent stratigraphic changes. Significantly, chlorite is absent in all the samples. Illite is present in most of the samples but usually in small proportion, except for a few samples in which the illite content is high. Smectite and kaolinite are the main minerals showing strong and distinctive variation in their relative proportions.

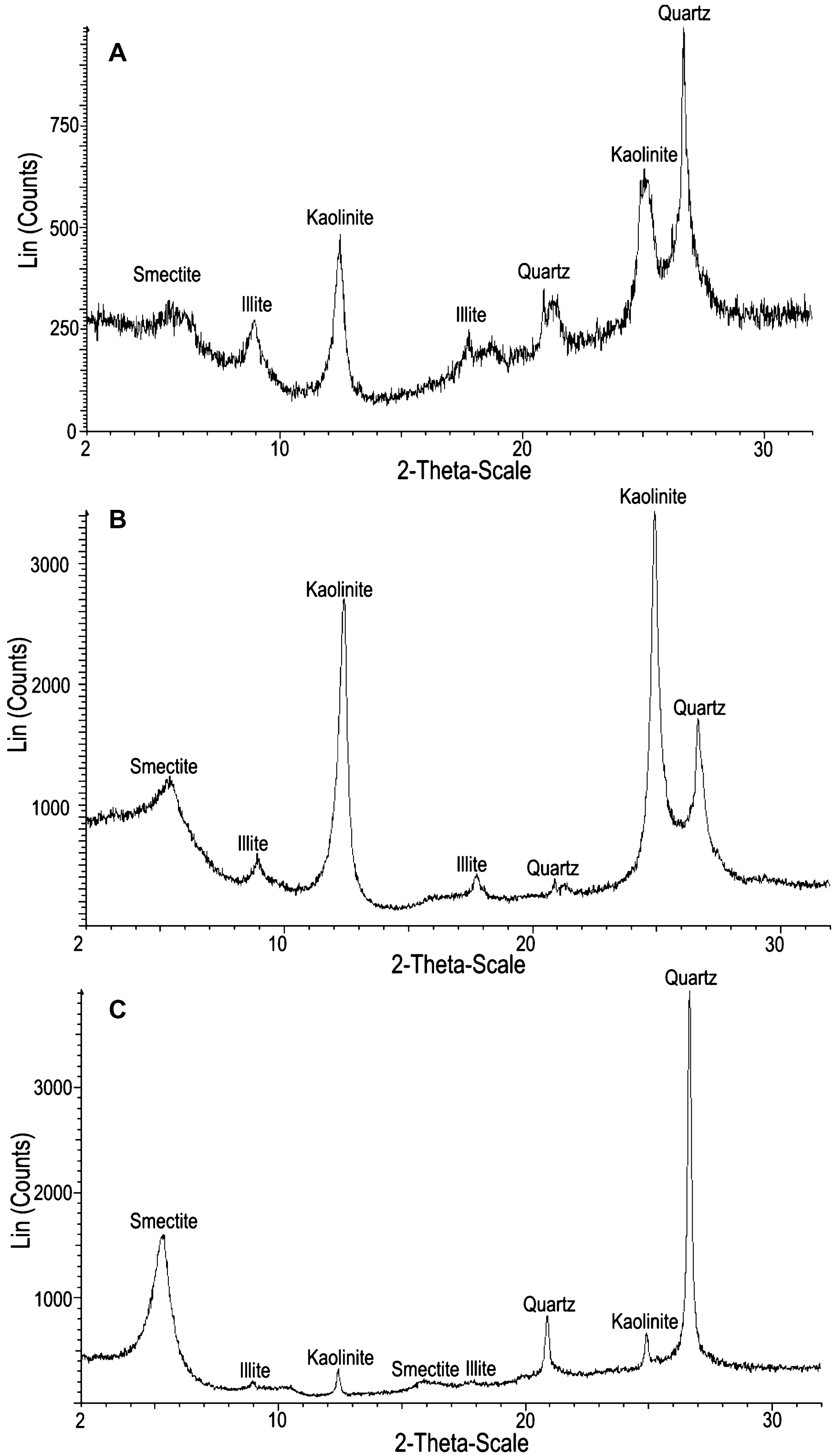
In the Jhura Dome section, the lowermost part of the Jhurio Formation is made up of equal proportions of smectite and kaolinite with illite being a minor constituent (Fig. 5). Towards the upper part, the smectite content gradually increases. The Patcham Formation is dominated by smectite with negligible amounts of kaolinite and illite (Fig. 5). The Chari Formation is low in illite and the content of smectite and kaolinite varies reciprocally. The Chari Formation can be subdivided into two clay mineral assemblage zones. The lower part is rich in smectite with moderate kaolinite content. The kaolinite content increases towards the middle part of the Chari Formation and becomes the dominant clay mineral. The upper part of the Chari Formation shows fluctuating proportions of kaolinite and smectite, though kaolinite is dominant (Fig. 5). Average clay mineral percentages for the different stratigraphic units of the Jhura Dome section are given in Table 2.

In the Jumara Dome section, only five samples were investigated. The sample from the Jhurio Formation has roughly equal proportions of smectite and kaolinite. The Patcham Formation samples are predominantly made up of smectite and very little kaolinite. In the sample from the Chari Formation smectite also prevails. The illite content is low in all samples. Although the number of samples from the Jumara Dome is low, the stratigraphic change in clay mineral composition is comparable to that of the Jhura Dome section (Table 2).

6. Discussion

As mentioned earlier (Fürsich et al., 2004), there are distinct lithological and benthic faunal changes in the Middle Jurassic of the Kachchh Basin, taking place around the boundary between the Patcham and Chari formations, which corresponds to the Bathonian–Callovian boundary (Callomon, 1993). Some of the changes in the faunal composition between the

Fig. 6. Diffractograms of clay mineralogical samples from the Jhura Dome. (A) Sample 161 characteristic of subtropical conditions; Jhurio Formation (Bajocian). (B) Sample 325 characteristic of subtropical conditions; upper Chari Formation (Upper Callovian). (C) Sample 216 characteristic of semi-arid conditions; Patcham Formation (Upper Bathonian). For position of samples within the section see Fig. 5.


A
Lin (Counts)
2-Theta-Scale
Smectite
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Kaolinite
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B
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Illite
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C
Smectite
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Kaolinite
Quartz

two formations appear to be related to changes in the palaeoclimate of the area. Thus, before discussing the results of isotopic and clay mineral studies, a short summary of the ecological and palaeoclimatic changes based on the sedimentological and faunal studies in the Middle Jurassic of the Kachchh Basin is given (see Fig. 7).

6.1. Palaeoecological and sedimentological evidence for climatic shift

A quantitative palaeoecological study of the Bajocian to Oxfordian biota of the Kachchh Basin has been combined with a facies analysis to reconstruct the palaeoecological history of the Kachchh Basin (Fürsich et al., 2004; Fürsich et al., in press and unpublished data). The benthic macrofaunal groups studied in the succession were mainly bivalves along with brachiopods, gastropods, and corals.

The predominance of offshore carbonate sediments of the Jhurio and Patcham formations (Bajocian–Bathonian) can be explained by a phase of tectonic quiescence or by semi-arid to arid climatic conditions. The latter factor not only reduced the input of siliciclastic material into the basin but due to high water temperatures favoured biologically mediated precipitation of calcium carbonate in sea-water. The analysis of the benthic macrofauna of the Kachchh Basin suggests that the carbonate phases were largely temperature-regulated and that climatic conditions within the basin changed from warm during the Bajocian–Bathonian (Jhurio and Patcham formations) to cooler in the Callovian–Oxfordian (Chari Formation) (Fürsich et al., 2004). This interpretation is based on the distribution pattern of corals and of some bivalves. In the late Middle Bathonian of Jumara Dome a high diversity coral fauna, represented by more than 60 taxa, has been documented (e.g. Fürsich et al., 1994b; Pandey and Fürsich, 2001). The corals are generally of only small size, and did not construct reefs but merely meadows on the soft sea floor. The lack of reef structures may be due to the low energy, turbid, and poorly lit conditions. The great abundance and diversity of reef corals in the late Middle Bathonian despite the relatively large water depth (middle shelf) at which they grew suggests optimal water temperature between 23 and 28 °C (Fagerstrom, 1987).

Corals are also found throughout the Callovian of the Kachchh Basin, but only at a single level they form small monospecific or near-monospecific patch reefs. Elsewhere, they occur in low abundance and very low diversity (Pandey and Fürsich, 2001).

Moreover, several bivalves associated with the Bathonian coral horizons are restricted in their distribution pattern within the basin to these levels. These bivalves belong to the subfamily Opinae of the family

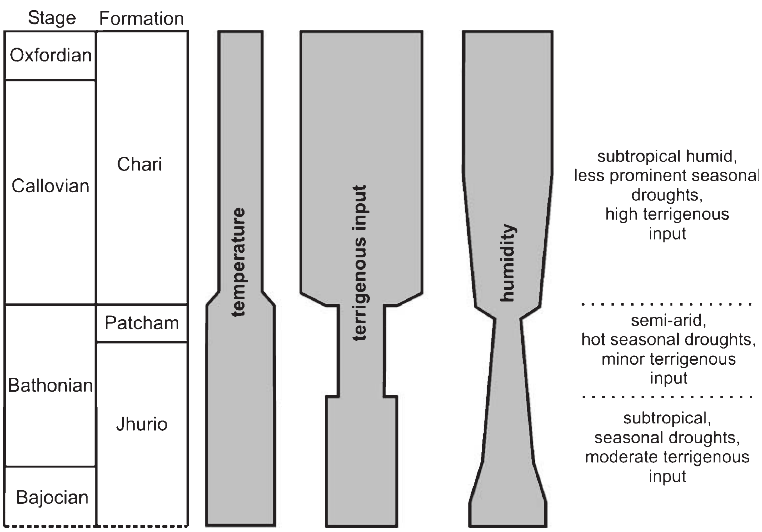

Fig. 7. Synopsis of palaeoclimatic (temperature, humidity, run-off) changes in the Middle Jurassic of the Kachchh Basin, based on palaeoecological, clay mineralogical, and oxygen isotopic data.

Astartidae (*Coelopis (C.) pulchella*, *C. (C.) ceratoides*, *C. (C.) deshayesi*, *Opis (Pachyopis) ganeshi*, and *O. (Trigonopis) acuta*; Fig. 8; see also Fürsich et al., 2000). In the Middle Jurassic, members of this subfamily had the peak of their distribution in tropical shelf carbonate environments of the Tethys. The occurrence of three subgenera and five species of this group in the Bathonian of Kachchh suggests that, at least in the late Middle Bathonian, tropical waters of the Tethys reached the Malagassy Gulf and extended into the Kachchh Basin and that the area experienced a tropical to subtropical climate.

Supportive evidence for a tropical climate during the Bathonian comes also from another bivalve genus, i.e. *Eligmus*, which is represented in Kachchh by the species *E. rollandi* (Fig. 8a). The oyster-like *Eligmus* is a relatively short-ranged bivalve genus which lived byssally attached on the substrate. It occurs exclusively in the Jhurio Formation (Bathonian) of the Jumara Dome, but there in so great numbers that it dominates two benthic associations and formed storm-reworked shell beds (Fürsich et al., 2004). The genus is largely restricted to the tropical belt occurring, for example, in large numbers in the Middle Jurassic of the Middle East, eastern and northern Africa (e.g. Howarth and Morris, 1998; Ahmad, 1999). Its expansion into higher latitudes for restricted time intervals such as into Normandy (France) in the north (e.g. Heinze, 1996) or the Kachchh Basin in the south can be most easily explained by a corresponding spread of tropical waters into these areas (Liu et al., 1998) accompanied by an increase in palaeotemperatures.

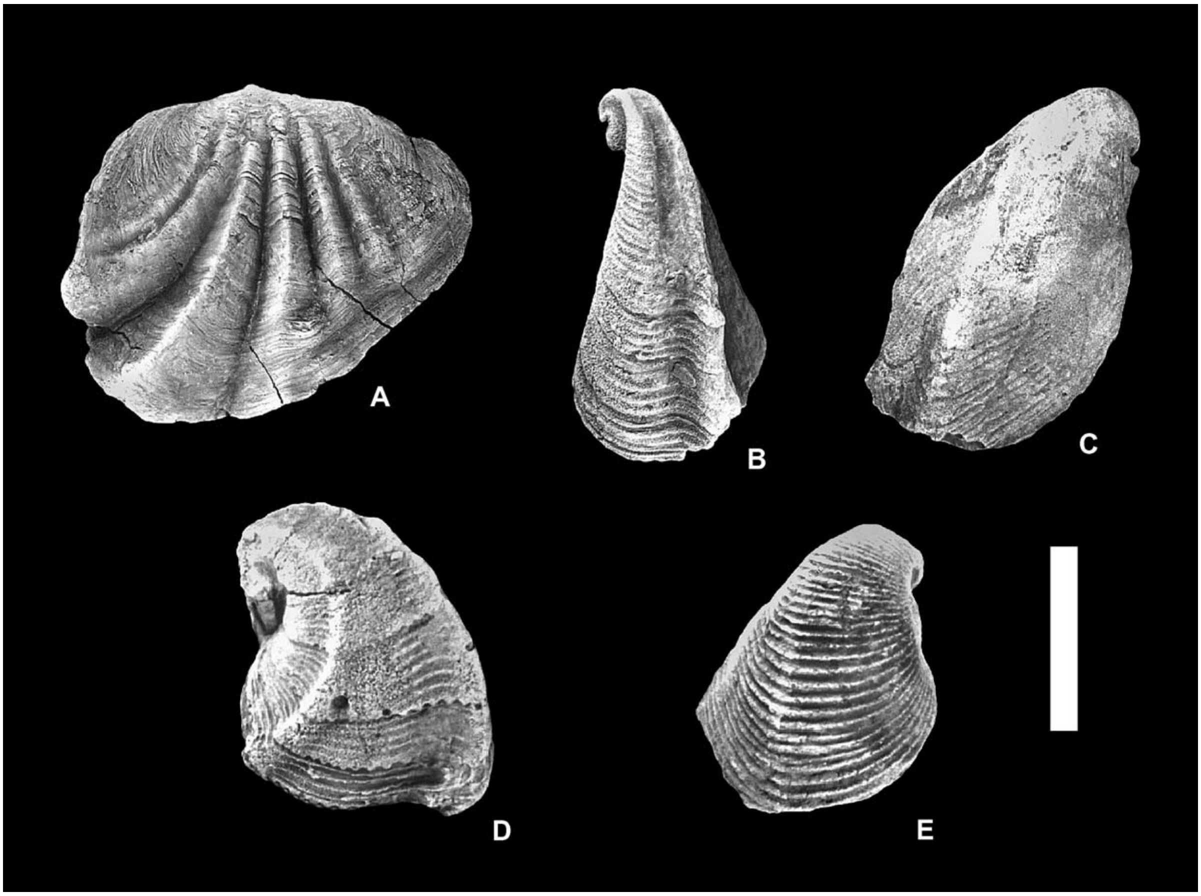

Fig. 8. Characteristic taxa of the Middle Bathonian Coral Limestone member (Jhurio Formation) of the Jumara Dome, interpreted as tropical faunal elements. (A) *Eligmus rollandi* Douville; (B) *Coelopis (C.) deshayesi* (Morris and Lycett); (C) *Opis (Trigonopis) acuta* Fürsich, Heinze and Jaitly; (D) *Coelopis (C.) ceratoides* (Laube); (E) *Opis (Pachyopis) ganeshi* Fürsich, Heinze and Jaitly. Scale bar: 1 cm.

Another important line of evidence for tropical climatic conditions is the high diversity of the benthic macrofauna in the Middle Bathonian coral meadows at the Jumara Dome locality. With more than 80 taxa, most of them bivalves and gastropods, the alpha diversity is more than twice that developed at any other stratigraphic level in the Callovian–Oxfordian Chari Formation of the Kachchh Basin. Pronounced time-averaging, a plausible explanation for such a diversity peak, can be ruled out judging from the taphonomic signatures of the skeletal elements (Fürsich et al., 1994b). Similarly, the Late Bathonian sponge meadows at the Jumara Dome (Mehl and Fürsich, 1997) contain, in addition to at least 11 taxa of "lithistid", hexactinellid and calcareous sponges, more than 30 taxa of associated macrobenthic faunal elements (bivalves, brachiopods, broyzoans, serpulids, crinoids, echinoids, and corals). Thus, they reflect a comparatively high diversity considering the soft carbonate substrate.

The low coral diversity in the Callovian partly reflects unsuitable substrate conditions (muddy softgrounds and shifting sandy substrates) and turbid waters. However, the existence of numerous concretion levels in the Callovian succession, which contain syndepositionally reworked and bored concretions (Fürsich et al., 1992), indicate the repeated occurrence of omission phases when relatively clear water and firmer substrate conditions suitable for coral growth existed. Thus, the lack of extended coral growth events in the Callovian appears to be due to additional limiting factors such as lowered temperatures.

In the Callovian–Oxfordian Chari Formation, carbonates are scarce. Offshore environments in which, at comparable depths, carbonate muds are deposited in the Middle and Late Bathonian were characterised by argillaceous-silty substrates. Large deltaic sand bodies existed in the eastern part of the basin (e.g. Wagad Dome; Deshpande and Merh, 1980) and are evidence of increased sediment input into the basin. The faunal composition of the Chari Formation differs distinctly from that of the Jhurio and Patcham formations. The most conspicuous feature of Callovian benthic fauna is the abundance of deposit-feeding nuculid bivalves (Fürsich et al., 2004), which indicates a greater influx of nutrients into the basin, most likely in response to cooler, more humid conditions. The alpha diversity of the benthic associations nowhere reaches the levels of the Bathonian coral meadows.

The time span of the Bajocian to Bathonian appears to have witnessed alternating humid and semi-arid conditions: Periods of increased rainfall may be suggested by sandstone packages in nearshore areas, which reflect increased terrigenous input by rivers, and heavily rooted, non-marine sediments. Phases of increased freshwater input are also indicated by widespread brackish water faunas, dominated by euryhaline taxa such as *Jurassicorbula*, *Eomiodon, Protocardia,* and *Bakevellia* in the Bajocian to Lower Bathonian sediments deposited in nearshore areas (e.g., Fürsich et al., 1994a). Semi-arid conditions, on the contrary, are indicated by red beds, and caliche horizons, which are widespread in Aalenian–Bajocian sediments of the island belt (Fig. 1).

In summary, sedimentary and faunal evidence suggest a change of palaeoclimate, especially in term of rainfall intensity around the Bathonian–Callovian boundary. In Bajocian to Bathonian times, phases of semi-arid conditions coupled with a low terrigenous clastic input and increased circulation of tropical water masses from the Tethys led to deposition of carbonate muds and the temporary establishment of a highly diverse fauna which generally was confined to lower and warmer latitudes. The change to a more humid and somewhat cooler climate in the Kachchh area in the Callovian continued at least until the Kimmeridgian and is reflected by the scarcity of carbonate sediments, lower diversity values of benthic faunas, and a change in the trophic structure of benthic associations, deposit-feeding nuculids playing a far greater role than during the Bajocian–Bathonian.

6.2. Carbon isotopes

The carbon isotope ratios of brachiopods and belemnites reflect comparable values with average values of +0.5±0.6‰ and +0.5±0.5‰, respectively. The δ^{13}C values of belemnites from individual horizons show a considerable spread in δ^{13}C (Fig. 3). We observe no secular trend in the δ^{13}C values of either brachiopod shells or belemnite rostra. In comparison, carbon isotope ratios reported for Middle Jurassic belemnite rostra (Podlaha et al., 1998; Jenkyns et al.,

2002) range from −1‰ to +5‰, with high $\delta^{13}C$ values (+1‰ to +5‰) generally encountered in the Bathonian and Callovian. The fact that we observe lower $\delta^{13}C$ values may be attributed to the carbon isotopic composition of waters in the Kachchh Basin and Malagassy Gulf that may have been different from the carbon isotope ratio of open ocean surface waters. The fact that we observe comparable $\delta^{13}C$ values for brachiopods and belemnites argues against a prominent metabolic fractionation effect on the carbon isotopic composition of belemnite calcite.

6.3. Palaeotemperatures estimated from oxygen isotopes

Oxygen isotope ratios of biogenic calcite may be used to reconstruct palaeotemperature if the calcite was precipitated in isotopic equilibrium with seawater and a diagenetic alteration of the primary isotope ratios can be ruled out. Modern brachiopods are thought to precipitate calcite in near-isotopic equilibrium with seawater (Carpenter and Lohmann, 1995; Brand et al., 2003), although a recent study of the modern brachiopod *Terebratalia transversa* showed a significant kinetic fractionation effect on both carbon and oxygen isotope ratios (Auclair et al., 2003). No studies are available concerning kinetic or metabolic fractionation effects during precipitation of belemnite calcite since belemnites became extinct in the latest Cretaceous. However, several authors proposed that oxygen isotope ratios of belemnite calcite represent equilibrium precipitation and that the ratios may be used to reconstruct palaeotemperature (Saelen et al., 1996; Price and Sellwood, 1997; Niebuhr and Joachimski, 2002; Wierzbowski, 2002, 2004; McArthur et al., 2004; Rosales et al., 2004).

Diagenetic alteration of the primary isotopic signatures was evaluated using cathodoluminescence microscopy. Diagenetic recrystallisation is expected to alter both the isotopic composition and trace element composition. Mn^{2+} and Fe^{2+} are preferentially incorporated during diagenetic recrystallisation whereas Sr is depleted. Mn^{2+} is considered as the main activator of an orange-coloured luminescence, whereas elevated Fe^{2+} contents result in a dark red or brownish (dull) luminescence. Only non-luminescent belemnite and brachiopod skeletons were accepted for stable isotope analysis.

Palaeotemperatures were calculated using the equation given by Anderson and Arthur (1983) assuming a $\delta^{18}O$ value for Jurassic seawater of −1‰ (ice-free world; Savin, 1977). Palaeotemperature estimates based on the oxygen isotope ratios of the brachiopods from the Patcham Formation range from 19.6 to 24.2 °C. The average temperature is 21.4±1.7 °C. The oxygen isotope composition of the brachiopod specimen from the Chari Formation gives a comparable palaeotemperature of 21.7 °C. The oxygen isotope ratios of the belemnite guards from the Chari Formation translate into palaeotemperatures ranging from 11.0 to 20.6 °C with an average value of 16.5±1.6 °C and reveal significantly lower temperatures in comparison to estimates derived from brachiopod calcite.

The difference in the palaeotemperatures calculated from the $\delta^{18}O$ values of brachiopod and belemnite calcite could be interpreted as evidence for climatic cooling from the Bathonian (Jhurio and Patcham formations) into the Callovian (Chari Formation). A decline in Tethyan sea surface temperatures starting in the Late Callovian was reported by Dromart et al. (2003a) based on oxygen isotope measurements of apatite enamel of shark and fish teeth. The inferred climatic refrigeration as well as its coincidence in time with a global sea-level fall, initiated speculations concerning a glaciation at the Middle–Late Jurassic transition (Dromart et al., 2003b). On a first sight, our data seem to support a climatic deterioration during the Callovian (Fig. 3). However, the brachiopod shell from the Chari Formation (sample Ja 2) gave a palaeotemperature comparable to those estimated from the brachiopod shells of the Patcham Formation. In addition, the oxygen isotopic composition of a bivalve shell from the basal part of the Chari Formation gave a comparable palaeotemperature of 20.0 °C. On the contrary, the belemnites from below and above the brachiopod sample Ja 2 reveal significantly cooler temperatures of 14.9–17.4 °C.

Brachiopods are epibenthic fixosessile organisms and should record temperatures comparable to or lower than those of nektonic belemnites thriving in the water column above. Instead, the brachiopods record significantly warmer temperatures than the belemnites. Similar observations have been made in studies on Cretaceous brachiopods and belemnites with belemnites having higher δ^{18}O values and thus indicating lower temperatures than brachiopods (Pirrie and Marshall, 1990; Tourtelot and Rye, 1969; Voigt et al., 2003). The higher δ^{18}O values of belemnite calcite cannot be explained by kinetic isotope fractionation since kinetic fractionation results in the precipitation of calcite depleted in both, ^{13}C and ^{18}O (McConnaughey, 1989). As a consequence, the imprint of kinetic fractionation is typically documented in a correlation of carbon and oxygen isotope values which is not observed in our dataset. The fact that the δ^{13}C values of brachiopods (average δ^{13}C: 0.7±0.6‰) and belemnites (average δ^{13}C: 0.5±0.5‰) are comparable also argues against a kinetic or metabolic isotope fractionation effect.

The Jurassic sediments of the Kachchh area were deposited essentially in an inner to middle shelf setting, where a significant temperature gradient in the water column seems implausible and where bottom water and sea surface water temperatures should have been comparable. In such a situation, both brachiopods and belemnites should give similar palaeotemperatures.

As already discussed, the faunal studies of the Kachchh Basin indicate tropical to subtropical climatic conditions. The predominance of corals in the upper part of the Jhurio Formation (upper Middle Bathonian) demands water temperatures of around 25 °C. The palaeotemperatures estimated from the oxygen isotope values of the brachiopod shells (19.6–24.2 °C) seem to support this assumption. Although we only investigated one brachiopod shell from the Chari Formation, its palaeotemperature is similar to those from the Jhurio Formation. Thus, the brachiopod shells do not record a significant change in palaeotemperature across the Bathonian–Callovian boundary.

The palaeotemperatures derived from the belemnites of the Chari Formation are significantly lower than those of the brachiopods from the Bathonian. Vertically closely spaced specimens show variation of several degree centigrade but we observed no secular trend in the calculated temperatures. The lower temperatures derived from the belemnite rostra can be explained if we assume that the belemnite animals spent a great part of their life span in colder areas and migrated into the warm Kachchh Basin, possibly to spawn. According to palaeogeographic reconstructions (Fig. 9; e.g., Riccardi, 1991and Enay and Cariou, 1997) the Malagassy Gulf between Africa and India extended southwards into the cooler high latitudes of the southern hemisphere. Possibly, these higher latitude areas were the preferred habitats of the belemnite animals, which occasionally migrated to the subtropical Kachchh Basin where they died.

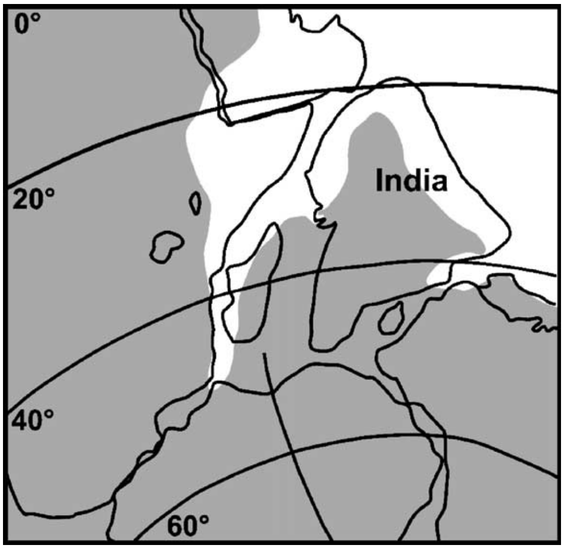

Fig. 9. Palaeogeographic sketch of the Malagassy Gulf, forming a southerly extension of the Tethys. Shaded area: land. Palaeogeography after Riccardi (1991) and Enay and Cariou (1997).

6.4. Clay minerals as palaeoclimatic indicators

A clay fraction (<2 μm grain size) is present in all types of terrigenous clastic rocks in variable proportions. The clay fraction is predominantly made up of clay minerals along with variable amounts of quartz, feldspar, iron oxides, carbonates, etc. (Shaw and Weaver, 1965). The clay minerals are phyllosilicates, primarily produced on the earth surface during weathering; to a lesser extent during diagenesis and hydrothermal alterations (Velde, 1992). As they are mostly produced during weathering processes, the nature of such clay minerals is strongly dependent on the climate, rock type, slope, and drainage characteristics of the area. Erosional processes remove clay material from the source area and move it to the basin of deposition (Velde, 1992; Millot 1970; Weaver, 1989).

The clay material reaching the marine realm may undergo minor changes or there may be effects of differential deposition in different parts of the marine basin (Füchtbauer, 1988). However, these factors are mostly of negligible significance; more so within the shallow marine coastal–shallow shelf setting, which was characteristic of the Kachchh Basin during Middle and early Late Jurassic time.

Diagenesis may also transform clay mineral assemblages, if the sediments are buried and undergo burial diagenesis (Dunoyer de Segonzac, 1970; Kisch, 1983). In the Middle Jurassic succession of Kachchh diagenetic effects on the clay mineral assemblage are likely to have been negligible, as the succession is overlain, towards the western part of the study area, only by a few hundred metres thick package of Early Cretaceous sediments, Late Cretaceous–Palaeocene Deccan traps, and Tertiary deposits. Moreover during burial diagenesis, illite crystallinity and the amount of illite increases with increasing depth of burial. The Middle Jurassic succession of Kachchh contains negligible amounts of illite and there is no increase in illite content in the older samples.

Thus, it seems reasonable to assume that the clay mineral assemblages of the Kachchh Basin reflect the original composition derived from the source area and may be used for palaeoenvironmental and palaeoclimate reconstruction of the source area (Deconinck and Chamley, 1995; Deconinck et al., 2003).

Four important clay mineral groups are produced during weathering processes, namely chlorite, illite, smectite and kaolinite groups, often accompanied by smectite-illite and chlorite-illite mixed layer groups. Chlorite and illite are considered to be detrital clay minerals or formed by transformation of ferromagnesium minerals and micas, respectively. These clay minerals are formed during the initial stages of weathering. During advanced stages of weathering, smectite and kaolinite are formed. The nature of clay mineral assemblages produced during weathering is primarily a function of climate, supported by length of time of weathering, slope, water–rock ratio, and water chemistry. Smectite is preferentially produced in semi-arid climate with low water–rock ratio and lower slopes and low relief with poor drainage. Kaolinite is produced due to intense chemical weathering in humid-subtropical to tropical climate supported by high water–rock ratio and steep slopes with good drainage (Velde, 1992). The formation of smectite at present takes place under a variety of conditions, probably the most favourable conditions are a warm climate with a seasonal contrast in humidity (Paquet, 1970; Singer, 1984). In general, dominance of illite and chlorite in a sample indicates relatively fast erosion of source area; while dominance of smectite and kaolinite indicates slow erosion rates or erosion of soil horizons formed over long periods of time. Clay mineralogy has been successfully used in palaeoclimate interpretation of Jurassic and Cretaceous rocks (e.g., Hallam, 1975; Hallam et al., 1991; Deconinck et al., 1982, 1985, 2003; Wignall and Ruffell, 1990).

6.4.1. Provenance of sediments

Systematic studies on the provenance of terrigenous clastic material of the middle and lower Upper Jurassic rocks of the Kachchh Basin are scant. In general, two important source areas are considered. One is in the north of the basin, the Nagar Parkar High, the other in the east of the basin, the Radhanpur High (Fig. 1). Dubey and Chatterjee (1997) describe that sandy terrigenous material of Middle to Late Jurassic rocks of the Kachchh Basin is essentially composed of polycrystalline quartz, K-felspar, albite, and rock fragments of schists, quartzite and granite. The heavy minerals are mostly garnet, tourmaline, zircon, and kyanite. They identify as source of the material essentially metamorphic and granitic rocks of the Nagar Parkar High in the north and Aravalli rocks (Radhanpur High) in the east. The conglomerates in the basal part of the Jhurio Formation (Bajocian or older) contain pebbles of gneissic rocks in outcrops close to the northern margin of the basin (Biswas, 1980). We presume that during the Middle to Late Jurassic both the source areas exposed similar rocks and produced similar clay mineral assemblages. In the present study, the clay mineral assemblages of one section (Jhura Dome section) has been studied in detail and only few samples from the Jumara Dome section were investigated. The clay mineral assemblages of the two sections are similar and show similar changes in their stratigraphic sequence (Table 2). It can be argued that for both sections the source area was the same and that any stratigraphic change in the clay mineral assemblage was a response to the climate-tectonic control in the source area. Alternatively, such stratigraphic variations in clay mineral composition could be due to autocyclic changes in sediment supply.

6.4.2. Middle Jurassic clay mineral assemblage

The samples from the Middle Jurassic of the Kachchh Basin do not contain any chlorite, and the content of illite is mostly very low except for a few samples (Fig. 6). The negligible amount of inherited clay minerals (chlorite and illite) in the samples suggests that in the source area the rate of erosion was low, so that weathering processes could modify the rock debris intensively. This would speak for a relatively low relief in the source area.

The lowermost part of the Jhurio Formation (Bajocian) is characterised by almost equal proportions of smectite and kaolinite. The source region had both low and high relief areas where smectite and kaolinite respectively formed under subtropical climatic conditions. There is a gradual increase in the smectite content from the base towards the top of the Jhurio Formation, with a corresponding decrease in kaolinite. This would indicate a gradual increase in seasonal warm droughts and a decrease in rainfall in the source area.

The Patcham Formation (Late Bathonian) is typified by a dominance of smectite, indicating low relief with low water–rock ratio in the source area along with a semi-arid climate with prolonged periods of seasonal high temperatures droughts. Due to low rainfall and a subdued relief only little terrigenous clastic material came to the basin of deposition, where essentially carbonate sedimentation took place from areas close to the shoreline to mid-shelf regions. A largely semi-arid climate during the deposition of the Patcham Formation is also indicated by the faunal study.

The change from the Patcham (Late Bathonian) to the Chari Formation (Callovian) is characterised by a slightly increased content of kaolinite, though smectite remains the dominant clay mineral. From the base towards the middle part of the Chari Formation a gradual increase in the kaolinite content and a corresponding decrease in smectite content is observed. This indicates a change from the semi-arid climate of the Patcham Formation to the humid-subtropical climate of the lower Chari Formation. Humidity seems to have increased from the basal part of the Callovian. In the upper part of the Chari Formation, both smectite and kaolinite are important constituents, but their relative proportions shift markedly in successive stratigraphic layers. In general, the Chari Formation was deposited during a humid-subtropical climate with short-term climate changes of high and low rainfall. Lithologically, the Chari Formation is essentially a terrigenous clastic succession forming when large amounts of land-derived material were brought into the basin due to high rainfall in the source area.

The gradual increase in the kaolinite content of the Chari Formation through time may be related to the rise in sea-level during the Callovian–Oxfordian. A rise in sea-level would submerge the low relief coastal areas where preferentially smectite was being formed. The higher relief areas with kaolinite formation mostly supplied the sediments. A lowering of sea-level would expose low relief areas to erosion, and the supply of smectite to the basin would increase. Short-term sea-level-changes during the deposition of the Chari Formation are indicated by numerous transgressive–regressive cycles (Fürsich et al., 1991; Fürsich and Oschmann, 1993). At present, it is difficult to assess the role of sea-level in changing the clay mineral assemblage during deposition of the Chari Formation.

The change from Bathonian to Callovian is marked by a change from carbonate to terrigenous clastic sedimentation along with a prominent change in the nature of the fauna and decrease in faunal diversity. It indicates a higher supply of terrigenous clastics due to increased rainfall and probably mild tectonic warping in the source area. The kaolinite content increases stratigraphically upwards pointing to an increase in rainfall. The upper part of the Chari Formation (Late Callovian) exhibits alternating zones of smectite and kaolinite dominance, probably related to transgressive–regressive events.

In summary, the clay mineral assemblage indicates a gradual increase in seasonal droughts and a decrease in average rainfall from the Bajocian to the Middle Bathonian. The Late Bathonian was an interval with prominent aridity and low rainfall. The Early to Middle Callovian was characterised by a gradual increase in rainfall intensity and less prominent seasonal droughts. The Late Callovian seems to have been a time of alternating periods of high and low rainfall intensity.

7. Conclusions

(1) Sediments, benthic faunas, oxygen stable isotopes, and clay mineral assemblages all point to changes in palaeoclimate in the Kachchh Basin during the Middle Jurassic.

(2) During the Bajocian to Middle Bathonian, a subtropical climate with seasonal droughts prevailed. As a result, the terrigenous sediment input was moderate and fluctuated. This is supported by carbonates, which predominated in offshore areas of the Kachchh Basin, and by intercalated siliciclastic sediments. The clay mineral assemblages show about equal proportions of smectite and kaolinite during the Bajocian, with smectite becoming more abundant towards the Bathonian. Oxygen isotope values of brachiopods, tropical elements among the benthic fauna (the bivalve *Eligmus* and members of the bivalve subfamily Opinae), and a highly diverse coral fauna in the Middle Bathonian suggest subtropical to tropical seawater temperatures.

(3) The Late Bathonian is characterised by a semiarid climate with hot seasonal droughts and only minor terrigenous input. The latter may also partly be due to tectonic quiescence in the source area. Carbonate sediments prevailed over large parts of the basin, and the strong dominance of smectite in the clay mineral assemblages indicates a low relief and a low water–rock ratio in the source area. Across the Bathonian–Callovian boundary, significant changes in the rainfall pattern towards higher humidity seem to have taken place.

(4) During the Callovian–Oxfordian the climate changed to subtropical and distinctly more humid conditions, which resulted in a high terrigenous input into the basin. This is supported by the siliciclastic nature of the sediments, the existence of large delta systems, and the lower diversity of the benthic fauna, which is commonly dominated by deposit-feeding nuculids. Clay mineral assemblages, in which kaolinite becomes the dominant mineral, and oxygen isotope values of belemnites corroborate this view. The latter yield slightly lower temperature values than the brachiopods from the Bathonian.

(5) The contradiction that nektic surface water organisms (belemnites) give lower palaeotemperatures (ranging from 11 to 21 °C) than benthic organisms can be resolved by postulating that the nektic belemnites may have migrated into the Kachchh Basin from cooler parts of the sea, e.g., the Malagassy Gulf.

(6) The oxygen isotope data indicate that the Kachchh Basin occupied a similar geographic position, oceanic circulation, and water temperature during the Bathonian–Callovian time interval.

(7) The changes in lithology and faunal composition taking place in the Kachchh Basin during the Middle Jurassic appear not so much to reflect a distinct decrease in water temperature, but a change towards increasing humidity.

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