ELSEVIER
Palaeogeography, Palaeoclimatology, Palaeoecology 167 (2001) 23–37
PALAEO
www.elsevier.nl/locate/palaeo

A review of the broad pattern of Jurassic sea-level changes and their possible causes in the light of current knowledge

A. Hallam*

School of Earth Sciences, University of Birmingham, Birmingham B15 2TT, UK

Received 24 March 2000; accepted for publication 28 August 2000

Abstract

An assessment is made of the current state of research into Jurassic sea-level changes based on new insights into depositional patterns in relation to these changes and new stratigraphic information from several widely separated regions across the world. The bearing of this information on alternative models, respectively, involving sea-level rise interrupted by stillstands or falls, is then evaluated. The gross pattern appears to be one of more or less gradual rise of sea level through the period, interrupted by episodes of comparative stillstand rather than eustatic fall and several episodes of significant regression are shown to be the result of regional tectonics. Major episodes of eustatic rise took place in the early Hettangian, early Sinemurian, early Pliensbachian, early Toarcian, early and late Bajocian, middle Callovian and late Oxfordian to Kimmeridgian. A significant episode of rapid and very extensive regression, possibly global, took place at the end of the Triassic, but other regressive episodes, in the late Aalenian, Bathonian, late Oxfordian–Kimmeridgian and Tithonian, are clearly only regional in extent. There is no evidence for glacioeustasy and most if not all of the regional or global changes recognised can readily be related to plate tectonics. The events at the Triassic–Jurassic boundary seem to be the result of mantle plume activity centred on the Central Atlantic region. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Jurassic; Eustasy; Regional tectonics

1. Introduction

In the approximately two decades since Jurassic sea-level curves were first proposed (Hallam, 1978; Vail and Todd, 1981), much new information on stratigraphic successions in different parts of the world has been acquired and the development of new concepts has required some revision. Thus it is timely to attempt a revised interpretation of at least major sea-level changes in full acknowledgement of the tentative and provisional nature of the exercise because a considerable amount of generalisation is required for the production of sea-level curves. It is not the intention here to produce a new sea-level curve but instead to highlight some major features, which have a stronger chance of achieving consensus among stratigraphers and which might therefore provide a solid basis for further knowledge.

The two sea-level curves and their subsequent modifications utilised different techniques. Hallam (1978, 1988) employed a combination of facies analysis in Europe to reveal a succession of shallowing and deepening cycles, a correlation with regression and transgression elsewhere and approximate determination of the extent of global marine cover of the continents for successive stages. The Exxon team's first curve (Vail and Todd, 1981) was based on a seismic

---

* Tel.: +44-121-414-6164; fax: +44-121-414-4942.
E-mail address: a.hallam@bham.ac.uk (A. Hallam).

PII: S0031-0182(00)00229-7

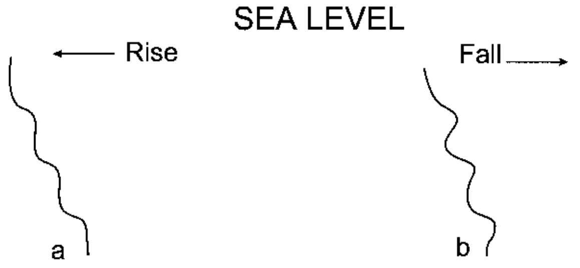

Fig. 1. Alternative models of sea-level rise through Jurassic time: (a) rise interrupted by stillstands; (b) rise interrupted by sea-level falls.

stratigraphic analysis of the Moray Firth in the North Sea on the assumption that this gave a global signal. Its subsequent modification (Haq et al., 1987) utilised sequence stratigraphic analysis of a few European sections but was strongly influenced by the initial Vail and Todd curve as pointed out by Hallam (1992). The subsequent production of sea-level curves or their coastal onlap equivalent in other parts of the world has confirmed a pattern of interrupted gradual rise of global sea-level through the course of the period (Surlyk, 1991; Li and Grant-Mackie, 1993; Legaretta and Uliana, 1996). The critical question that has emerged and which has an important bearing on the nature of the underlying mechanism is whether the interruptions involved episodes of stillstand or sea-level fall (Fig. 1). The original sea-level curves implied the latter, involving a more or less regular cyclicity, but doubts have begun to emerge about such an interpretation.

Before proceeding further, it is clearly necessary to outline the criteria for determining sea-level rise and fall in the light of modern developments.

Rise. One of the most important insights into the sequence stratigraphic approach originally presented by Haq et al. (1987) is that in offshore basinal settings, a sea-level rise (or marine deepening) is characteristically marked by a condensed section as signified by concentrations not only of fossils but also glaucony and phosphorite. On basin margins, they may be represented by marine shales in non-marine sediments and have been referred to as maximum flooding surfaces. Such deposits, if they contain fossils of restricted stratigraphic range, such as ammonites, offer by far the best means of correlation in basin analysis (Galloway, 1989; Underhill and Partington, 1993; Stephen and Davies, 1998). Furthermore, ammonites are the only serious Jurassic biostratigraphic contenders for intercontinental correlation of the sort required to investigate eustatic phenomena (Hallam, 1978, 1992). The basal deposits of marine deepening events within the basinal settings are characteristically though not invariably black shales signifying bottom-water anoxia and transgressive events might be marked by a geographic expansion of the area of anoxia (Hallam, 1992; Wignall, 1994).

Fall. As first pointed out by Hallam (1978), evidence of extensive sea-level fall is generally much more difficult to establish than sea-level rise. While local sea-level fall is readily determined by shallowing-upward successions and erosional unconformities, especially towards basin margins, correlation over wide regions is often handicapped by the absence of ammonites because of inappropriate facies, high sedimentation rates or erosional hiatuses on basin margins. Whereas progradation of sandstones over shales is rightly seen as good evidence of relative sea-level fall in siliciclastic successions, the problem can become more acute in fine-grained carbonate-dominated successions. Thus the presence of hardgrounds and hiatuses has normally been taken in the past Jurassic studies as evidence of shallowing but under the new sequence stratigraphy paradigm, they should be held to signify the reverse. Therefore it is imperative to seek such evidence as erosional truncation of consolidated rock to support an interpretation of relative sea-level fall, perhaps leading to local emergence (Hallam, 1999).

The Exxon team originally proposed a hierarchical division of eustatically controlled sea-level cycles with the lowest numbered ranking representing the longest in duration (Vail et al., 1977). Thus first-order cycles correspond broadly to the Paleozoic and Mesozoic–Cenozoic, second-order cycles lasted 10–80 and third-order cycles 1–10 million years. While there are legitimate grounds for questioning such a hierarchical division (Drummond and Wilkinson, 1996), they have proved useful as approximations and have been widely adopted subsequently. In the recent sequence stratigraphic analysis of western Europe, dominated by the study of French successions (de Graciansky et al., 1998; Jacquin et al., 1998) second- and third-order cycles are distinguished. Although sequences are by

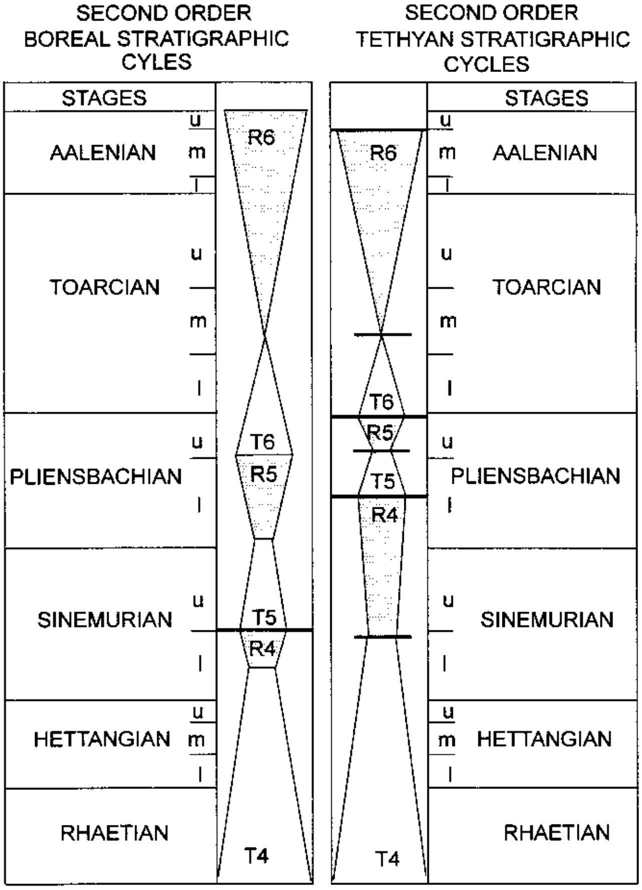

Fig. 2. Transgressive (T)–regressive (R) cycles in the Lower Jurassic of western Europe. Simplified from de Graciansky et al., 1998, Fig. 2.

definition unconformity-bound units, the units recognised by these authors are essentially transgressive–regressive cycles (cf. Embry, 1993) and unconformities are recorded only to a limited extent. The simplified version of their scheme (Figs. 2 and 3) represents only their second-order cycles because these are the only realistic ones for global correlation. This does not mean that none of the third-order cycles are eustatically controlled, merely that the supporting evidence from ammonite correlation is unlikely to be present on a sufficiently refined scale across the world for these relatively minor events. There may well be particular instances where this is indeed possible, perhaps with independent evidence in support from isotope stratigraphy, but it is beyond the scope of this broad review to pursue such matters in detail, beyond pointing out some striking examples, such as the Lower Toarcian *falciferum* Zone.

In the years since Jurassic sea-level curves were first proposed, there have been many advances in sequence stratigraphy, most notably in its use by oil companies in conjunction with intensive basin analysis involving, for instance, backstripping methods. While it may well be difficult in many cases to separate the eustasy component from other relevant variables such as local subsidence and sedimentation rates (Burton et al., 1987), it is quite unrealistic to expect the application of such methods globally to the Jurassic, or indeed any other system, for the foreseeable future because the relevant data are unlikely to become available. Nor is it realistic in the present state of knowledge to expect precise

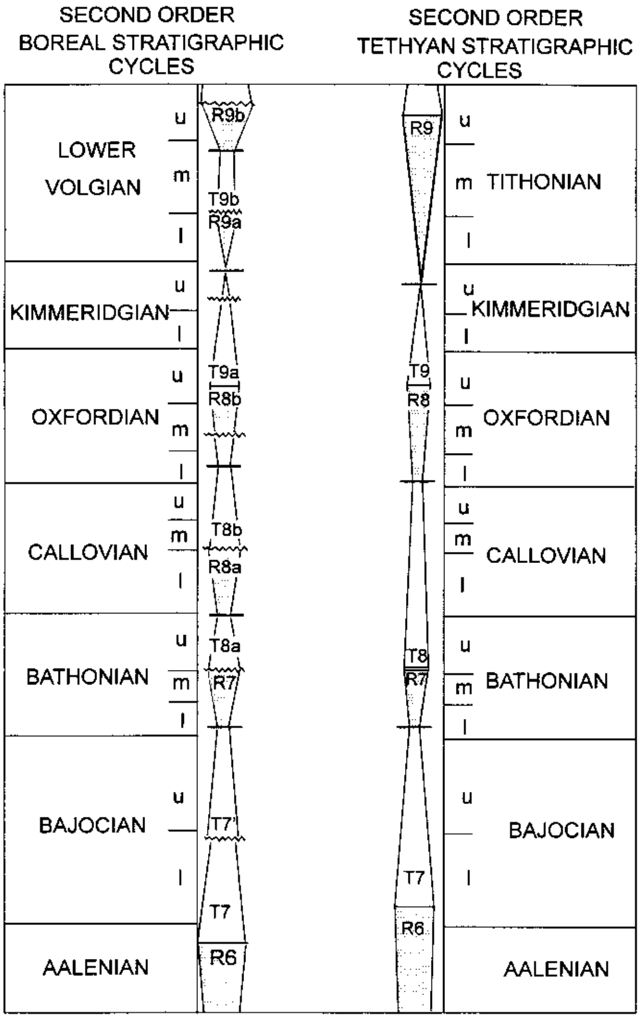

Fig. 3. Second-order transgressive (T)–regressive (R) cycles in the Middle and Upper Jurassic of western Europe. Simplified from Jacquin et al., 1998, Fig. 2.

quantitative estimates of the rate and amount of sea-level changes except in particular cases (e.g. Hallam, 1997). However, it would be unduly pessimistic to dismiss the prospect of establishing the pattern of broad eustatic change because of the excellence of the biostratigraphic control afforded by ammonites. Thus if, for example, a given marine deepening/transgressive event can be traced not only widely across continents to the precision of a zone, independent of a regional pattern of basins and swells, but also between widely separated continent to the precision of a substage or even zone, a strong case for eustatic control can be put forward (Hallam, 1992).

In the survey that follows, attention is almost entirely confined in addition to three regions outside Europe, which have a sufficiently good stratigraphic succession through the Jurassic as to allow the tentative production of sea-level or coastal onlap curves: Greenland, the Himalayas and Argentina (Figs. 4 and 5). Since the four regions considered are widely scattered across the world, they offer a good prospect

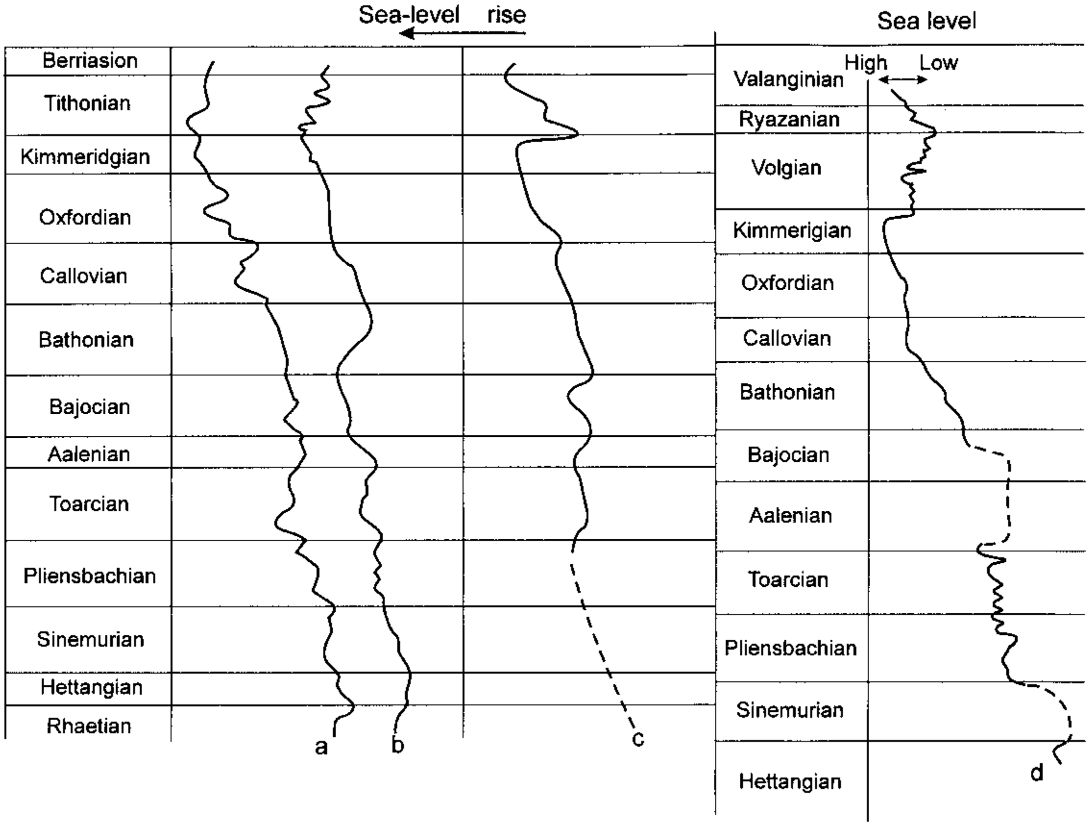

Fig. 4. Sea level curves for Himalayas (c) and East Greenland (d) compared with the proposed global curves of (a) Hallam (1988) and (b) Haq et al. (1987b). (c) Based on Li and Grant-Mackie, 1993. (d) After Surlyk, 1991.

of identifying genuine eustatic signals. A recently published eustatic analysis for the West Siberian basin (Zakharov et al., 1998) shows, in general, a broad conformity with the other regions.

2. Major episodes of sea-level rise

2.1. Early Hettangian

Although the *planorbis* Zone transgression was a striking event, following a latest Rhaetian regression, it was missed both by Haq et al. (1987) and de Graciansky et al. (1998). It marked the first spread of fully marine conditions into north-west Europe after a long late Paleozoic to Triassic continental interval. Genuine emergence at the Triassic–Jurassic boundary in both northern and southern Europe (Northern Calcareous Alps of Austria) is signified by such varied features as erosional channelling, erosion of consolidated limestone and notable erosional hiatuses (Hallam, 1997). In the western Alps and adjacent areas, the transgression though not the preceding regression is well marked (Dumont, 1998). Evidence outside Europe for a regression–transgression couplet will be more fully considered when sea-level fall is considered.

2.2. Early Sinemurian

There is clear evidence of a widespread *semicostatum* Zone transgressive event, not only in Europe but in widely separated parts of the world extending from western North and South America to Hong Kong making it one of the strongest candidates for being under eustatic control (Hallam, 1981). According to

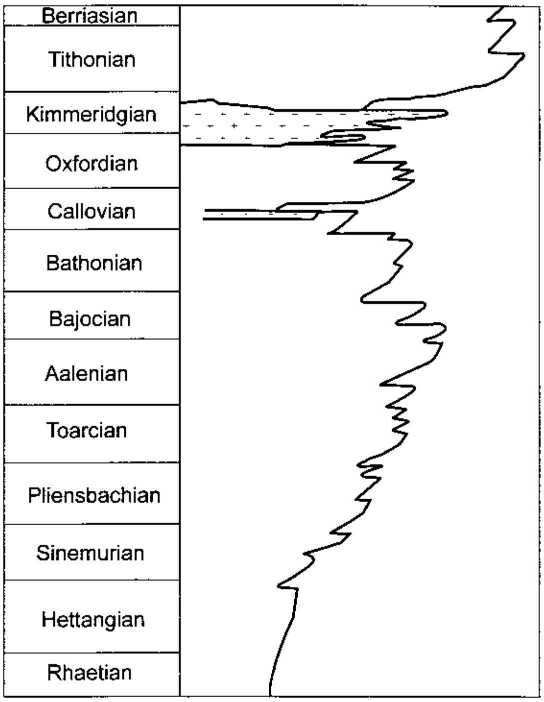

Fig. 5. Coastal onlap chart for western Argentina. Evaporite horizons signified by crosses. Simplified from Legaretta and Uliana, 1996, Fig. 6. Direction of sea-level rise is to the right.

de Graciansky et al. (1998), the peak transgression of their cycle 4a (Fig. 3) is either mid-*liasicus* (Hettangian) or *semicostatum* Zone. This appears to confuse two distinct events, which are recognised by Hesselbo and Jenkyns (1998) in the British successions as well as by Hallam (1981) but are evidently less clearly distinguished in the French successions. As for event 1, there is no evidence from Greenland because the pre-Pliensbachian succession is non-marine. In the Himalayas, the shallow marine Liassic succession lacks ammonites and hence no such event is as yet discernible (Gaetani and Garzanti, 1991; Gradstein et al., 1991) but it is clearly discernible in the Argentinian coastal onlap chart (Fig. 5) of Legaretta and Uliana (1996).

2.3. Early Pliensbachian

A major marine transgression of *jamesoni* Zone age took place in Greenland where it marks the earliest Jurassic invasion of the sea into a non-marine zone (Surlyk, 1991; Fig. 4d) and a comparable transgression is recognised in north-east Scotland by Stephen and Davies (1998). An important water-deepening event in the marine regime is also clearly recognisable in north-east England (Hallam 1981; Hesselbo and Jenkyns, 1998). An important transgression evidently also took place in the southern Andes (Legaretta and Uliana, 1996) but because of lack of recorded ammonites, no such event has yet been discovered in the Himalayas.

2.4. Early Toarcian

The *falciferum* Zone deepening and transgressive event is one of the most striking in the Jurassic and is associated with the spread of black shales; an anoxic event comparable to that at the Cenomanian–Turonian boundary, signified by a marked positive carbon isotope excursion, has been established by Jenkyns (1988). It is clearly manifested in both Europe and South America as well as in western Siberia (Zakharov et al., 1998) but not in Greenland or the Himalayas (Figs. 4 and 5), in the latter region perhaps because of inadequate stratigraphic resolution as yet. Elsewhere in the world, its most striking manifestation is in an extensive region stretching from the Middle East to Madagascar where Lower Toarcian deposits approximately equivalent in age to the *falciferum* Zone represent the oldest marine Jurassic (Hallam, 1978, 1988). These *Bouleiceras*-bearing beds can be traced into northern Pakistan as far as the Himalayas margins (Fatmi, 1972).

2.5. Early Bajocian

Though it cannot be pinned down precisely to a zone, an Early Bajocian transgessive/deepening event can be recognised widely across the world (Hallam, 1978, 1988). Its importance in northern Europe is somewhat exaggerated by the preceding pronounced Aalenian regression but its effects can be recognised as far south as the Jura Mountains of southern France and northern Switzerland (Jacquin et al., 1998). A distinct Early Bajocian transgression is also recognised in the southern Andes, although the Aalenian here is not regressive (Legaretta and Uliana, 1996). The facies in Greenland at this time is non-marine and stratigraphically indeterminate, but in the Himalayas, although the stratigraphy has not been fully worked out, it is clear that the only widespread pre-Callovian ammonites are of Lower Bajocian age (Westerman and Wang, 1988; Gradstein et al., 1991).

2.6. Late Bajocian

To this time is attributed a major flooding event in northern Europe, extending into the early Bathonian, with a peak transgression at the Bajocian–Bathonian boundary (Jacquin et al., 1998). These authors point out that the evidence for this 'Vesoulian' transgression extends from the western Paris Basin to Dorset in southern England, but they omitted to mention that it extends further west also into Gloucestershire and Somerset. Surlyk (1991) recognises this as one of the most important transgressive events in Greenland with a widespread marine flooding of continental sediments (Fig. 4d). An important Late Bajocian event is also recognised in Argentina by Legaretta and Uliana (1996) but according to them, it did not extend into the Bathonian (Fig. 5). In the Himalayas, clear evidence is lacking, though Fig. 4c indicates a sea-level fall at the end of the stage. It is not obvious, however, on what basis this inference has been made.

2.7. Middle Callovian

This represents one of the most important transgressive/deepening events in the whole Jurassic. While there is some complication because of regional tectonics, Europe saw the onset of shales, characteristically organic-rich, over a vast area, usually overlying manifestly shallower water sediments. The underlying Upper Bathonian and Lower Callovian often also signify relative sea-level rise, but the extent to which they represent independent pulses or a temporally extended event expressed regionally as diachronism has not in general been clearly established. It is noteworthy, however, that over wide areas, the Lower Callovian marks a distinctive cycle of shales passing up into sandstones or in Burgundy, limestones capped by an erosion surface.

In Greenland as in Europe, there was an overall transgressive trend in the Late Bathonian and Early Callovian but with a major pulse in the Middle Callovian before greater sea-level stability was achieved (Fig. 4d). In the Andes, a major transgession at this time put an end to a regressive interval and had important biogeographic consequences. Thus a distinctive East Pacific ammonite province came to an end as free links were re-established with Europe (Westermann, 1993). The Himalayas and Pakistan Salt Range demonstrate, like in Europe, a stepwise transgressive event. A widespread ferruginous oolite dated variously as latest Bathonian or earliest Callovian marks the initiation of a transgression over very shallow marine strata lacking ammonites (Fatmi, 1972; Gaetani and Garzanti, 1991; Gradstein et al., 1991; Li and Grant-Mackie, 1993). There follows over the whole area a major argillaceous unit known as the Spiti Shales and stratigraphic equivalents extending up into the youngest Jurassic. Dating of the lower part of this unit has been uncertain until recently, but now it has been confidently established from new ammonite discoveries as Middle Callovian (Enay and Cariou, 1997). In this regard, Fig. 4b seems to mark a closer approximation to reality than Fig. 4a, which overemphasises regressive events.

2.8. Late Oxfordian to Kimmeridgian

The base of their cycle 9, at the Lower–Upper Oxfordian boundary, is taken by Jacquin et al. (1998) as marking the beginning of this event in Europe (Fig. 3) with the peak transgression taken as the *eudoxus* Zone of the Kimmeridgian marked by widespread black shales. An important Late Oxfordian–Kimmeridgian sea-level rise is also recognised in Greenland by Surlyk (1991) with a maximum flooding surface in the *eudoxus* Zone (Fig. 4d). Adjacent to the Himalayas, in the Salt Range of Pakistan, the same event is recognised by Fatmi (1972) but the situation within the Himalayas is less clear. Enay and Cariou (1997) recognise the widespread presence of Middle Oxfordian ammonites in the Spiti Shales after a barren interval of uncertain age and have proved the presence of Kimmeridgian after a long period of doubt. Gradstein et al. (1991) record a Middle Oxfordian transgression. The situation in the Andes is anomalous because the Late Oxfordian to Kimmeridgian records a regressive interval between the marine Callovian and Tithonian (Riccardi, 1983; Legaretta and Uliana, 1996).

A feature that needs reporting here is the extensive condensed nature of Upper Callovian to Lower Oxfordian deposits, suggesting a global phenomenon. This is well recorded over a wide area in western Europe by Norris and Hallam (1995) and in the Andes, where there is a widespread late *athleta* to early *cordatdum* Zone hiatus (Legaretta and Uliana, 1996). It is evident also in the Salt Range (Fatmi, 1972) and the limited evidence available from the Himalayan Spiti Shales is at least consistent with it.

3. Major episodes of sea-level fall

As noted earlier, episodes of extensive sea-level fall are much harder to establish and correlate than episodes of sea-level rise. In particular, it is more difficult to distinguish global events from those related to regional tectonics. Although this paper essentially addresses Jurassic sea-level change, it is desirable in this case to extend consideration also to the latest Triassic and earliest Cretaceous.

3.1. Latest Rhaetian

The best evidence for extensive sea-level fall, which could well be global, is at the end of the Triassic (Hallam and Wignall, 1999). This important episode is worth considering in some detail because it has been hitherto neglected. The evidence is especially clear in Germany. There was extensive shallowing of inland sea in the latest Rhaetian, marked by widespread progradation of sandstones over shales (Will, 1969). In northern Frankonia (Bavaria), fluviatile Hettangian occurs in marine channels cut into Rhaetian sandstones and clays and is overlain by marine Hettangian of the *planorbis* Zone (Bloos, 1990). A clear end-Triassic regressive pulse can be recognised in the Danish Basin (Bertelson, 1978) while both in southern Sweden and north-west Poland, the Upper Rhaetian is missing and there is an unconformity at the base of the Jurassic (Dadlez, 1976; Bertelson, 1978). In the Northern Calcareous Alps of Austria, widespread emergence at the end of the Triassic is also recognised with the creation of karst surfaces on emergent reef complexes (Satterley et al., 1994) while in the few areas of more continuous sedimentation in basinal settings, the base of the Jurassic is marked by eroded limestone clasts derived from emergent areas (Hallam and Goodfellow, 1990) or by an exceptional red mudstone horizon, interpreted as marginal marine, in the midst of blue-grey, fully marine deposits (McRoberts et al., 1997).

In most parts of England, the marine Hettangian Blue Lias Formation rests with a hiatus on an eroded top of the Rhaetian Penarth Group, with the upper Lilstock formation being partly or wholly missing (Hallam, 1995). This is true even of the most complete section in Somerset where a horizon of reworked limestone clasts at the base of the Blue Lias has been discovered (Hallam, 1990). On the borders of Devon and Dorset, there was formerly well exposed at the boundary in the coastal section a horizon of truncated *Diplocraterion* burrows proving the erosional removal of at least 15 cm of consolidated Rhaetian marine limestone (Hallam, 1988; Fig. 3a).

In other continents, the best evidence comes from North America. While there is a good sedimentary record of Late Triassic and Early Jurassic on the eastern margins (Newark Supergroup), none of the beds are marine, but marine deposits occur in the Sverdrup Basin of Arctic Canada. Here there is a regional unconformity at the Triassic–Jurassic boundary separating an Upper Rhaetian succession with prograding from a Lower Hettangian succession with retrograding coarse siliciclastics (Embry and Suneby, 1994). In the classic section in and around New York Canyon in Nevada, the regression is marked by a topmost Rhaetian siltstone unit separating Norian–Rhaetian and Hettangian–Sinemurian limestones (Hallam and Wignall, 2000). The situation is more equivocal in areas further afield where a full marine succession has been recorded, such as the western borders of North and South America and parts of eastern Asia (Hallam and Wignall, 1999).

It is unlikely to be coincidental that this stratigraphically spectacular event coincides closely with one of the five biggest mass extinction events in the Phanerozoic (Hallam and Wignall, 1999). Remarkable though it may seem, the event was completely missed by Haq et al. (1987), who record no significant sea-level change across the system boundary (nor do de Graciansky et al., 1998) despite the strong evidence of both a sharp fall quickly followed by a rapid rise in the Early Hettangian. This probably reflects several things: no notable pattern or inadequate chronostratigraphy in the seismic reflection profiles of the Moray Firth; obscured stratal exposures in Dorset;

no exposures in Yorkshire and a failure to consult the extensive European literature.

3.2. Aalenian

The most spectacular regressive event in Europe before the end of the Jurassic took place in Aalenian times in the North Sea and surrounding areas with effects extending as far south as the Paris Basin (Jacquin et al., 1998) and the Cotswold Hills of England where marine Liassic shales are abruptly replaced by shallow water limestones, mainly oolites. Its effects have been most thoroughly researched by Underhill and Partington (1993) who have demonstrated convincingly that what Haq et al. (1987) took to be the most significant eustatic sea-level fall in the Jurassic was in fact a phenomenon of regional tectonics. It is not indeed clearly recognisable elsewhere in the world although a claim has been made on inadequate grounds for an end-early Jurassic sea-level fall in the Himalayas by Li and Grant-Mackie (1993). It should also be noted that one of the more important regressive events in Legaretta and Uliana's coastal onlap curve for Argentina is at the base of the Aalenian *murchisonae* Zone (Fig. 5). The situation in Greenland between the Late Toarcian and Late Bajocian is stratigraphically indeterminate (Surlyk, 1991 and Fig. 4d).

3.3. Bathonian

Over western Argentina and Chile, the Bathonian was a time of general regression (Riccardi, 1983) and marks the time of a distinct East Pacific ammonite biogeographic domain (Westermann, 1993). In the sequence stratigraphic scheme of Legaretta and Uliana (1996), the base of the Bathonian regressive event is marked by widespread discontinuity involving shelfal exposure and incision signifying a forced regression and was followed by the widespread deposition of continental redbeds. The overlying Lower Callovian includes evaporites, which are interpreted to signify a transgressive event under negative hydrogeological balance. This regressive situation in the Bathonian is anomalous globally and clearly marks a regional and not a eustatic event, but it is noteworthy that there is a spread of coastal onlap, presumably corresponding to a more extensive sea-level rise in Legaretta and Uliana's diagram (Fig. 5). A sharp regression between the Bathonian and Callovian is indicated, however, in this diagram, comparable to what has been recognised in some other parts of the world (Hallam, 1988) but is not yet established as a genuinely eustatic event.

3.4. Late Oxfordian–Kimmeridgian

Whereas this time was generally one of marked sea-level rise, the Andes are strikingly anomalous in signifying a pronounced regression indicated by extensive deposition of a thick evaporite unit now preserved at the surface as gypsum (Riccardi, 1983; Legaretta and Uliana, 1996; Fig. 5). These evaporites are sandwiched between marine limestone-shale units of Callovian to Middle Oxfordian and Tithonian age and extend far beyond the Neuquen Basin of western Argentian where the stratigraphy is best known. There can be no doubt about the regional character of this event, which is clearly related to Andean tectonics (Hallam, 1991).

3.5. Tithonian

The Tithonian part of the eustatic sea-level curve of Haq et al. (1987) shows several unusually rapid oscillations. Hallam (1988) argued that this was a consequence rather of tensional tectonic activity, producing rotated fault blocks, in the Moray Firth region and is one of the clearest examples of how the widely cited Exxon sea-level curve was influenced by the original seismic stratigraphy study of Vail and Todd (1981). This proposal of Hallam was subsequently confirmed by the detailed study of Underhill (1991). A similar pattern in Greenland at this time (Fig. 4) is also attributed by Surlyk (1991) to the effects of regional tectonics.

Both Haq et al. (1987) and Hallam (1988) agree that the Tithonian marked a sea-level peak followed by a fall into the earliest Cretaceous. The latest Jurassic and earliest Cretaceous in the classic area of northwest Europe is clearly regressive but such a regression is not evident in other parts of the world excepting New Zealand, although Surlyk (1991; Fig. 4d) marks a sea-level low in the basal boreal Cretaceous (Ryazanian). While there was an early Cretaceous regression in the Himalayan region, marked by the progradation of deltaic facies over the relatively deep marine Spiti Shales and equivalent, it was manifestly diachronous and no clear-cut event is determinable (Gaetani and Garzanti 1991). Indeed, in the Pakistan Salt Range, Spiti Shales facies continues without manifest change into the Valanginian before being replaced by a shallowing up deltaic succession (Hallam and Maynard, 1987). In the southern Andes of Argentina and Chile, a shallow marine limestone-shale facies passes without change into the Berriasian and the shallowest-water interval in a thick marine package ranging in age from Tithonian to Hauterivian is in the Early Valanginian (Hallam, 1991). This offers some support to the eustatic curve of Haq et al. (1987) who propose a pronounced sea-level low at this time.

4. Possible causes of regional and global sea-level change

There are two distinct and widely recognised causes of eustatic sea-level changes, the melting and freezing of polar icecaps and the changing volume of ocean basins bound up with the creation and destruction of ocean ridges and swells (Hallam, 1992). The latter process produces changes about three orders of magnitude slower than glacioeustatic changes, so while they are most probably relevant to Exxon-type first and probably second-order sea-level changes, they cannot plausibly be invoked for their third-order changes (Dewey and Pitman, 1998). The Exxon workers have favoured a glacioeustatic interpretation for their third- and higher order cycles (Vail and Haq, 1988) as has Brandt (1986) for cycles in the Lower Jurassic. There is, however, no evidence of waxing and waning polar icecaps in the Jurassic and the Jurassic world is generally accepted as lacking significant quantities of polar ice and as being relatively equable compared with the present day (Frakes et al., 1992; Hallam, 1993).

In a recent review, Price (1999) argued that there was evidence in the Bajocian–Bathonian and Tithonian/Volgian for episodes of cold or subfreezing polar climates with a possible extent of polar ice sheets approximately one-third of those at the present day. A match of geological data with different global circulation models for the Late Jurassic allows for the possibility of ephemeral ice caps during times of minimal seasonal forcing but with the southern continents being generally free of an ice cap (Sellwood et al., 2000). Any glacially induced sea-level changes would have been no more than metre-scale. It is thus highly implausible to argue that there was ever sufficient ice to effect sea-level changes discernible in the stratigraphic record.

Thus we are left with only tectonoeustatic mechanisms. This present evaluation indicates that, with almost no exceptions, the only convincing cases for eustatic sea-level change concerns rise and is more consistent with successive phases of rise interrupted by periods of stillstand than with alternating phases of rise and fall (Fig. 1). Such a pattern seems readily explicable in a general way to plate tectonics, at a time when the central Atlantic and Indian Oceans were beginning to open with newly created ocean ridges displacing seawater onto continental margins. Most major regressions are then explicable by regional tectonics of various sorts, which could perhaps also be related to plate tectonics, at least in some cases. Perhaps the most interesting exception concerns the Triassic–Jurassic boundary event with which we start. There follows a brief consideration of a number of subsequent events for which a plausible mechanism can be invoked.

4.1. Triassic–Jurassic boundary

As noted earlier, the best case for relatively rapid change, involving regression quickly followed by transgression, is at this system boundary. If not eustatic, it involved a very large area embracing more than one continent. Hallam (1997) attempted an approximate estimate of the amount and rate of sea-level change based on evidence from European sections. The most direct evidence comes from Bavaria, where channels cut into the Rhaetian with a maximum depth of 13 m have been described by Bloos (1990). As a result of a diagenetic study of an Upper Triassic reef in the Austrian Alps, an end-Triassic emergence of 5–15 m for a very brief geological duration of ca 10–15 ka was inferred by Satterley et al. (1994) based on the time evidently required to form the discovered karst cavities. On the basis of this and other evidence, Hallam inferred a rate of sea-level change of at least 1 cm in 0.2 ka. This rate is far too rapid to be plausibly accounted for by changing ocean ridge volume tectonoeustasy. Instead, the regression–transgression couplet at this horizon could be a good candidate for the Cathles and Hallam (1991) model involving stress-induced changes in plate density. Stress changes can produce significant changes in the density of the lithosphere and propagate across even the largest plates in less than 30 ka. Lithospheric plates interacting at existing boundaries can produce stress/density changes sufficient to cause several metres change in plate elevation; these may account for many of the transgressions and regressions inferred from the stratigraphic record. The creation of new rifts could increase plate compression enough to cause about 50 m of plate subsidence.

The rifting in question would be the initiation of break-up of Pangaea by tensional activity recorded on both sides of the present sector of the Atlantic Ocean (Manspeizer, 1988). This event is associated with the extrusion in the earliest Jurassic of extensive flood basalts on the eastern margins of North America (Olsen, 1997). Recently dated basic sills and dykes in both French Guyana and Guinea suggest a much more extensive zone of igneous activity at this time affecting the entire length of the central Atlantic region during the initial breakup of Pangaea. It differs from other magmatic provinces such as the Deccan and Paraná in that voluminous flood basalts are not observed. However, they may exist as suggested by offshore seismic sections supporting the existence of a major volcanic band emplaced along the north-eastern American margin (Deckart et al., 1997). More recently, dating of this so-called Central Atlantic Magmatic province magmatism has been extended to rocks in Brazil by Marzoli et al. (1999). Their work suggests that this magmatism exceeded 7 million sq. km in a few million years with peak activity at 200 Ma. This data is now thought to be the most accurate one for the T–J boundary (Palfy et al., 2000).

This association with volcanism suggests the existence of a mantle plume. Ernst et al. (1995) locate the focal point of a giant radial Central Atlantic dyke swarm of this approximate age between Florida and north-west Africa. This is therefore the likeliest central location of one of the mantle plumes discussed by White and McKenzie (1989). Rifting above a hot mantle region results in immediate uplift above sea level rather than subsidence due to stretching. Uplift occurs largely because crust is thickened by large quantities of new igneous rock generated by decompression melting. Since stretched regions have little flexural strength, uplift occurs to maintain isostatic equilibrium. Additional factors acting in concert to produce uplift are dynamic support of the underlying hotspot, decrease in density of residual melt as partial melt is extracted and initial heating of continental crust by intruded melt (White 1989). Because of the relatively low densities of crustal rocks, basaltic magmas generated beneath continental areas are probably frequently trapped at or near the Moho, a process known as underplating. The area affected by uplift appears to be much wider than for uplifted rift shoulders and could extend laterally for hundreds of kilometres (Cox, 1993). The well-established latest Triassic regression in Europe could well be bound up with such phenomena, with the initiation of basaltic extrusion in the earliest Jurassic marking the time of some subsequent collapse. Whether these various processes could account, however, for evidence of a regression–transgression couplet further afield is more dubious and it is probably relevant to note that changes across the T–J boundary appear to be least marked in areas most distant from the Central Atlantic zone. However, the Cathles–Hallam model can have global effects in exceptional circumstances with a maximum sea-level change of the order of 50 m. However, there is a potential problem for eustasy in this case because no oceanic sector is involved, the Atlantic not opening until well into the Jurassic.

The sea-level change at the T–J boundary seems to be recorded in a short positive excursion in the strontium isotope curve (Fig. 6) of Jones et al. (1994). The main fluxes that control the Sr isotope ratio are: (1) river inflow, especially those dominated by erosion of old metamorphic and igneous rocks, with heavy $^{87}Sr/^{86}Sr$ and (2) 'exchange' of Sr with young basalts with light $^{87}Sr/^{86}Sr$ in seawater hydrothermal systems beneath mid-ocean ridges (Veizer, 1989). Thus a positive blip is consistent with a short-term regression on a very extensive if not global scale. The steady fall of the curve through the later Hettangian to the earliest Toarcian is consistent with the record of more or less steadily rising sea-level with consequent diminution of continental input, but the sharp reversal of this trend subsequently is anomalous in this respect.

4.2. Early Toarcian

It has been generally thought, on the basis of deep

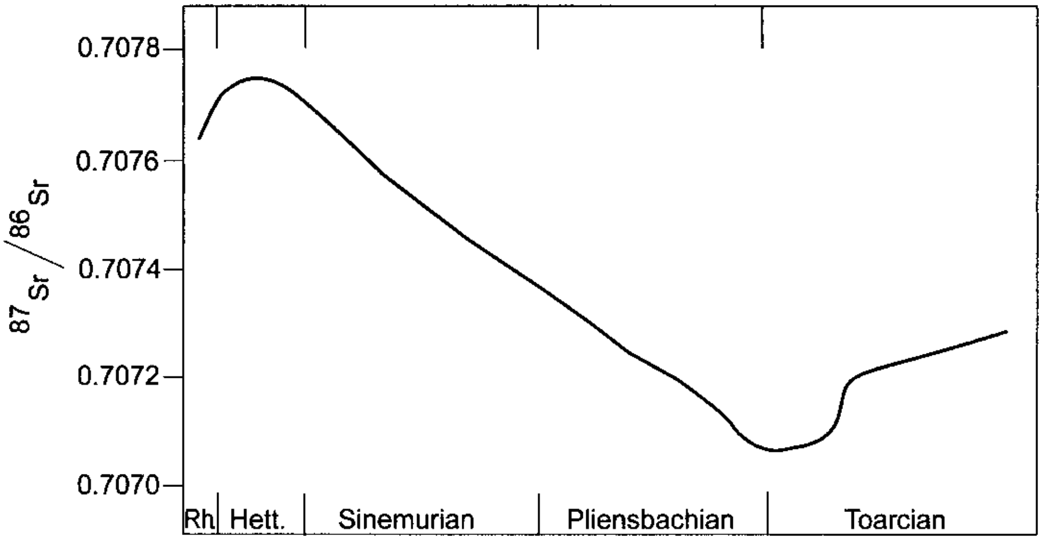

Fig. 6. Lower Jurassic strontium isotope curve. Simplified from Jones et al., 1994, Fig. 9.

ocean drilling and magnetic anomaly data, that the oldest Atlantic sea floor is Middle Jurassic in age (Sheridan, 1983; Klitgord and Schouten, 1986) but new research in the Canary Islands involving the dating of basalts suggests that sea floor spreading may have commenced as early as Toarcian times (Steiner et al., 1998). This is likely to be relevant to the Early Toarcian episode of pronounced sea-level rise associated with a minor mass extinction event. Hallam's (1997) estimate, based upon facies comparisons of the classic Yorkshire coast section with some modern marine environments, ranges from lowest to highest rates of 1 cm in 1.2 and 0.4 ka, respectively. These rates are compatible with normal tectonoeustasy associated with a newly created oceanic ridge.

4.3. Aalenian

The Aalenian regression event in north-west Europe is most plausibly related to thermal doming in the North Sea with basaltic volcanicity associated with subsequent collapse (Hallam and Sellwood, 1976; Underhill and Partington, 1993; Hesselbo and Jenkyns, 1998). This could perhaps have some relationship to plate tectonic activity in the Atlantic region, because the subsequent Late Jurassic–Early Cretaceous rifting in the North Sea, which could have led to ocean opening, ceased at about the same time as seafloor spreading west of the British Isles commenced, suggesting possibly a westerly transfer of mantle energy.

4.4. Middle Callovian to Late Callovian–Early Oxfordian

We have seen that in the Middle Callovian, there was an episode of marked sea-level rise on a global scale. The slightly later pulse of sea-level rise in the Late Callovian to Early Oxfordian is marked less by transgression than by widespread condensation, probably because it is manifested over large areas in different continents in deeper water, more offshore facies. It is tempting to relate these events to initial opening of the Atlantic Ocean in its central sector, between eastern North America and north-western Africa, perhaps also with associated Tethyan opening.

The oldest sediments overlying basaltic basement in the Atlantic have been dated by nanofossils from DSDP site 534 as Middle Callovian in age and Sheridan (1983) considers that initial breakup is associated with the Blake Spur magnetic anomaly and occurred in the earliest Callovian or latest Bathonian. However, the oldest oceanic crust on both flanks of the Mid-Atlantic Ridge was generated during a magnetic quiet zone and no seafloor spreading magnetic lineation isochrons have been identified for calculating the initial opening reconstruction pole (Klitgord and Schouten, 1986). Thus a Toarcian initial opening event cannot be excluded from the Atlantic data, which would imply a somewhat slower rate of initial opening than that inferred by Sheridan (1983). There could, however, have been a pulse of increased activity at this later time when some plate reorganisation took place (Klitgord and Schouten, 1986).

4.5. Late Oxfordian–Kimmeridgian

This latest pulse of significant rise of sea level is not obviously related to changing activity in the Central Atlantic because a more or less uniform rate of seafloor spreading can be inferred through the Late Jurassic (Klitgord and Schouten, 1986). The most plausible, albeit tentative, suggestion is that it relates to the initial breakup of eastern Gondwana leading to the formation of the Indian Ocean, with new sea floor being generated both east of Africa and west of Australia.

The regressive event in western South America at this time, so well recorded by evaporites intercalated in the midst of marine sediments, can probably be related to the initiation of tensional activity between this continent and Africa prior to seafloor spreading in the Early Cretaceous because the evaporites can be traced along much of the length of the Andes (Hallam, 1991). The Bathonian regression event in the same region is more difficult to explain unless it relates to premonitory tectonic movements heralding the same major event.

5. Conclusions

The gross pattern of Jurassic sea-level change, based on a comparison of four widely separated areas from which a sufficiently good record is available, is one of more or less gradual rise of sea level through the period, interrupted by episodes of still-stand rather than eustatic fall. The pattern matches well that inferred for East Greenland by Surlyk (1991) and for the Oxfordian by Gygi (1986). There is no convincing evidence for the sort of third-order cycles described by the Exxon group.

Major episodes of eustatic rise occurred in the Early Hettangian, Early Sinemurian, Early Pliensbachian, Early Toarcian, Early and Late Bajocian, Middle Callovian and Late Oxfordian to Kimmeridgian.

A significant episode of rapid and very extensive regression, most manifest in areas near the present Atlantic, took place at the end of the Triassic. It was possibly global in extent but evidence from areas most distal from the Atlantic region is indecisive.

Other episodes of notable regression, in the Late Aalenian, Late Oxfordian–Kimmeridgian and Tithonian are clearly only regional in extent, related to tectonic events in north-west Europe and Andean South American.

Evidence for glacioeustasy is lacking and most if not all the regional or global change recognised can plausibly be related to plate tectonics, the global sea-level rise being associated with the opening of the Atlantic and Indian Oceans. The exception concerns events at the Triassic–Jurassic boundary, which may be associated with mantle plume activity and extensive epeirogenic movements associated with volcanism.

Acknowledgements

I thank the two reviewers, Dave Bottjer and Jack Grant-Mackie, for their helpful comments.

References

Bertelson, F., 1978. The Upper Triassic–Lower Jurassic Vinding and Gassum formations of the Norwegian–Danish Basins. Danm. Geol. Undersøg., Ser. B 3, 1–26.

Bloos, G., 1990. Sea level changes in the Upper Keuper and in the Lower Lias of Central Europe. Cahiers Inst. Cathol. Lyon, Ser. Scientifique 3, 5–16.

Brandt, K., 1986. Glacioeustatic cycles in the Early Jurassic? N. Jahrb. Geol. Paläont. Mh., 257–274.

Burton, R., Kendall, C.G.St.C., Lerche, I., 1987. Out of our depth: on the impossibility of fathoming eustasy from the stratigraphic record. Earth-Sci. Rev. 24, 237–277.

Cathles, L.M., Hallam, A., 1991. Stress-induced changes in plate density, Vail sequences, epeirogeny and short-lived global sea-level fluctuations. Tectonics 10, 659–671.

Cox, K.G., 1993. Continental magmatic underplating. Phil. Trans. R. Soc. (Lond.) A 342, 155–166.

Dadlez, R., 1976. Lower Jurassic. In: Sokolowski, A. (Ed.). Geology of Poland. Geol. Inst. (Wydawnicta Geologiczne), Warsaw, pp. 156–164.

Deckart, K., Feraud, G., Bertrand, H., 1997. Age of Jurassic continental tholeites of French Guyana, Surinam and Guinea:

implications for the initial opening of the Central Atlantic Ocean. Earth Planet. Sci. Lett. 150, 205–220.

De Graciansky, P.-C., Jacquin, T., Hesselbo, S.P., 1998. The Ligurian cycle: an overview of Lower Jurassic 2nd-order transgressive/regressive facies cycles in western Europe. In: de Graciansky, P.-C., Hardenbol, J., Jacquin, T., Vail, P.R. (Eds.), Mesozoic and Cenozoic Sequence Stratigraphy of European Basins. SEPM (Society for Sedimentary Geology) Special Publication 60, pp. 467–479.

Dewey, J.F., Pitman, W.C., 1998. Sea-level changes: mechanisms, magnitudes, rates. In: Pindell, J.L., Drake, C. (Eds.), Paleogeographic Evolution and Non-Glacial Eustasy: Northern South America. SEPM (Society for Sedimentary Geology) Special Publication 58, pp. 1–16.

Drummond, C.N., Wilkinson, B.H., 1996. Stratal thickness frequencies and the prevalence of orderedness in stratigraphical sequences. J. Geol. 104, 1–18.

Dumont, T., 1998. Sea-level changes and early rifting of a European Tethyan margin in the Western Alps and south eastern France. In: de Graciansky, P.-C., Hardenbol, J., Jacquin, T., Vail, P.R. (Eds.), Mesozoic and Cenozoic Sequence Stratigraphy of European Basins. SEPM (Society for Sedimentary Geology) Special Publication 60, pp. 623–640.

Embry, A.F., 1993. Transgressive–regressive sequence analysis of the Jurassic succession of the Sverdrup Basin, Canadian Arctic Archipelago. Can. J. Earth Sci. 30, 301–320.

Embry, A.F., Suneby, L.B., 1994. The Triassic–Jurassic boundary in the Sverdrup Basin, Arctic Canada. Can. Soc. Petrol. Geol. Mem. 17, 857–868.

Enay, R., Cariou, E., 1997. Ammonite faunas and palaeobiogeography of the Himalayan belt during the Jurassic: initiation of a Late Jurassic austral ammonite fauna. Palaeogeogr. Palaeoclimatol. Palaeoecol. 134, 1–38.

Ernst, R.E., Head, J.W., Parfitt, E., Grosfils, E., Wilson, L., 1995. Giant radiating dyke swarms on Earth and Venus. Earth-Sci. Rev. 39, 1–58.

Fatmi, A.N., 1972. Stratigraphy of the Jurassic and Lower Cretaceous rocks and Jurassic ammonites from northern areas of West Pakistan. Bull. Brit. Mus. (Nat. Hist.) Geol. 20, 299–380.

Frakes, L.F., Francis, J.-E., Syktus, J.I., 1992. Climate Modes of the Phanerozoic. Cambridge Univ. Press, Cambridge.

Gaetani, M., Garzanti, E., 1991. Multicyclic history of the northern India continental margin (north western Himalaya). Am. Assoc. Pet. Geol. Bull. 75, 1427–1446.

Galloway, W.E., 1989. Genetic stratigraphic sequences in basin analysis. In: Architecture and genesis of flooding-surface bounded depositional units. Am. Assoc. Pet. Geol. Bull. 73, 125–142.

Gradstein, F.M., Gibling, M.R., Sarti, M., Von Rad, U., Thurow, J.W., Ogy, J.G., Jansa, L.F., Kaminski, M.A., Westermann, G.E.G., 1991. Mesozoic Tethyan strata of Thakkhola, Nepal: evidence for the drift and breakup of Gondwana. Palaeogeogr., Palaeoclimatol., Palaeoecol. 88, 193–218.

Gygi, R., 1986. Eustatic sea level changes of the Oxfordian (Late Jurassic) and their effect documented in sediments and fossil assemblages of an epicontinental sea. Eclogae. Geol. Helvet. 79, 455–491.

Hallam, A., 1978. Eustatic cycles in the Jurassic. Palaeogeogr. Palaeoclimatol. Palaeoecol. 23, 1–32.

Hallam, A., 1981. A revised sea-level curve for the early Jurassic. J. Geol. Soc. (Lond.) 138, 735–743.

Hallam, A., 1988. A re-evaluation of Jurassic eustasy in the light of new data and the revised Exxon curve. In: Wilgus, C.K., Hastings, B.S., Kendall, C.G.St.C., Posamatir, H.W., Ron, C.A., van Wagner, J.C. (Eds.), Sea-Level Changes — An Integrated Approach. SEPM Special Publication, 42, pp. 261–273.

Hallam, A., 1990. Correlation of the Triassic–Jurassic boundary in England and Austria. J. Geol. Soc. (Lond.) 147, 421–424.

Hallam, A., 1991. Relative importance of regional tectonics and eustasy for the Mesozoic of the Andes. In: Macdonald, D.I.M. (Ed.), Sedimentation, Tectonics and Eustasy. Blackwell, Oxford, pp. 189–200.

Hallam, A., 1992. Phanerozoic Sea-Level Changes. Columbia Univ. Press, New York.

Hallam, A., 1993. Jurassic climates as inferred from the sedimentary and fossil record. Phil. Trans. R. Soc. London B 341, 287–296.

Hallam, A., 1995. Oxygen-restricted facies of the basal Jurassic of north west Europe. Hist. Biol. 10, 247–257.

Hallam, A., 1997. Estimates of the amount and rate of sea-level changes across the Rhaetian–Hettangian and Pliensbachian–Toarcian boundaries (latest Triassic to early Jurassic). J. Geol. Soc. London 154, 773–779.

Hallam, A., 1999. Evidence of sea-level fall in sequence stratigraphy. Examples from the Jurassic. Geology 27, 343–346.

Hallam, A., Sellwood, B.W., 1976. Middle Mesozoic sedimentation in relation to tectonics in the British area. J. Geol. 84, 302–321.

Hallam, A., Maynard, J.B., 1987. The iron ores and associated sediments of the Chichali Formation (Oxfordian to Valanginian) of the Trans-Indus Salt Range, Pakistan. J. Geol. Soc. London 144, 107–114.

Hallam, A., Goodfellow, W.D., 1990. Facies and geochemical evidence bearing on the end-Triassic disappearance of the Alpine reef ecosystem. Hist. Biol. 4, 131–138.

Hallam, A., Wignall, P.B., 1999. Mass extinctions and sea-level changes. Earth-Sci. Rev. 48, 217–250.

Hallam, A., Wignall, P.B., 2000. Facies changes across the Triassic–Jurassic boundary in Nevada, USA. J. Geol. Soc. London 157, 49–54.

Haq, B.U., Hardenbol, J., Vail, P.R., 1987. Chronology of fluctuating sea levels since the Triassic (250 million years ago to present). Science 235, 1156–1167.

Hesselbo, S.P., Jenkyns, H.C., 1998. In: de Graciansky, P.-C., Hardenbol, J., Jacquin, T., Vail, P.R. (Eds.), British Lower Jurassic Sequence Stratigraphy. SEPM (Society for Sedimentary Geology) Special Publication 60, pp. 561–581.

Jacquin, T., Dardeau, G., Durlet, C., de Graciansky, P.-C., Hantzpergue, P., 1998. In: de Graciansky, P.-C., Hardenbol, J., Jacquin, T., Vail, P.R. (Eds.), The North Sea Cycle: An Overview of 2nd-order Transgressive/Regressive Facies Cycles in Western Europe. SEPM (Society for Sedimentary Geology) Special Publication, 60, pp. 445–466.

Jenkyns, H.C., 1988. The Early Toarcian (Jurassic) Anoxic Event: stratigraphic, sedimentary and geochemical evidence. Am. J. Sci. 288, 101–151.

Jones, C.J., Jenkyns, H.C., Hesselbo, S.P., 1994. Strontium isotopes in Early Jurassic seawater. Geochim. Cosmochim. Acta 58, 1285–1301.

Klitgord, K.D., Schouten, H., 1986. Plate kinematics of the Central Atlantic. In: Vogt, P.R., Tucholke, B.E. (Eds.), The Western North Atlantic Region. The Geology of North America, pp. 19–55.

Legaretta, L., Uliana, M.A., 1996. The Jurassic succession in west-central Argentina: stratal patterns, sequences and paleogeographic evolution. Palaeogeogr., Palaeoclimatol., Palaeoecol. 120, 303–330.

Li, X., Grant-Mackie, J.A., 1993. Jurassic sedimentary cycles and eustatic sea-level changes in southern Tibet. Palaeogeogr., Palaeoclimatol., Palaeoecol. 101, 27–48.

McRoberts, C.A., Furrer, H., Jones, D.S., 1997. Palaeoenvironmental interpretation of a Triassic–Jurassic boundary section from Western Austria based on palaeoecological and geochemical data. Palaeogeogr., Palaeoclimatol., Palaeoecol. 136, 79–95.

Manspeizer, W., 1988. Triassic–Jurassic rifting and opening of the Atlantic: an overview. In: Manspeizer, W. (Ed.). Triassic–Jurassic Rifting: Continental Breakup and the Origin of the Atlantic Ocean and Passive Margins, Part A. Elsevier, Amsterdam, pp. 41–79.

Marzoli, A., Renne, P.R., Piccirillo, E.M., Ernesto, M., Bellieni, G., De Min, A., 1999. Extensive 200-million-year-old continental flood basalts of the Central Atlantic Magmatic Province. Science 284, 616–618.

Norris, M., Hallam, A., 1995. Facies variations across the Middle–Upper Jurassic boundary in Western Europe and the relationship to sea-level changes. Palaeogeogr., Palaeoclimatol., Palaeoecol. 116, 189–245.

Olsen, P.E., 1997. Stratigraphic record of the Early Mesozoic breakup of Pangaea in the Laurasian–Gondwana rift system. Am. Rev. Earth Planet. Sci. 25, 337–401.

Palfy, J., Mortensen, J.K., Carter, E.S., Smith, P.L., Friedman, R.M., Tipper, H.W., 2000. Timing the end-Triassic mass extinction: first on land, then in the sea? Geology 28, 39–42.

Price, G.D., 1999. The evidence and implications of polar ice during the Mesozoic. Earth-Sci. Rev. 48, 183–210.

Riccardi, A., 1983. The Jurassic of Argentina and Chile. In: Moullade, M., Nairn, A.E.M. (Eds.), The Phanerozoic Geology of the World II. Elsevier, Amsterdam, pp. 201–263.

Satterley, A.K., Marshall, J.D., Fairchild, I.J., 1994. Diagenesis of an Upper Triassic reef complex, Wilde Kirche, Northern Calcareous Alps, Austria. Sedimentology 41, 935–950.

Sellwood, B.W., Valdes, P., Price, G.D., 2000. Geological evaluation of multiple general circulation model simulations of Late Jurassic palaeoclimate. Palaeogeogr. Palaeoclimatol. Palaeoecol. 156, 147–160.

Sheridan, R.E., 1983. Phenomena of pulsation tectonics related to the breakup of the eastern North American continental margin. Init. Rep. DSDP 76. US Govt. Printing Office, pp. 897–909.

Steiner, C., Hobson, A., Faure, P., Stampfli, D., Henandez, J., 1998. Mesozoic sequence of Fuerteventura (Canary islands): witness of Early Jurassic sea-floor spreading in the central Atlantic. Geol. Soc. Am. Bull. 110, 1304–1317.

Stephen, K.J., Davies, R.J., 1998. Documentation of Jurassic sedimentary cycles from the Moray Firth Basin, United Kingdom North Sea. In: de Graciansky, P.-C., Hardenbol, J., Jacquin, T., Vail, P.R. (Eds.), Mesozoic and Cenozoic Sequence Stratigraphy of European Basins. SEPM (Society for Sedimentary Geology) Special Publication, 60, pp. 481–506.

Surlyk, F., 1991. Sequence stratigraphy of the Jurassic–lowermost Cretaceous in East Greenland. Bull. Am. Assoc. Petrol. Geol. 75, 1468–1488.

Underhill, J.R., 1991. Late Jurassic seismic sequences, Inner Moray Firth, UK: a critical test of a key segment of Exxon's original global cycle chart. Basin Res. 3, 79–98.

Underhill, J.R., Partington, M.A., 1993. Jurassic thermal doming and deflation in the North Sea: implications of the sequence stratigraphic evidence. In: Parker, J.R. (Ed.), Petroleum Geology of North West Europe: Proceedings of the 4th Conference. Geological Society, London, pp. 337–345.

Vail, P.R., Mitchum, R.M., Todd, R.G., Widmier, J.M., Thompson, S., Songree, J.B., Bubb, J.N., Hatlelid, W.G., 1977. Seismic stratigraphy and global changes of sea level. Am. Assoc. Petrol. Geol. Mem. 26, 49–212.

Vail, P.R., Todd, R.G., 1981. Northern North Sea Jurassic unconformities, chronostratigraphy and sea-level changes from seismic stratigraphy. In: Illing, L.V., Hobson, G. (Eds.), Petroleum Geology of the Continental Shelf of North-West Europe. Keyden, London, pp. 216–235.

Vail, P.R., Haq, B.U., 1988. Sea level history: response to R.K. Matthews. Science 241, 599.

Veizer, J., 1989. Strontium isotopes in seawater through time. Annu. Rev. Earth Planet. Sci. 17, 141–167.

Westermann, G.E.G., 1993. Global bio-events in mid-Jurassic ammonites controlled by seaways. In: House, M.R. (Ed.), The Ammonoidea: Environment, Ecology, and Evolutionary Change. Oxford Univ. Press, Oxford, pp. 187–226.

Westerman, G.E.G., Wang, Y.-g., 1988. Middle Jurassic ammonites of Tibet and the age of the Lower Spiti Shales. Palaeontology 31, 295–339.

White, R.S., 1989. Igneous outbursts and mass extinctions. EOS, 1480–1482.

White, R.S., McKenzie, D.P., 1989. Magmatism and rift zones: the generation of volcanic continental margins and flood basalts. J. Geophys. Res. 94, 7685–7730.

Wignall, P.B., 1994. Black Shales. Oxford Univ. Press, Oxford.

Will, H.J., 1969. Untersuchungen zur Stratigraphie und Genese des Oberkeupers in Nordwestdeutschland. Beih. Geol. Jb. 54, 1–240.

Zakharov, V.A., Shurygin, B.N., Levchuk, M.A., Pinous, O.V., Sahajian, D.L., 1998. Eustatic signals in the Jurassic and Lower Cretaceous (Neocomian) deposits of the West-Siberian sedimentary basin. Russ. Geol. Geophys. 39, 1493–1504.