Acta Geologica Polonica, Vol. 54 (2004), No. 4, pp. 611-627

The mid-Cenomanian eustatic low

JAKE M. HANCOCK

Department of Earth Science and Engineering, Royal School of Mines, Imperial College, London SW7 2BP, U.K.

ABSTRACT:

HANCOCK, J.M. 2004. The mid-Cenomanian eustatic low. *Acta Geologica Polonica*, **54** (4), 611-627. Warszawa.

Through much of the earlier part of the Middle Cenomanian the sea-levels in western Asia, northern Europe and the Western Interior of the U.S.A. were lower than during the later Early Cenomanian and most of the later Middle Cenomanian. In north-west Europe the first sign of this Mid-Cenomanian Eustatic Low was just before the end of the Zone of *Cunningtoniceras inerme*. There was then an abrupt and strong fall of sea-level at the base of Milankovitch couplet C 1, early in the Subzone of *Turrilites costatus.* Sea-level continued to be low through couplets C 1 to C 3 for some 60,000 years: this is the Mid-Cenomanian Regressive Trough. In western Germany it has been distinguished as the *Primus* Event. In north Texas and the Western Interior of the U.S.A. the Trough occurred in the Zone of *Conlinoceras tarrantense* which can be dated as 95.78 ± 0.61 Ma. A later regressive trough occurred at the start of the Subzone of *Turrilites acutus*, which is marked by the Mid-Cenomanian Event in Germany.

The overall lower sea-level from late in the zone of *C. inerme* to early in the subzone of *T. acutus* is the Mid-Cenomanian Eustatic Low. It lasted some 300,000 years.

Key words: Cenomanian, *T. costatus* Subzone, *Primus* Event, Mid-Cenomanian Event, Anglo-Paris Basin, Münster Basin, north Texas, Colorado, South Dakota.

INTRODUCTION

In 1876 the French geologist HÉBERT, working in the Paris basin, noted that his 'Craie á *Inoceramus labiatus*' "...est terminée par un banc durci á sa surface sur une épaiasseur variable de 20 á 50 centimètres, percé de tubulures, dans lesquelles pénètre la craie tendre de l'assise suivante...."; i.e. above the banc durci there was a break in sedimentation (HÉBERT 1876, p. 26). HÉBERT visualised that this break in sedimentation was associated with a shallowing of the sea. This seems to have been the earliest recognition that a horizontal break in marine sedimentation could represent a fall in sea-level. The idea was elaborated by BARROIS (1877, pp. 173-175) who distinguished between local hardgrounds (and associated breaks in deposition) and those widespread enough to be called 'oscillations générales'.

Almost all the early studies of such lows in sea-level in the Chalk were concentrated on the exceptionally strong regressive trough(s) around the boundary between Middle and Upper Turonian: the Chalk Rock of eastern and southern England; the hardgrounds near the base of the Pont de Caffiers Member in the Boulonnais (ROBASZYNSKI & AMÉDRO 1986). The earliest mention of a mid-Cenomanian trough is possibly a throw away remark by HUME (1894, p. 228). Amazingly, the regressive significance of the Rouen fossil bed and the hardground beneath at Côte St. Catherine does not seem to have been recognised until the work of JUIGNET (1971, 1980). His work is outstandingly important since his interpretation of the chalk rhythm from hardground to hardground (JUIGNET 1980, fig. 7a) is the first to show its relation to a transgressive-regressive cycle. The more recent work (in ROBASZYNSKI & *al.* 1999) puts the development into EXXON nomenclature but does not change

JUIGNET's interpretation. And JUIGNET (1980) had already recognised that the Rouen fossil bed marked a 'discontinuité majeure'.

I applied JUIGNET's method more generally to the British Chalk in the late 1980's (HANCOCK 1990): hardgrounds and condensed nodular beds in the Chalk were interpreted as regressive troughs, i.e. lows in sea-level; and mid-way points between hardgrounds were the dates of transgressive peaks, i.e. highs in sea-level.

This approach is still valid but in some chalks another line of evidence can also be used. As recognised by HATTIN (1966), more fully developed by KAUFFMAN (1969), and summarised by HANCOCK & KAUFFMAN (1979, fig. 3), where true pelagic chalks are interbedded with clays, the chalk:clay ratio is a measure of relative water-depth. The same criterion is also recognised by ROBASZYNSKI & *al.* (1999, p. 364). In the Cenomanian Chalk of north-west Europe there is an apparent complication to this signal: there are clay-chalk couplets which represent Milankovitch cycles (GALE 1989b; GALE & *al.* 1999). In practice this is not a problem. While sea-levels were low, each couplet has a thicker clay unit and a thin marly chalk unit (HART 1987, fig. 1a). While sea-levels were high, chalk dominates each couplet; the clay content of the chalk itself is low (HART 1987, fig. 1b): this can be measured by a grey-scale reflectance on fresh samples (HERBERT & FISCHER 1986; GALE & *al.* 1999).

SEA-LEVEL CHANGES IN NORTH-WEST EUROPE

There have already been recent discussions of the Cenomanian sequence-stratigraphy in north-west Europe, particularly by OWEN (1996) and ROBASZYNSKI & *al.* (1999). Their descriptions are in the terminology of EXXON sequence-stratigraphy 'whose jargon is legendary and off putting' (Peter Ciift, Woods Hole Oceanographic Institution, in letter). The EXXON system is not the only type of sequence-stratigraphy, as succinctly explained by HALLAM (1999); see also FÜRSICH & *al.* (1992). Therefore an attempt is made here to describe the changes during the late Early Cenomanian and early Middle Cenomanian in simple terms.

The detailed stratigraphy is provided by AMÉDRO (1993), PAUL & *al.* (1994), GALE (1995) and KAPLAN (in KAPLAN & *al.* 1998). The ammonite zonation goes back to WRIGHT, KENNEDY & HANCOCK (1984) but there have been important modifications in the above works. The Milankovitch couplet stratigraphy is from GALE (1995), each couplet of marly-clay and marly-chalk probably representing a precession cycle of 20 to 21 k.y. (ROBINSON 1986; BERGER & *al.* 1989), illustrated by HART (1987, fig. 1a, 1b).

Open sea chalk successions, e.g. Sussex

Zone of Mantelliceras dixoni *(Couplets B1 to B36)*

There is a break in sedimentation at several localities at the bottom of the Zone of *Mantelliceras dixoni*: this corresponds to a minor sea-level low. At Folkestone this is the base of Band 4 of KENNEDY (1969). The carbonate rich couplets B11 to B18, and particularly B13 - B17 (GALE 1995, fig. 4) correspond to a sea-level high: a peak which in 1990 I mistakenly placed at the start of the *dixoni* Zone.

There are minor oscillations in sea-level through B19 to B33, and then a low through clay dominated couplets B34 to B39, well seen in Southerham Grey Pit near Lewes in Sussex (GALE 1995, fig. 7a). The highest *Mantelliceras* in England is in B27, but higher *M. dixoni* probably occurs at Lengerich in Germany where it is recorded only 5.45 m below the base of the Zone of *Cunningtoniceras inerme* (KAPLAN & *al.* 1998, fig. 17). Thus the low of B34-B39 is in the highest part of the *dixoni* Zone and just into the base of the *inerme* Zone, the lowest *C. inerme* being found in England in couplet B37.

Zone of Cunningtoniceras inerme *(Couplets B37 to B42)*

In their monograph on the Ammonoidea of the Lower Chalk, WRIGHT & KENNEDY (1987, pp. 194-195) regarded *Cunningtoniceras* as a derivative of *Acanthoceras* and recorded *C. inerme* (PERVINQUIÈRE) from the *Turrilites costatus* Subzone. GALE (1989) showed that there are lower *C. inerme*, above the highest *M. dixoni* and below the lowest *Acanthoceras rhotomagense* and *Turrilites costatus* LAMARCK. These intermediate levels are now assigned to a Zone of *C. inerme*. In Britain the lowest *C. inerme* has been found in couplet B37 and the lowest *A. rhotomagense* (with *Inoceramus tenuis* MANTELL) occur in the limestone of couplet B43.

At Rheine-Waldhügel in the Münster Basin the *inerme* Zone is limited to couplet B42 (2.5 m) and possibly the basal part of B43 (Text-fig. 1), but at Lengerich there are about 5.6-5.8 m of *inerme* Zone. For interpretation of sea-level changes, one needs to use evidence from both England and Germany.

Couplets B37 to B39 represent the end part of the sea-level low which started near the end of the *dixoni* Zone.

B40 and B41 are relatively more carbonate rich than B39 below or B42 above, but sea-level will only have been slightly higher. B42 has an exceptionally prominent clay unit in the couplet, so much so that KAPLAN (in KAPLAN & *al.* 1998) uses this clay as a marker for the base of his *inerme* Zone in the middle and northern part of the Münster Basin. The chalky unit in couplet B42 is

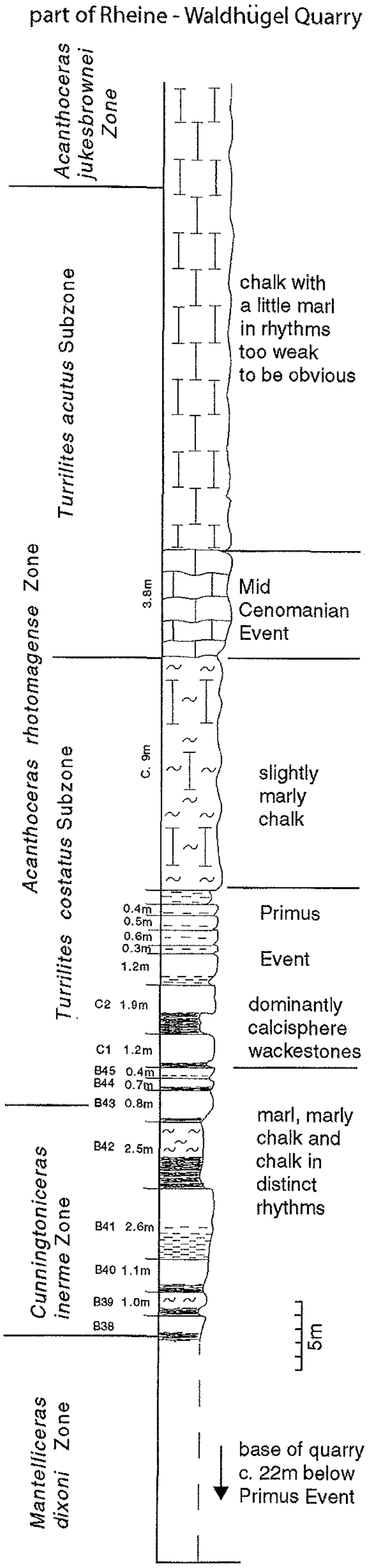

Fig. 1. Part of the succession in Rheine-Waldhügel Quarry, on the northern flank of the Münster Basin, approximately 2 km south of Rheine, 40 km west of Osnabrück, Germany. Based on MEYER (1990), GALE (1995) and KAPLAN in KAPLAN & *al.* (1998)

also relatively argillaceous. Couplet B42 represents a brief, sharp, lowering of sea level. This event marks the start of the broad Mid-Cenomanian Eustatic Low.

There is another possible interpretation of couplet B41, the couplet in which *Chlamys arlesiensis* (WOODS) is widespread. Andy Gale has pointed out to me that at several localities there is erosion beneath this bed, indicating a fall in sea-level immediately prior to B41. It could be that KAPLAN's prominent *inerme* Zone marl actually represents couplets B41 and B42 combined without a carbonate component.

Lowest part of the subzone of Turrilites costatus *(Couplets B43 to B45).*

Acanthoceras, particularly *A. rhotomagense* (BRONGNIART), probably appears simultaneously with *Turrilites costatus*: they may represent an immigration level into couplet B43 in north-west Europe. Couplets B44 and B45 have only been recorded in the Münster Basin (GALE 1995, fig. 10). Even couplet B43 is only present at a few localities in England and France, e.g. Folkestone, Lewes and le Cran d'Escalles. It is not known for certain if there are any more missing couplets above B45.

All these three couplets represent a slight re-rise of sea-level after the low of B42.

The deep regressive trough early in the costatus *Subzone: the* Primus *Event in Germany*

More than a quarter of a century ago it was pointed out that the sequence of facies is predominantly transgressive in the Upper Cretaceous of northern Europe; regressive sequences are mostly insignificant (HANCOCK 1975, p. 93). The fall in sea-level early in the *costatus* Subzone does not produce a startling effect on the lithic succession and the scarcity of near-shore regressive sediments means that its exact dating has to be assessed from the open sea facies.

Basinal successions: One of the most basinal successions is seen at Southerham Grey Quarry, near Lewes in Sussex (GALE in PAUL & *al.* 1994, fig. 10). The base of the couplet C1 is sharp and underlain by *Chondrites* indicating that this is an omission surface. Not only are couplets C1 to C3 so argillaceous that they are difficult to distinguish as distinct couplets, their combined thickness of 2.28 m is equal to $6^{1/2}$ couplets in the higher part of the *T. costatus* Subzone. At least two couplets were eroded away during the sharp fall in sea-level before C1 and the large amount of clay in C1 to C3 is a measure of how deep the trough was. The end of the really deep part of the trough was relatively abrupt, with deposition of couplets C4 to C6.

There is evidence of widespread erosion beneath Couplet C1. It rests on B45 at Wunstorf and Rheine in Germany (GALE 1995); on B44 at Lengerich; on B43 at Folkestone, Lewes and Cran d'Escalles; B42 at Eastbourne and Culver Cliff (Isle of Wight); B41 at Ventnor (Isle of Wight). And there may be younger couplets above B45 and below C1 still to be discovered. At Wunstorf, 25 km west of Hannover, where this is one of the most basinal successions in the Cenomanian of north Germany, there are prominent basal scours beneath C 1 (Markus WILMSEN and Birgit NIEBUHR, personal communication).

If the trough extended through three couplets, this would indicate a duration of at least 60 k.y., but of course if the succession below C1 is incomplete, it may have lasted longer.

Chalk successions influenced by underlying massifs: On the northern and eastern flanks of the Münster Basin and on the northern flank of the Harz Massif in the Lower Saxony Basin the strong trough is represented by a distinctive set of beds known as the *Primus* Event from the occurrence of the belemnite *Actinocamax primus* ARKHANGELSKY. The fullest succession is possibly seen at localities in Münsterland, described in detail by MEYER (1990). On top of couplet B45 there are 4.5 to 6.4 m of coarser chalk (calcisphere-wackestones) containing possibly as many as seven couplets (MEYER 1990, fig. 25) suggesting a duration of the effect of perhaps 150 k.y. But at basinal Wunstorf also the *Primus* Event is developed (MEYER 1990, fig. 4).

Even in the *Primus* Event beds, *A. primus* is not common, but there is a distinctive fauna – one of the 'pulse faunas' of JEANS (1973), his *Orbirhynchia* Band 2 (JEANS 1968). MEYER (1990) mentions thin-shelled bivalves (e.g. *Entolium*), brachiopods (*Orbirhynchia mantelliana, Grasirhynchia martini*), serpulids, solitary corals and small gastropods. All authors note the prevalence of *Chondrites* beneath omission surfaces The faunal features of the *Primus* Event are seen in other areas. Thus at Folkestone in England the basal 3/4 m is the Cast Bed of Price, famous for its composite moulds of gastropods. In the Pas de Calais the *Primus* Event is seen at le Cran d'Escalles in Bed 17 of AMÉDRO (1993).

A more spectacular development of the equivalent of the *Primus* Event is seen over the London-Brabant High in eastern England, where it is represented by the Totternhoe Stone. At some places, e.g. Chinnor (25 km south-east of Oxford), there is less than a metre of Totternhoe Stone underlain by small scours (SUMBLER & WOODS 1992). In other areas, including Totternhoe itself (3 km west of Dunstable), there are major erosional channels, tens of metres or more across, giving rise to thicknesses of the Stone up to 6 m (SHEPHARD-THORN & *al.* 1994; HOPSON & *al.* 1996); these sometimes cut down to the Zone of *Mantelliceras mantelli* in the lower Lower Cenomanian. At an intermediate locality, such as Houghton Regis (north of Dunstable), where the Totternhoe Stone is 3.8 m thick, the chalk matrix is coarser at the base and fines upwards. Near the base there are pebbles of phosphate and brachiopods floating in the chalk, rather than as a basal lag. Thomas MEYER has pointed to me that this is a debris-flow; there was a succession of these at some localities. The total fauna known from the Totternhoe Stone, which includes *A. primus* (see CHRISTENSEN 1990), is large (see WORSSAM & *al.* 1969, 58-59; SUMBLER & WOODS 1992; SHEPHARD-THORN & *al.* 1994). It probably represents a condensation of most of the Subzone of *Turrilites costatus.*

BLACK (1980, fig. 11) produced a detailed mechanical analysis of Totternhoe Stone from Burwell, 7 km north-west of Newmarket. The bulk of the material in Black's sample was sized a little below 0.04 mm, i.e. very fine sand on the Atterberg scale but coarse silt on the Wentworth scale. Most of this material was shell fragments, inoceramid prisms and benthic foraminifera, but about 3% is quartz sand. Coccoliths and coccolith debris make up no more than 10% of the rock and were probably the matrix of a debris-flow.

The subzone of Turrilites costatus *above the* Primus *Event and the subzone of* Turrilites acutus

Although there is a rise of sea-level after the Trough of the Primus Event, with a return to the normal sedimentation of chalk and marl couplets in basinal regions, it did not return to the highest sea-levels of the peaks in the *Mantelliceras dixoni* Zone, e.g. during couplets B13-1317. All through the Subzone of *T. costatus* the sea-levels were on the low side. At the start of the Subzone of *Turrilites acutus* there was another trough. During most of the *T. acutus* Subzone there was a distinctly higher sea-level again (Text-fig. 2).

This general picture shows well in the Münsterland sections (Text-fig. 1). KAPLAN (1998, figs 23-24) for Rheine-Waldhügel records 'kalkmergelstein' for most of the *costatus* Subzone but 'kalkstein' for the *acutus* Subzone. At the boundary between the two subzones is the 'Mid Cenomanian Event'. At Rheine this is up to 3.7 m thick and contains at least three couplets; towards the Teutoburger Wald there is an erosion lag with graded chalk (MEYER 1990). In the Lower Saxony Basin, at places like Salzgitter, there is a hardground with 'solution pebbles' (ERNST & *al.* 1983). Clearly this 'Mid Cenomanian Event' is a brief (c. 70 k.y.) but sharp fall in sea-level.

A similar pattern is seen at Eastbourne in Sussex where the records of KENNEDY (1969) show that the *acu-*

tus Subzone, particularly the upper half, is distinctly more calcareous, and the *costatus* Subzone more argillaceous. The equivalent of the Mid Cenomanian Event is found in KENNEDY's Band 6 with some 3½ couplets, the limestones being nodular as appropriate facies during a fall in sea-level. These beds are KENNEDY's *Orbirhynchia mantelliana* Band. MEYER (1990) has pointed out that the Mid Cenomanian Event in Germany corresponds to the 'mid-Cenomanian non-sequence' of CARTER & HART (1977): in the chalk of couplet C11 above the '*Orbirhynchia* Band' – but not in the band itself – there is an abrupt increase in the ratio of planktic:benthic foraminifera corresponding to the deepening of the sea with the *acutus* Subzone (CARTER & HART 1977, fig. 12), which they equated with an increase in water depth at the base of the Lincoln Limestone in Colorado.

The interpretation of the section at Grand Blanc-Nez, west of Calais, is not quite so clear. The clay rich couplets immediately above AMÉDRO's 3rd niveau á *Orbirhynchia mantelliana* in his Unit 19' possibly correspond to the Mid Cenomanian Event (AMÉDRO 1993, fig. 3). This Event

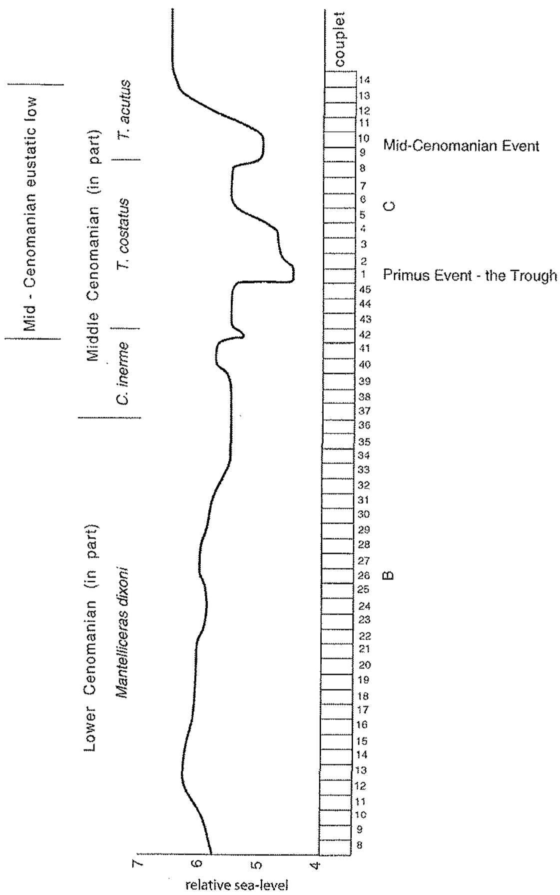

Fig. 2. Relative sea-level changes through the late Earth Cenomanian and early Middle Cenomanian, based on evidence in text. The succession of couplets is from GALE (1995)

does not seem to show up in the Calais area from the wonderfully detailed study of GRÄFE (1999).

Summary (Text-fig. 2)

Sea-level reached a high early in the *M. dixoni* Zone and then fell back. A broad and shallow but distinct low occurred during the latest *dixoni* Zone and through much of the *inerme* Zone. Near the end of the *inerme* Zone there was a brief sharp trough which marks the start of the general Mid-Cenomanian eustatic low, a dating recognised some years ago (HANCOCK 1993). There was a faint recovery of sea-level at the very beginning of the *Acanthoceras rhotomagense* Zone, *T. costatus* Subzone. Early in the *costatus* Subzone there was a rapid and very large drop in sea-level: this was the mid-Cenomanian eustatic Trough. Regression during the Trough cut down into earlier chalk. In most places, even in the basins, the earliest part of the *costatus* Subzone is missing. In some places much of the *inerme* Zone may be lost. In chalk successions over structural highs the trough induced the production of winnowed micro-wackestones and mass-flow deposits: the *Primus* Event in Germany.

Comparison with the succession in the Western Interior seaway in the United States suggests that nowhere onshore in north-west Europe is the sedimentary record complete across the Trough: the deepest part of the Trough is unrepresented. This would make it easier to understand that whilst C1 to C3 (and particularly C1) represents a low in sea-level, the sediments in C1 to C3 are transgressive. See discussion of the Thatcher Limestone in section 3 below. If this sounds an unlikely speculation, one should remember that it is now reckoned that there are no sediments representing 1 - 2 m.y. across the Albian-Cenomanian boundary in north-west Europe (GALE & *al.* 1996).

Sea-level only partly recovered during the later *costatus* Subzone, only to be hit by another sharp drop in sea-level at the end of the *costatus* Subzone. Sea-level started to fall before the end of the *costatus* Subzone, but the second rather deep trough of the Middle Cenomanian, lies very early in the *acutus* Subzone. It was only during the deposition of the main part of the *T. acutus* Subzone that sea-levels recovered to the heights that they had reached during the *dixoni* Zone peak.

Even the mid-Cenomanian eustatic Trough early in the *costatus* Subzone is not that obvious in most chalk successions. In their survey of 'event stratigraphy' of north-west Germany, ERNST & *al.* (1983) did not even recognise a *Primus* Event with its concomitant strong fall in sea-level. To get some measure of how severe the early *costatus* drop really was, one has to go to the margins of chalk basins, but it is not practicable to discuss all margins of all basins.

Chalk successions towards the margins of basins

Because there was little erosion on the remaining land areas during the Cenomanian (discussed in HANCOCK 1975), any drop in sea-level shows up as a hardground or the development of nodular chalk in the Chalk succession, even perhaps no more than 50 km from the shoreline.

South-west England

In spite of later work, all the essential detail is available in KENNEDY (1970). There were small earth movements in this region during the Cenomanian (e.g. SMITH 1957, 1961; DRUMMOND 1970), but these only produce local variations. It is a region of extreme condensation, the whole of the Cenomanian being only a metre or two thick on much of the coast (SMITH 1965).

The *dixoni* Zone peak is represented by Bed A of JUKES-BROWNE and HILL on the Dorset-Devon coast; a shelly limestone containing a little quartz-sand which often rests directly on Upper Greensand facies (highest Albian or basal Cenomanian) (SMITH 1961).

Inland, the *dixoni* Zone peak is represented in the higher grizzle facies (nodular calcareous sandstone) in the upper part of the Wilmington Sands.

No evidence has been produced of an *inerme* Zone in this region and only at a few localities has any *costatus* Subzone sediment been formed and survived, e.g. in the pebbles of phosphatised calcareous sandstone within the highest grizzle facies at the top of the Wilmington Sands.

The Mid-Cenomanian Regressive Trough, indeed, the whole mid-Cenomanian eustatic low, is seen on the prominent hardground (named on the coast as the King's Hole Hardground by JARVIS & WOODROOF 1984) which is overlain by various sorts of limestones with a phosphatised *acutus* Subzone at the base, e.g. Snowdon Hill, Chard; Maiden Newton, north-west of Dorchester. At a few places, e.g. Small Point on the west side of the beach at Beer, west of Seaton, glauconitic sandy limestone (Bed B) which is probably *acutus* Subzone, rests directly on Upper Greensand.

Normandy

The extremes of marginal developments seen near the Devon-Dorset border have not been preserved in Normandy, but there are also several differences from central Dorset. In particular the Cenomanian on the Pays de Caux coast in northern Normandy contains glauconite and chert which are almost absent in mid-Dorset. Like south-west England, there were minor earth movements but not sufficient to interfere with the pattern of sea-level controls.

This is the region of the Rouen Fossil Bed, known to geologists for some two centuries, but this is not the best place to start the description because it is so condensed. The detailed sections by JUIGNET in JUIGNET & KENNEDY (1976) show that the successions at places like the Falaise du Cap Fagnet (their fig. 7) and the Carrière de la Vallèe at La Perrière (their fig. 13) contain two Rouen hardgrounds: the lower one, 'Rouen No. 1 Hardground', lies near the base of the Subzone of *T. costatus*; the higher one, 'Rouen No. 2 Hardground', appears to be within, or close to the base of the Subzone of *T. acutus*. These two correspond to the *Primus* Event and the Mid-Cenomanian Event of Sussex and the Münsterland.

At la Côte Sainte-Catherine in Rouen (JUIGNET & KENNEDY 1976) these two hardgrounds have coalesced. Rouen lies over a structural high, the Ride de Rouen (JUIGNET 1980). The phosphatised fossils on this joint hardground are mainly *costatus* Subzone material but include *acutus* Subzone forms. There does not seem to be evidence of the *inerme* Zone which was either never deposited or removed by erosion during the mid-Cenomanian eustatic low, deposition as no more than phosphatised fossils starting in the later part of the *costatus* Subzone and continued into the *acutus* Subzone. Only during the later part of the *acutus* Subzone was sea-level high enough again for ordinary sedimentation of glauconitic chalk to return.

Rouen No. 1 Hardground is still developed at the base of the glauconitic chalk of the Craie de Théligny in Maine, 16 km south of Nogent-le-Rotrou, some 130 km south of Rouen. There is some indication that older elements occur in the phophatised ammonites as one goes southwards because *Cunningtoniceras inerme* is recorded from the base of the equivalent of the Craie de Théligny at la Perrière, 29 km west-north-west of Nogent-le-Rotrou (KENNEDY & JUIGNET 1993). *Cunningtoniceras* has been figured from Nogent-le-Rotrou itself (KENNEDY & HANCOCK 1970, pl. 93, fig. 2)

Marginal facies with clastics

In spite of a non-seasonal climate and low relief on the land, there were some regions in north-west Europe where clastic sediments formed at the margins of the basins. In central Europe in northern Bohemia and south-east Germany the regime was different and there are thick clastic successions (HANCOCK 1975).

In some marginal areas the Middle Cenomanian is absent and there is no record of the eustatic low being discussed here. On the south-western border of the Münster basin the upper Upper Cenomanian Zone of *Metoicoceras geslinianum* rests directly on the Lower Cenomanian (Zone of *Mantelliceras saxbii* – WIEDMANN & SCHNEIDER 1979).

Le Mans area, Maine

This basin-marginal region, of mostly arenaceous sediments, is more difficult to interpret than might be expected. There are now few exposures in the hillside ('La Butte du Mans') on which much of older Le Mans is built. Piecing together data from a borehole put down north of the Gazonfier suburb, recorded in outline by JUIGNET (1973), and a section seen in the 19th century in the foundations of the tram station on the south side of the hill, recorded by GUILTIER (1886, fig. 35), the succession is:

Sables et Grès du Mans 16.8m
with argile grise (0.8 m) at base (eustatic trough)

Sables et Grès de la Trugalle 24.0 m
with coarse glauconitic sandstone (this sandstone represents containing *Anorthopygus orbicularis* a hardground immediately (Grateloup) and numerous other beneath the mid-Cenomanian fossils, surmounted by sandy clay eustatic trough) at top (1.4m).

Elsewhere in the Sarthe the *Anorthopygus* sandstone is equated with hardgrounds: the Dollon Hardground and the Théligny Hardground. The ammonite fauna known from the Sables et Grès du Mans shows that its basal part belongs to the Subzone of *T. costatus* (JUIGNET 1974, 1977; KENNEDY & JUIGNET 1983, 1993). Hence the sea-level interpretation given above. The argile grise at the base can be interpreted as the transgressive sediment following the mid-Cenomanian eustatic low.

Thus the eustatic Trough is not conspicuous in this near-shore succession. It is not until one gets about 30 km east and north-east of Le Mans where the Craie de Théligny, representing the deeper water of the higher part of the *costatus* Zone, starts to be developed, that one sees a sharp vertical change of facies.

Only the summit of the underlying Sables et Grès de la Trugalle has ever been seen at Le Mans itself. Although there have been exposures at Yvré-I'Evêque and at La Trugalle near Le Mans, neither showed critical parts of the succession. One has to go 10 km north-east of the centre of Le Mans to Savigné-I'Evêque where there are two small cycles of sea-level change in the upper part of the Formation. The lower cycle, some $3^{1/2}$ m thick, is a clearer development (JUIGNET 1968, fig. 7; 1974, fig. 111A). It starts with deeper water fine grained glauconitic sands. On top of this are cross-bedded coarse sands: a small development of sandsteinbank facies deposited in water shallow enough to be tidally controlled (HANCOCK 1975). On top of the sandsteinbank lithology is a carbonate-cemented hardground ('Longueville no. 1').

These shallow water cross-bedded sands and hardground on top possibly correspond to couplet B42 in basinal successions at the top of the *inerme* Zone. If this is true, the top part of the Sables et Grès de la Trugalle will fall into the Subzone of *T. costatus*. Only a few ammonites are known from this formation and most of them clearly belong to the Zone of *M. dixoni* (e.g. *Mantelliceras dixoni* SPATH, formerly recorded as *Metacalycoceras orbignyi* COLLIGNON). Older records are sometimes suspect because of uncertainties over the boundary between the Grès de la Trugalle and the Grès du Mans. There are still modern records of *Turrilites costatus* itself from the upper part of the Grès de Lamnay (which are believed to be equivalent to the Grès de la Trugalle) by KENNEDY & JUIGNET (1983). According to WRIGHT & KENNEDY (1996, p. 358): '*Turrilites costatus* is common in the lower half of the *Acanthoceras rhotomagense* Zone, where it serves as a subzonal index. Records from the Lower Cenomanian are based on fragments of other taxa'.

The recovery of sea-level through the *costatus*, and more particularly the *acutus* Subzone, are seen in the Sables et Grès du Mans. The higher sea-level after the mid-Cenomanian low, at the base the formation, is shown by the development of greensand facies, particularly near the summit of the Sables et Grès du Mans. Rouen No. 2 Hardground may once have been exposed in the lower part of the Carrières de Butte du Mans (GUILLIER 1886, fig. 36) but has not been detected in recent years.

County Antrim, Northern Ireland

The Trough is probably represented by one of the levels with phosphatic nodules in the top part of the Glauconite Sands of the Hibernian Sandstones Group. *Actinocamax ? primus* is known from several specimens from four localities in Co. Antrim (HANCOCK 1961; CHRISTENSEN 1990).

The lesson of Antrim is that the mid-Cenomanian eustatic Trough was not great enough to always show up in a marginal succession. The whole of the Cenomanian in Antrim is only 2-13 m thick.

Central Europe

On the flanks of the Bohemian Massif in the Czech Republic and in Saxony (Germany) marine Middle Cretaceous is absent, even in the Dresden Trough, and is represented by the non-marine Niederschöna Formation (Saxony) and the Peruc Formation (TRÖGER 1996). Since there is marine upper Lower Cenomanian (Meissen Formation), this non-marine Middle Cenomanian is probably mainly the result of a regional tectonic uplift.

Eastern Europe to central Asia

Only a few localities can be mentioned here, but in all of these the affects of non-deposition and submarine erosion during the mid-Cenomanian was severe.

In the Central Polish Uplands there was a tectonic interference, with the result that the Cenomanian is usually condensed (MARCINOWSKI & RADWAŃSKI 1989). Thus at Annopol, 63 km south-west of Lublin and on the north-east flank of the Holy Cross massif, there is only 2.7 m of Cenomanian: the Lower and Middle Cenomanian faunas are so mixed by re-working that it is probably impossible to know how much is missing. In the Polish Jura Chain at places like Sucha and Glanów, around 35 km north-north-west of Kraków, condensed upper *rhotomagense* Zone rests directly on the *Mantelliceras mantelli* Zone (at Sucha), or even on the Oxfordian (at Glanów) (MARCINOWSKI 1974).

Even relatively expanded chalky successions in this vast region, such as that at Selbukhra in the Crimean Highland, around 30 km south of Simferopol, show a large break (MARCINOWSKI 1980; NAIDIN & ALEKSEEV 1981; GALE & *al.* 1999). Submarine erosion went down to the top of the *dixoni* Zone and sedimentation did not re-start until near the end of the *costatus* Subzone.

In the Mangyshlak Hills in western Kazakhstan there was not quite so much erosion during the eustatic low, but sedimentation did not resume until the high Middle Cenomanian Zone of *Acanthoceras jukesbrownei* (NAIDIN & *al.* 1984; MARCINOWSKI & *al.* 1996; GALE & *al.* 1999, figs 4 and 6).

In all these three areas the amount of the succession missing in the lower Middle Cenomanian is too great to elicit the sort of detail which is possible in north-west Europe.

U.S.A.: COLORADO, SOUTH DAKOTA, TEXAS

The Rocky Mountain Seaway (Text-fig. 3)

During most of the Late Cretaceous there was a seaway-connection, up to 1,400 km wide, between Arctic Canada and Mexico. As world sea-level rose and fell the boundaries of this linear "Western Interior" basin widened and narrowed. Of course, these transgressions and regressions were also affected by earth-movements, such as the Sevier Orogeny and early part of the Laramide Orogeny. Overall the combination of tectonics and eustatic changes are reflected in a pattern of facies which has been studied for many years: see particularly WEIMER 1960, 1984, 1986; KAUFFMAN 1969; KAUFFMAN & *al.* 1969; MCGOOKEY & *al.* 1972; DYMAN & *al.* 1994). For the interaction with tectonics, see MEREWETHER & COBBAN (1986).

The western side abutted the proto-Rockies which provided large quantities of detritus into the seaway-basin. On this side the position of the shoreline is often relatively easy to fix. The lower lying land on the eastern side suffered little erosion and the eastern limits of the seaway are often uncertain.

A map of the time under discussion is provided by COBBAN & *al.* (1994, fig. 4). Pueblo in Colorado was around the middle of the seaway, about 250 km east of the western shoreline. Maverick Junction in South Dakota was also around the middle of the seaway, about 300 km west of the eastern shoreline. The Fort Worth – Dallas area was more part of the Gulf of Mexico Basin rather than the Western Interior Seaway.

Colorado

The relevant succession in Colorado is well described by COBBAN & SCOTT (1972). In the middle of the Graneros Shale (a grey, fissile, silty clay) is developed a prominent thin limestone, the Thatcher Limestone Member (Text-fig. 4). Only centimetres beneath the limestone there is a persistent bentonite (COBBAN & SCOTT 1972, fig. 6). There has been erosion beneath this bentonite, although the length of the break is unknown. The shale sediment only resumed for a few cm before there was more submarine erosion. On this erosion surface the Limestone itself was deposited. In the sections around 200 - 500 m east and north-east of the dam of the Pueblo Reservoir in southern Colorado the Limestone forms a prominent feature in the hillside. It varies between 0.2 and 0.4 m thick (occasionally going down to 0.15 m) because the base is strongly erosive; there is a sharp top but no great break other than a burrowed surface beneath the higher Graneros Shale.

At Pueblo the Thatcher Limestone is largely massive but in more weathered sections at Old Hatchet Ranch, on Greenhorn Creek, south of Pueblo, the Limestone is divided into at least six beds, some of which are themselves laminated calcarenites; some contain mud-flake pebbles.

When Graneros Shale sedimentation re-started it is not only micaceous and silty but contains cm long lenticles of fine sand. Perfect preservation of laminations confirms the complete absence of benthos, i.e. the smothering of carbonate forming organisms was rapid, and sea-level rise was probably rapid.

The interpretation of the succession through the Thatcher Limestone needs some careful argument. The Limestone itself reflects a water-depth shallow enough to allow carbonate building organisms to flourish. Maximum useful light penetration is almost 100 m but for the Thatcher Limestone something in the range of tens of metres is more likely. The occurrence of *Ostrea beloiti*

LOGAN indicates water probably no more than 15 m deep (KAUFFMAN & *al.* 1977). The Graneros Shales, both below and above, is probably deeper: hence the scarcity or absence of benthos, even burrowers.

Another way of looking at this succession is in terms of the standard lithologies of KAUFFMAN (1969), related to regressions and transgressions in the Western Interior (HANCOCK & KAUFFMAN 1979). The Graneros Shale is largely his lithology 6: dark clay-shale, finely laminated, possibly more than 60 m water-depth. The Thatcher Limestone is his lithology 4a: shallow water, rusty brown calcarenites; water-depth no more than 15 m. The higher the lithology number, the deeper the water. So in going from Graneros Shale beneath the Limestone into the Limestone itself one is not merely going into shallower water, but a jump in shallowing: lithology 5 (which is a shale with numerous septarian and carbonate concretions) is not represented.

The degree of the erosion beneath the Thatcher Limestone is unknown but it must have been substantial since south of Pueblo it has gone down below the bentonite. The Limestone, although a shallower facies than the enclosing Graneros Shale, is a transgressive deposit on the erosion-surface at its base (KAUFFMAN & PRATT 1985).The Thatcher Limestone transgression is described by COBBAN & *al.* (1994) who showed that the transgression extended along the Rocky Mountain seaway into Canada. The pre-Thatcher Limestone erosion is so marked that it must represent a very rapid drop in sea-level.

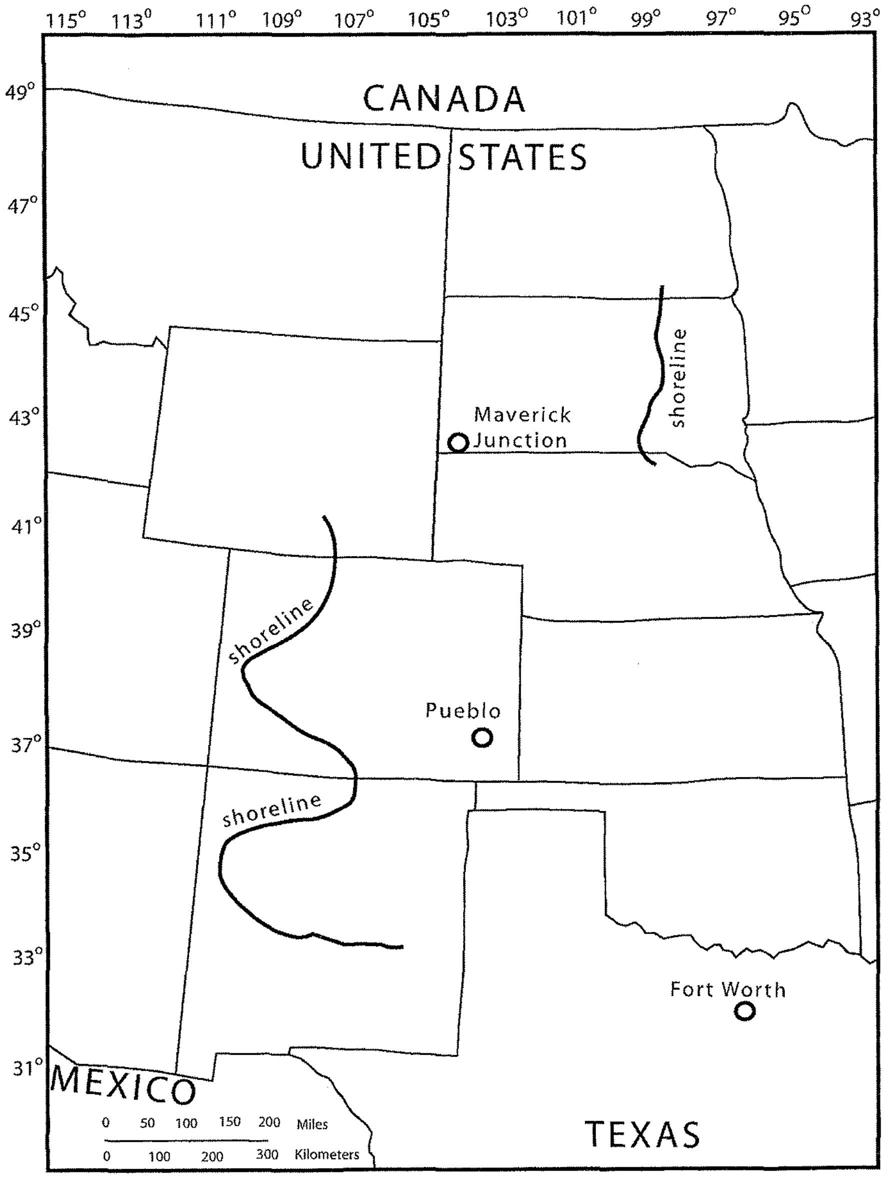

Fig. 3. Position of localities in the U.S.A. mentioned in the text (derived from COBBAN & *al.* 1994, fig. 4)

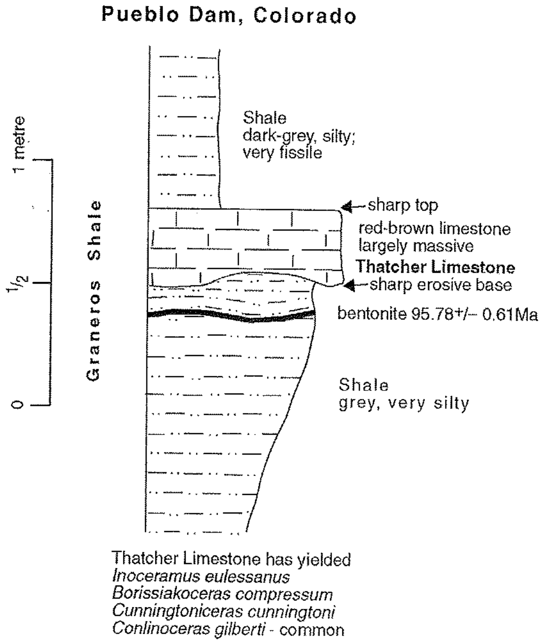

Fig. 4. Part of the section around 500 m east of the dam in Pueblo State Recreational Park, south-east Colorado. The date of the bentonite is from OBRADOVICH (1994). Ammonite records are from COBBAN & SCOTT (1972)

The ammonites known from the Thatcher Limestone include: *Conlinoceras tarrantense* (Adkins) – the most common ammonite by far (see COBBAN & SCOTT 1972, fig. 7); formerly recorded as *Calycoceras* (*Conlinoceras*) *gilberti* COBBAN & SCOTT; used as a zonal index. *Paraconlinoceras leonense* (ADKINS), *Cunningtoniceras cunningtoni* (SHARPE), *Borissiakoceras compressum* COBBAN; *Turrilites scheuchzerianus* BOSC, *Turrilites actus* PASSY. In addition there is the stratigraphically valuable inoceramid, *Inoceramus eulessanus* STEPHENSON, *C. cunningtoni* is now known to be mainly a species of the Zone of *C. inerme* (GALE & *al.* 2002). *T. acutus* characterises its own subzone, and is known to extend above the Thatcher Limestone into the highger Graneros Shale. Thus, in terms of the north-west European succession, the Thatcher Limestone represents a sea-level low from couplet B42 (possibly even as low as B37) up to couplet C10 (see Text-figs 2, 7).

The Thatcher Limestone is obviously condensed. Its 0.2 to 0.4 m is represented by about 8 m in the chalk-marl facies at Escalles near Calais (AMÉDRO 1993); and by about 28 m of marly clays and marly limestones at Vergons in the Vocontian trough in Provence (GALE 1995).

South Dakota (Text-fig. 5)

The critical section at Maverick Junction in South Dakota has not previously been described in detail. I am indebted to Bill Cobban of the U.S. Geological Survey for introducing me to the region and giving me details of the fossils he has found. Although this area is a similar distance from a shoreline as Pueblo, there was less detritus available.

The main part of the Belle Fourche Snare is of black laminated shales, possibly even less aerated than the Graneros Shale of Colorado.

It is possible that the thin beritonite corresponds to the bentonite beneath the Thatcher Limestone. It was not possible to detect if there was sub-bentonite erosion.

The Junction Bed (Text-fig. 5) has yielded *Conlinoceras tarrantense, Borissiakoceras compressum* and *Inoceramus eulessanus*, and clearly correlates with the Thatcher Limestone but is a very different lithology. It is even possible that the 10 cm limestone on top of the Junction Bed is the actual equivalent.

The Junction Bed lithology is not easily interpreted and although only 1/4 m thick, may involve several sedimentological environments. The quartz sand indicates shallower water than the rest of the Belle Fourche Shale. The clay pebbles show that there was contemporaneous re-working. The rapid changes in lithology suggests condensation. This Junction Bed is the South Dakota represetative of the Mid- Cenomanian Eustatic Low, but the evidence is not tight enough to fix the lower and upper limits in time.

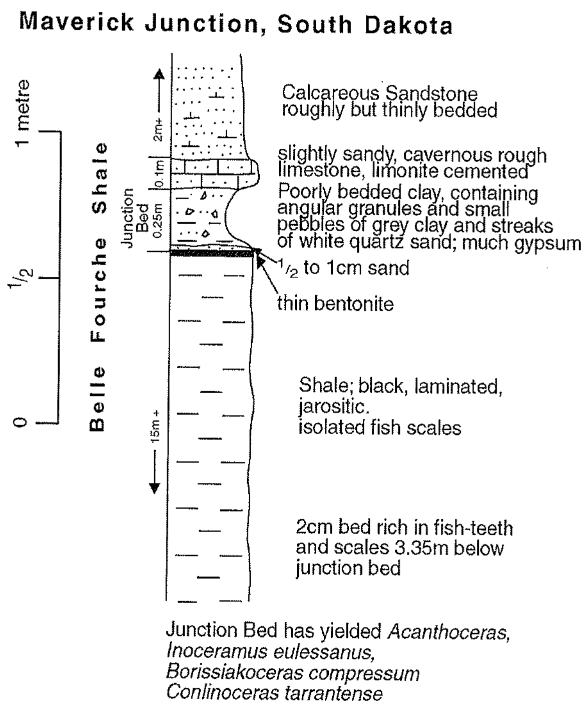

Fig. 5. Part of section in hillside beside route 79, opposite the Dakota Rose Restaurant, 7 km south-east of Hot Springs, Fall River County, south-west South Dakota. Ammonites from records of Dr. W.A. COBBAN

Texas (Text-fig. 6)

Although there was often a marine connection across New Mexico and western Texas between Mexico and the western interior seaway, the Cretaceous of Texas lies in the Gulf of Mexico Basin. This is emphasised because the pattern of sea-level changes in Texas is often not that of the broad eustatic pattern, whether one uses the standard of HANCOCK & KAUFFMAN (1979), HAQ & *al.* (1989), or HANCOCK (1990) for the British Isles. This discrepancy was already recognised by YOUNG (1986) in his study of sea-level changes over the San Marcos Platform in central Texas. It has recently been found to be true for the main rise in sea-level from Turonian into Coniacian in the Dallas area (HANCOCK & WALASZCZYK 2004). In the Gulf of Mexico Basin there were broad movements of the crust of the type which used to be called 'epeirogenic'.

On the other hand, fine details of eustatic movements can often be picked out, specially if they were strong enough. These complications mean that one needs to consider a greater part of the succession than has been done for Colorado and South Dakota.

Part of the Lower Cenomanian Zone of *Mantelliceras mantelli* extends as marine sediment from north Texas (main part of the Grayson Marl) to the far south-west as Buda Limestone, a distance of some 800 km. The top part of the Grayson Marl (above the Modlin Limestone) in the Fort Worth – Dallas area belongs to the local Zone of *Budaiceras hyatti*. This Zone probably ranges from the upper part of the *M. saxbii* Subzone into the *M. dixoni* Zone in European terms (HANCOCK & *al.* 1994). Hence the overlying Woodbine Formation probably belongs to the Zone of *M. dixoni* since the Woodbine Formation itself is overlain by the Zone of *C. tarrantense*.

The Woodbine Formation contains some marine fossils (mainly gastropods and bivalves such as mytilids) at several levels, but no ammonites or inoceramids. Most of the Formation in the Fort Worth – Dallas district is a 'coastal barrier facies' and 'channel-mouth bar facies' (OLIVER 1971). There is a detailed and complicated lithostratigraphy, best described by DODGE (1969; fig. 2 of DODGE is reproduced by KENNEDY & COBBAN 1990, fig. 2).

DODGE recorded a break between his Arlington Limestone Member (at the top of the Woodbine Formation) and the overlying Tarrant Formation at the base of the Eagle Ford Shales Group (Text-fig. 6). At Fort Worth – Dallas Airport the top of the Arlington Limestone is an undulating surface studded with oysters. Nearer Dallas the base of the Tarrant Formation is said to be on a marked unconformity with a basal phosphatic conglomerate (BROWN & PIERCE 1962).

The bottom metre of the Tarrant Formation represents the sudden return to full marine conditions and yields: *Conlinoceras tarrantense* (common), *Metengonoceras dumbli* (CRAGIN) (common), *Paraconlinoceras barcusi* (JONES). *Cunningtoniceras ineme, Forbesiceras conlini* STEPHENSON, *Turrilites dearingi* STEPHENSON (rare). The *C. inerme* gives a correlation with the *inerme* Zone of Europe; the *C. tarrantense* correlates with the Thatcher Limestone, at least in part. *T. dearingi* is similar to *T. acutus* and is often regarded as a synonym: if so the basal part of the Tarrant Formation embraces the same stratigraphic range as the Thatcher Limestone: *inerme* to basal *acutus* Zone.

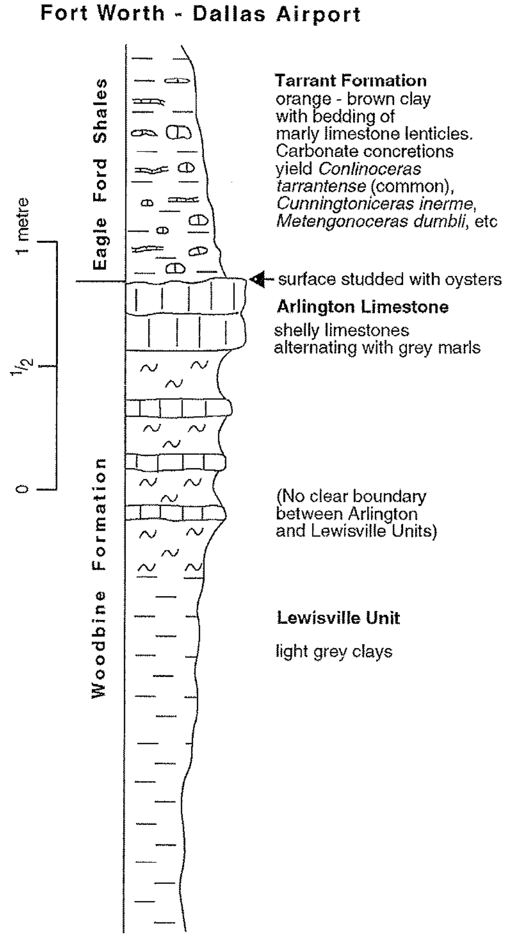

Fig. 6. Section beside stream spillway, south-east of control gates at airport entrance on south side of Fort Worth-Dallas airport. Section measured in 1973. Ammonite records from HANCOCK & *al.* (1994). Those readers familiar with the geology of north Texas may note a potential anomaly in this section. Following STEPHENSON (1952) the highest unit of the Woodbine Formation is the Templeton Member which is high Middle Cenomanian and low Upper Cenomanian (HANCOCK & *al.* (1994), i.e. much younger than the Tarrant Formation of the Eagle Ford Group. The Templeton Member is oOnly known some distance to the north of Dallas – Fort Worth, mainly in Grayson County. Either the Woodbine Formation – Eagle Ford Group boundary is extraordinarily diachronous, or the Templeton Member is really a partial synonym of the Britton Formation of the Eagle Ford Group. The problem does not affect the subject of this paper. For more discussion of this problem see NORTON (1965, p. 55)

That the basal metre of the Tarrant Formation does not range above the low part of the *T. acutus* Subzone is shown by the fact that the higher Texas Zone of *Acanthoceras bellense* is itself still within the *acutus* Subzone (HANCOCK & *al.* 1994, section 21).

Thus the Fort Worth succession is similar to that at Pueblo in that both have a *C. inerme* Zone transgression resting on an erosion surface. But the Thatcher Limestone in Colorado rests on a deeper water facies; the base of the Tarrant Formation rests on a distinctly shallower water facies in the Woodbine Formation. In fact, the whole of the Woodbine and Tarrant Formations indicate relatively low sea-levels in north Texas at this time. As one goes southwards from Fort Worth towards the San Marcos Platform, both formations disappear. By 60 km south-south-west of Waco the Zone of *Acanthoceras bellense* (equivalent to part of the *T. acutus* Subzone) represented by the Bluebonnet Member in the Lake Waco Formation, rests directly on one of the *Graysonites* zones in the Grayson Marl (probably the equivalent of the lower part of the *Mantelliceras mantelli* Zone). Put another way, the whole of the upper part of the *mantelli* Zone, the *dixoni* Zone, the *inerme* Zone and the *costatus* Subzone of Europe are all missing (see WILLIAMSON in BARNES 1970; ADKINS & LOZO 1951; KENNEDY & COBBAN 1990; HANCOCK & *al.* 1994). This is the 'mid-Cenomanian unconformity' of SALVADOR (1991, 418-422).

Other regions

A major eustatic fall and subsequent rise in sea-level will not be limited to a belt from central Asia through northern Europe to the U.S.A. There is scope for investigation in other regions.

GALE (1995) has recorded appropriate lithological changes in the Vocontian Basin.

In Tunisia, ROBASZYNSKI & *al.* (1993) have examined in detail the Cenomanian succession in the area east of Kalaat es Senam, around 200 km south-west of Tunis. They record a 'lowstand wedge' of 115 m (in a section around 620 m) which starts at the base of the *C. inerme* Zone and extends through the *T. costatus* Subzone and possibly just extends into the base of the *T. acutus* Subzone. This is approximately in agreement with north European evidence.

Further south in Tunisia at Djebel Mrhila, north-east of Sbeitla, Jim KENNEDY and I have found two regressive nodular limestones in a dominantly clay succession in the Middle Cenomanian.There is some ammonite evidence

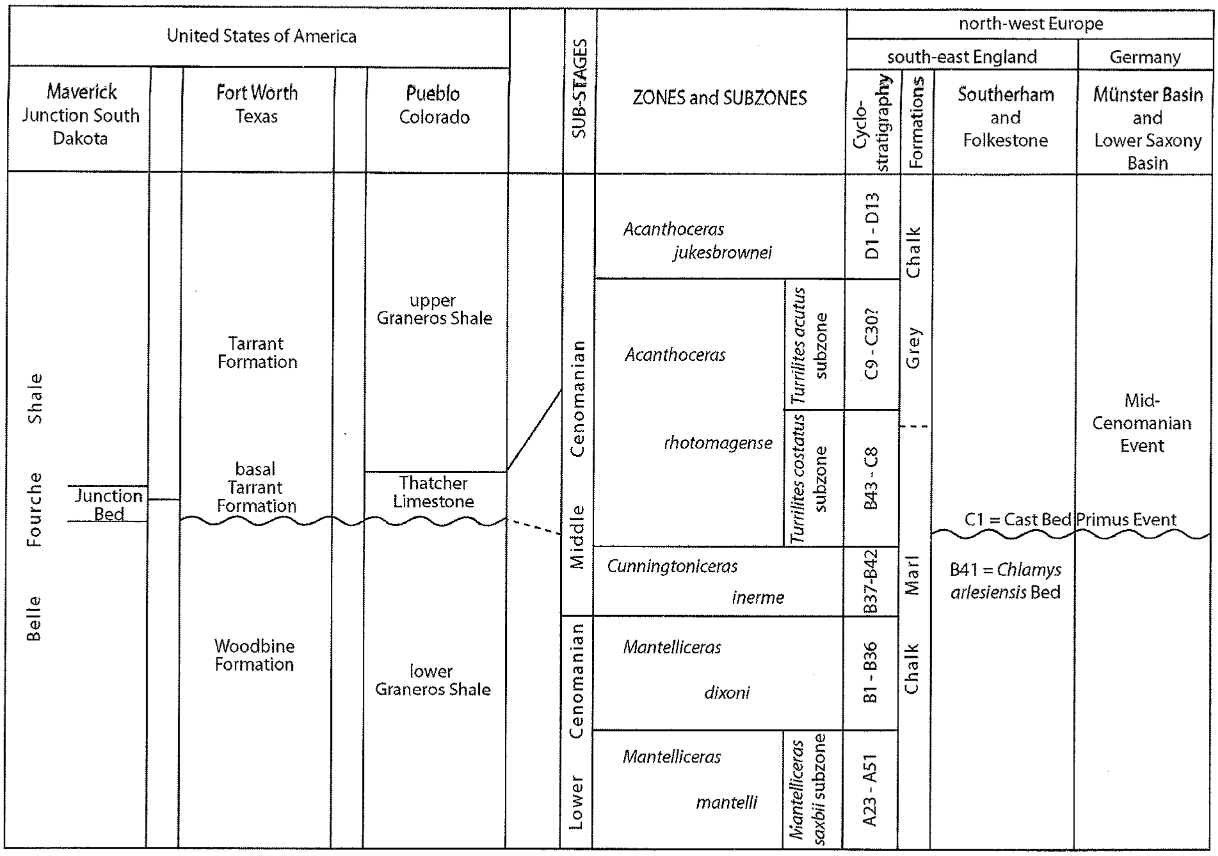

Fig. 7. Outline correlation of the top Lower Cenomanian and Middle Cenomanian between western USA and north-west Europe

that these may correspond to the eustatic lows of both the *Primus* Event and mid-Cenomanian Event.

Andy GALE and Jim KENNEDY have now examined the ammonite succession in the Cauvery Basin of Tamil Nadu in southern India (GALE & *al.* 2002). This shows a marked eustatic low at precisely the same level as the *Primus* Event in Europe, i.e. the same regressive trough; local zone in India is *Cunningtoniceras cunningtoni* (= *Ammonites meridionale* (STOLICZKA)). There is a higher eustatic low in the middle of the local range of *Turrilites acutus* which might be the equivalent of the Mid-Cenomanian Event.

Much more exploration is possible.

CONCLUSIONS

1. The Mid-Cenomanian Eustatic Low and its Trough were real and strong enough to affect successions from the Western Interior of the USA to western Kazakhstan in central Asia. The effects are detectable in sediments deposited in depths ranging from a coastal barrier facies in north Texas and tidally controlled sands on the south-west flank of the Paris Basin, to pelagic facies accumulated in water perhaps 100 m deep in Sussex in southern England and in the Pas de Calais in northern France.

2. The deep water succession provides the most reliable evidence of the exact relative timing of the sea-level changes and of the Trough itself. The maximum drop in sea-level was sudden, early in, but not at the start of, the Subzone of *Turrilites costatus* in Europe and the Zone of *Conlinoceras tarrantense* in the USA. The time was 95.78 ± 0.61 Ma from the dating of the associated bentonite in Colorado (OBRADOVICH 1994).

3. The vertical scale on Text-fig. 2 is approximate and unquantified; it is approximately the same as I have used in the past, e.g. HANCOCK 1990, fig. 11, which already showed the Mid-Cenomanian Low.

To estimate these changes in metres is not easy. The duration of the extreme low – the Trough – was no more than about 60,000 years, too brief to allow a widespread regressive facies to be formed and preserved. Most commonly the Trough is simply represented by an erosion surface. In Antrim there was only a pause without even a change of facies across the Trough. This may suggest that the Trough was no more than a fall of 10-30 m.

On the other hand the rise in sea-level late in the *costatus* Subzone across a now eroded surface, was sufficient in the north-east Sarthe for the lithology to change from sands, cross-bedded in places, deposited in depths possibly less than 5 m, to glauconitic chalk which probably involved a water depth too great for high light penetration, i.e. more than 30 m. This implies that the increase in water depth during the *costatus* Subzone was at least 25 m and could have been 50 m.

4. The evidence in Colorado is important in demonstrating the changes in sedimentology across a regressive trough in sea-level, principles which were worked out by Erle KAUFFMAN more than 30 years ago (KAUFFMAN 1969). The Thatcher Limestone is simultaneously transgressive but a shallower water facies than the underlying Graneros Shale. When this pattern is transferred to north-west Europe we find that couplets C1 to C3 represent transgressive sediments although their high clay:carbonate ratio shows that the sea-level was lower than the highest sediments beneath the trough, the sediments which are topped by a surface which is both a surface of erosion and a transgressive surface.

Acknowledgements

This has been a field based study and I am indebted to geologists, too numerous to list fully, for help in the field: Vladimir BENJAMOVSKY, Bill COBBAN, Charlie DODGE, Andy GALE, Erle KAUFFMAN, Jim KENNEDY, Ryszard MARCINOWSKI, Thomas MEYER, Dimitri NAIDIN, Ray PARISH and Irek WALASZCZYK. The ideas expressed result from conversations with Erle KAUFFMAN, Bill COBBAN, Jim KENNEDY, Dave OWEN. Andy GALE, Peter VAIL and Jan HARDENBOL. The ms has been checked by Bill COBBAN, Andy GALE and Jim KENNEDY but none should be blamed! Andrew BOWMAN and Karla KANE drafted the figures and Betty ROSSI arranged the lay-out.

REFERENCES

ADKINS, W.S. & LOZO, F.E. 1951. Stratigraphy of the Woodbine and Eagle Ford, Waco area, Texas. *In*: F.E. LOZO & B.F. PERKINS (*Eds*), The Woodbine and adjacent strata of the Waco area of central Texas. *Fondren Science Series*, **4**, 101-164.

AMÉDRO, F. 1993. La lithostratigraphie et les bofacies: des outils de corrélation dans les craies Cénomaniennes de detroit du Pas de Calais. *Annales Société Géologique du Nord* (2) **2**, 73-80.

BARNES, V.E. (*Ed.*) 1970. Waco sheet. Geologic Atlas of Texas, 1:250,000. Bureau of Economic Geology, University of Texas.

BARROIS, C. 1877. Recherches sur le terrain crétacé supérieur de l'Angleterre et de l'Irlande. *Mémoires Société Géologique du Nord*, **1**, 1-232.

BERGER, A., LOUTRE, M.F. & DEHANT, V. 1989. Pre-Quaternary Milankovitch frequencies. *Nature*, **323**, 133.

BLACK, M. 1980. On Chalk, Globigerina ooze and aragonite mud.

In: C.V. Jeans & P.F. Rawson (*Eds*), Andros Island, Chalk and oceanic oozes. *Occasional Publications Yorkshire Geological Society*, **5**, 54-85.

Brown, C.W. & Pierce, R.L. 1962. Palynologic correlations in Cretaceous Eagle Ford Group, northeast Texas. *Bulletin of the American Association of Petroleum Geologists*, **46**, 2133-2147.

Carter, D.J. & Hart, M.B. 1977. Aspects of mid-Cretaceous stratigraphical micopalaeontology. *Bulletin British Museum (Natural History), Geology*, **29**, 1-135.

Christensen, W.K. 1990. *Actinocamax primus* Arkhangelsky (Belemnitellidae; Upper Cretaceous) Biometry, comparison and biostratigraphy. *Palaeontologische Zeitschrift*, **64**, 75-90.

Cobban, W.A., Merewether, E.A., Fouch, T.D. & Obradovich, J.D. 1994. Some Cretaceous shorelines in the Western Interior of the United States. *In*: M.V. Caputo, J.A. Peterson & K.J. Franczyk (*Eds*), Mesozoic systems of the Rocky Mountain region, USA. Rocky Mountain Section, SEPM (Society for Sedimentary Geology), Denver, pp. 393-414.

Cobban, W.A. & Scott, G.R. 1972. Stratigraphy and ammonite fauna of the Graneros Shale and Greenhorn Limestone near Pueblo, Colorado. *Professional Papers United States Geological Survey*, **645**, 1-108.

Dodge, C.F. 1969. Stratigraphic nomenclature of the Woodbine Formation Tarrant County, Texas. *Texas Journal of Science*, **21**, 43-62.

Drummond, P.V.O. 1970. The Mid-Dorset Swell. Evidence of Albian-Cenomanian movements in Wessex. *Proceedings of the Geologists' Association*, **81**, 679-714.

Dyman, T.S., Merewether, E.A., Molenaar, C.M., Cobban, W.A., Obradovich, J.D., Weimer, R.J. & Bryant, W.A. 1994. Stratigraphic transects for Cretaceous rocks, Rocky Mountains and Great Plains regions. *In*: M.V. Caputo, J.A. Peterson & K.J. Franczyk (*Eds*), Mesozoic systems of the Rocky Mountain region, USA. Rocky Mountain Section, SEPM (Society for Sedimentary Geology), Denver, pp. 365-392.

Ernst, G., Schmid, F. & Seibertz, E. 1983. Event-Stratigraphie im Cenoman und Turon von NW-Deutschland. *Zitteliana*, **10**, 531-554.

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

Gale, A.S. 1989a. Field meeting at Folkestone Warren, 29th November, 1987. *Proceedings of the Geologists' Association*, **100**, 73-82.

— 1989b. A Milankovitch scale for Cenomanian time. *Terra Nova*, **1**, 420-425.

— 1995. Cyclostratigraphy and correlation of the Cenomanian Stage in western Europe. *In*: M.R. House, & A.S. Gale (*Eds*), Orbital forcing timescale and cyclostratigraphy. *Special Publications Geological Society of London*, **85**, 177-197.

Gale, A.S., Hancock, J.M. & Kennedy, W.J. 1999. Biostratigraphical and sequence correlation of the Cenomanian successions in Mangyshlak (W.Kazakhstan) and Crimea (Ukraine) with those in southern England. *Bulletin de l'Institut Royal des Sciences Naturelles de Belgique. Sciences de la Terre*, **69A**, 67-86.

Gale, A.S., Hardenbol, J., Hathway, B., Kennedy, W.J., Young, J.R. & Phansalkar, V. 2002. Global correlation of Cenomanian (Upper Cretaceous) sequences: evidence for Milankovitch control on sea level. *Geology*, **30**, 291-294.

Gale, A.S., Kennedy, W.J., Burnett, J.A., Caron, M. & Kidd, B.E. 1996. The Late Albian to Early Cenomanian succession at Mont Risou near Rosans (Drôme, SE France): an integrated study (ammonites, inoceramids, planktonic foraminifera, nannofossils, oxygen and carbon isotopes. *Cretaceous Research*, **17**, 515-606.

Gale, A.S., Young, J.R., Shackleton, N.J., Crowhurst, S.J. & Wray, D.S. 1999. Orbital tuning of Cenomanian marly chalk successions: towards a Milankovitch time-scale for the Late Cretaceous. *Philosophical Transactions of the Royal Society (A)*, **357**, 1815-1829.

Gräfe, K.-U. 1999. Foraminiferal evidence for Cenomanian sequence stratigraphy and palaeoceanography of the Boulonnais (Paris Basin, northern France). *Palaeogeography, Palaeoclimatology, Palaeoecology*, **153**, 41-70.

Guillier, A. 1886. Géologie du Département de la Sarthe, 1-430. *Monnoyer*; Le Mans.

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

Hancock, J.M. 1961. The Cretaceous system in Northern Ireland. *Quarterly Journal of the Geological Society of London*, **97**, 11-36.

— 1975. The sequence of facies in the Upper Cretaceous of northern Europe compared with that in the Western Interior. *In*: W.G.E. Caldwell & E.G. Kauffman (*Eds*), The Cretaceous system in the western interior of North America. *Geological Association of Canada Special Paper*, **13**, 83-118.

— 1990. Sea-level changes in the British region during the Late Cretaceous. *Proceedings of the Geologists' Association*, **100** (for 1989), 565-594.

Hancock, J.M., Kennedy, W.J. & Cobban, W.A. 1994 (misdated 1993). A correlation of the Upper Albian to basal Coniacian sequences of northwest Europe, Texas and the United States Western Interior. *In*: W.G.E. Caldwell & E.G. Kauffman (*Eds*), Evolution of the Western Interior Basin. *Geological Association of Canada Special Paper*, **39**, 453-476.

Hancock, J.M. & Kauffman, E.G. 1979. The great transgressions of the Late Cretaceous. *Journal of the Geological Society of London*, **136**, 175-186.

Hancock, J.M. & Walaszczyk, I. 2004. Mid-Turonian to

Coniacian changes of sea-level around Dallas, Texas. *Cretaceous Research*, **25** (4).

HART, M.B. 1987. Orbitally induced cycles in the Chalk facies of the United Kingdom. *Cretaceous Research*, **8**, 335-348.

HATTIN, D.E. 1966 (mis-dated 1964). Cyclic sedimentation in the Colorado Group of west-central Kansas. *In*: D.F. MERRIAM (*Ed*.), Symposium on cyclic sedimentation. *Kansas Geological Survey Bulletin*, **169**, 205-217.

HÉBERT, E. 1876. Notes sur le terrain crétacé du département de l'Yonne. *Bulletin de la Société des Sciences de l'Yonne*, **30**, 15-46.

HERBERT, T.D. & FISCHER, A.G. 1986. Milankovitch climatic origin of Mid-Cretaceous black shale rhythms in central Italy. *Nature*, **321**, 739-743.

HOPSON, P.M., ALDIS, D.T. & SMITH, A. 1996. Geology of the country around Hitchin. *Geological Survey of England & Wales Memoir*, **221**, 1-153.

HUME, W.F. 1894. The genesis of the Chalk. *Proceedings of the Geologists' Association*, **13**, 211-246.

JARVIS, I. & WOODROOF, P.B. 1984. Stratigraphy of the Cenomanian and basal Turonian (Upper Cretaceous) between Branscombe and Seaton, SE Devon, England. *Proceedings of the Geologists' Association*, **95**, 193-215.

JEANS, C.V. 1968. The origin of montmorillonite of the European Chalk with special reference to the Lower Chalk of England. *Clay Minerals*, **7**, 311-329.

— 1973. The Market Weighton structure: tectonics, sedimentation and diagenesis during the Cretaceous. *Proceedings of the Yorkshire Geological Society*, **39**, 409-444.

JUIGNET, P. 1968. Faciés littoraux du Cénomanien des environs du Mans (Sarthe). *Bulletin Bureau de Recherches Géologiques Miniéres (2), section*, 4, **4**, 5-20.

— 1971. Modalités du contrôle de la sédimentation sur la marge armoricaine du bassin de Paris á l'Aptien-Albien-Cénomanien. *Bulletin Bureau de Recherches Géologiques Miniéres (2), section* 1, **3**, 113-126.

— 1973. Sondage de Gazonfier. *In:* P. JUIGNET, G. MARY & L. MENILLET, Le Mans. Carte Géologique de la France á 1:50,000 feuille 358.

— 1974. La transgression crétacés sur la bordure orientale du Massif armoricain, 1-808, 174 figs, 28 pls, Thése de l'Université, Caen.

— 1977. Ammonite faunas from the Cenomenian around Le Mans (Sarthe, France). *Palaeontological Society of Japan Special Paper*, **21**, 143-150.

— 1980. Transgressions-régressions, variations eustatiques et influences tectoniques de l'Aptien au Maastrichtien dans le Bassin de Paris occidental et sur la bordure du Massif Armoricain. *Cretaceous Research*, **1**, 341-357.

JUIGNET, P. & KENNEDY, W.J. 1976. Faunes d'ammonites et biostratigraphie comparée du Cénomanien du nord-ouest de la France (Normandie) et du sud de l'Angleterre. *Bulletin trimestriel de la Société Géologique de Normandie*, **63** (2), 1-193.

KAPLAN, U., KENNEDY, W.J., LEHMANN, J. & MARCINOWSKI, R. 1998. Stratigraphie und Ammonitenfauna des westfälischen Cenoman. *Geologie und Paläontologie in Westfalen*, **51**, 1-243.

KAUFFMAN, E.G. 1969. Cretaceous marine cycles of the Western Interior. *Mountain Geologist*, **6**, 227-245.

KAUFFMAN, E.G., HATTIN, D.E. & POWELL, J.D. 1977. Stratigraphic, paleontologic, and paleoenvironmental analysis of the Upper Cretaceous rocks of Cimarron County, northwestern Oklahoma. *Geological Society of America Memoir*, **149**, 1-150.

KAUFFMAN, E.G., POWELL, J.D. & HATTIN, D.E. 1969. Cenomanian-Turonian facies across the Raton basin. *Mountain Geologist*, **6**, 93-118.

KAUFFMAN, E.G. & PRATT, L.M. 1985. A field guide to the stratigraphy, geochemistry, and depositional environments of the Kiowa-Skull Creek, Greenhorn, and Niobrara marine cycles in the Pueblo-Canon City area, Colorado. *In*: L.M. PRATT, E.G. KAUFFMAN & F.B. ZELT (*Eds*), Fine-grained deposits and biofacies of the Cretaceous western interior seaway: evidence of cyclic sedimentary processes. SEPM 2nd Annual Midyear Meeting, Field Trip 9, FRS1-26.

KENNEDY, W.J. 1969. The correlation of the Lower Chalk of south-east England. *Proceedings of the Geologists' Association*, **80**, 459-560.

— 1970. A correlation of the uppermost Albian and the Cenomanian of south-west England. *Proceedings of the Geologists' Association*, **81**, 613-677.

KENNEDY, W.J. & COBBAN, W.A. 1990. Cenomanian ammonite faunas from the Woodbine Formation and lower part of the Eagle Ford Group, Texas. *Palaeontology*, **33**, 75-154.

KENNEDY, W.J. & HANCOCK, J.M. 1970. Ammonites of the genus Acanthoceras from the Cenomanian of Rouen, France. *Palaeontology*, **13**, 462-490.

KENNEDY, W.J. & JUIGNET, P. 1983. A revision of the ammonite faunas of the type Cenomanian. 1. Introduction, Ancyloceratina. *Cretaceous Research*, **4**, 3-83.

— & — 1993. A revision of the ammonite faunas of the type Cenomanian. 4. Acanthoceratinae (*Acompsoceras*, *Acanthoceras*, *Protacanthoceras*, *Cunningtoniceras* and *Thomelites*). *Cretaceous Research*, **14**, 145-190.

MCGOOKEY, D.P. & *al.* 1972. Cretaceous system. In: Geologic Atlas of the Rocky Mountain Region, United States of America, 190-228. Rocky Mountain Association of Geologists; Denver.

MARCINOWSKI, R. 1974. The transgressive Cretaceous (Upper Albian through Turonian) deposits of the Polish Jura Chain. *Acta Geologica Polonica*, **24**, 17-217.

— 1980. Cenomanian ammonites from German Democratic Republic, Poland and the Soviet Union. *Acta Geologica Polonica*, **30**, 215-325.

MARCINOWSKI, R. & RADWAŃSKI, A. 1989. A biostratigraphic approach to the mid-Cretaceous transgressive sequence of the Central Polish Uplands. *Cretaceous Research*, **10**, 153-172.

MARCINOWSKI, R., WALASZCZYK, I. & OLSZEWSKA-NEJBERT, D. 1996. Stratigraphy and regional development of the mid-Cretaceous (Upper Albian through Coniacian) of the

Mangyshlak Mountains, western Kazakhstan. *Acta Geologica Polonica*, **46**, 1-60.

MEREWETHER, E.A. & COBBAN, W.A. 1986. Biostratigraphic units and tectonism in the mid-Cretaceous foreland of Wyoming, Colorado, and adjoining areas. *In*: J.A. PETERSON (*Ed.*), Paleotectonics and sedimentation in the Rocky Mountain region, United States. *American Association of Petroleum Geologists Memoir*, **41**, 443-468.

MEYER, R. 1990. Biostratigraphie und sedimentologische untersuchungen in der Plänerfazies des Cenoman von Nordwestdeutschland. *Mitteilungen aus dem Geologisch-Paläontologischen der Universität Hamburg*, **30**, 1-115.

NAIDIN, D.P. & ALEKSEEV, A.S. 1981. Importance of ocean drilling data for the interpretation of sedimentation and life of the fauna in the Cenomanian of the Crimean highlands. *In*: KRASSILOV (*Ed.*), Evolution of organisms and biostratigraphy of the mid-Cretaceous, 7-21. Academy of Sciences of the USSR, Far Eastern Centre, Vladivostock. [*In Russian*]

NAIDIN, D.P., BENJAMOVSKY, V.N. & KOPAEVICH, L.F. 1984. Methods of studying transgressions and regressions (exemplified by the Late Cretaceous basins of western Kazakhstan), 1-164. *Moscow University*; Moscow. [*In Russian*]

NORTON, G.H. 1965. Surface geology of Dallas County. *In*: The geology of Dallas County, 40-125. *Dallas Geological Society*; Dallas.

OBRADOVICH, J.D. 1994 (mis-dated 1993). A Cretaceous time-scale. *In*: W.G.E. CALDWELL & E.G. KAUFFMAN (*Eds*), Evolution of the Western Interior Basin. *Geological Association of Canada Special Paper*, **39**, 379-396.

OLIVER, W.F. 1971. Depositional systems in the Woodbine Formation (Upper Cretaceous), northeast Texas. *Bureau of Economic Geology, University of Texas, Report of Investigations*, **73**, 1-28.

OWEN, D. 1996. Interbasinal correlation of the Cenomanian Stage; testing the lateral continuity of sequence boundaries. *In*: J.A. HOWELL & J.F. AITKEN (*Eds*), High resolution sequence stratigraphy: innovations and applications. *Geological Society of London Special Publication*, **104**, 269-293.

PAUL, C.R.C., MITCHELL, S.F., MARSHALL, J.D., LEARY, P.N., GALE, A.S., DUANE, A.M. & DITCHFIELD, P.W. 1994. Palaeoceanographic events in the Middle Cenomanian of northwest Europe. *Cretaceous Research*, **15**, 707-738.

ROBASZYNSKI, F. & AMÉDRO, F. 1986. The Cretaceous of the Boulonnais (France) and a comparison with the Cretaceous of Kent (United Kingdom). *Proceedings of the Geologists' Association*, **97**, 171-208.

ROBASZYNSKI, F., GALE, A., JUIGNET, P., AMÉDRO, F. & HARDENBOL, J. 1999 (mis-dated 1998). Sequence stratigraphy in the Upper Cretaceous series of the Anglo-Paris basin: exemplified by the Cenomanian stage. *In*: P.-C. DE GRACIANSKY & *al.* (*Eds*), Mesozoic and Cenozoic sequence stratigraphy of European basins. *SEPM Special Publication*, **60**, 363-386.

ROBASZYNSKI, F., HARDENBOL, J., CARON, M., AMÉDRO, F., DUPUI, C., GONZALEZ DONSO, J.-M., LINARES, D. & GARTNER, S. 1993. Sequence stratigraphy in a distal environment: the Cenomanian of the Kalaat Senan region (central Tunisia). *Bulletin des Centres de Recherches Exploration-Production Elf-Aquitaine*, **17**, 395-433.

ROBINSON, N.D. 1986. Fining-upward microrhythms with basal scours in the Chalk of Kent and Surrey, England and their stratigraphic importance. *Newsletters on Stratigraphy*, **17**, 21-28.

SALVADOR, A. 1991. Origin and development of the Gulf of Mexico basin. *In*: A. SALVADOR (*Ed.*), The Gulf of Mexico Basin. Geology of North America J, 389-444. *Geological Society of America*; Boulder.

SHEPARD-THORN, E.R., MOORLOCK, R.S.P., COX, B.M., ALLSOP, J.M. & WOOD, C.J. 1994. Geology of the country around Leighton Buzzard. *Geological Survey England and Wales Memoir*, **220**, 1-127.

SMITH, W.E. 1957. The Cenomanian limestone of the Beer district, south Devon. *Proceedings of the Geologists' Association*, **68**, 136-152.

— 1961. The Cenomanian deposits of south-east Devonshire. The Cenomanian limestone and contiguous deposits west of Beer. *Proceedings of the Geologists' Association*, **72**, 91-134.

— 1965. The Cenomanian limestone east of Seaton. *Proceedings of the Geologists' Association*, **76**, 121-136.

STEPHENSON, L.W. 1952. Larger invertebrate fossils of the Woodbine Formation (Cenomanian) of Texas. *United States Geological Survey Professional Paper*, **242**, 1-226, 59 pls.

SUMBLER, M.G. & WOODS, M.A. 1992. The stratigraphy of the Lower and Middle Chalk at Chinnor, Oxfordshire. *Proceedings of the Geologists' Association*, **103**, 111-118.

TRÖGER, K.-A. 1996. The Upper Cretaceous of Saxony in the framework of the European Cretaceous development. *Mitteilungen aus dem Geologisch-Paläontologischen Institut der Universität Hamburg*, **77**, 95-104.

WEIMER, R.J. 1960. Upper Cretaceous stratigraphy, Rocky Mountain area. *American Association of Petroleum Geologists Bulletin*, **44**, 1-20.

— 1984. Relation of unconformities, tectonics and sea-level changes, Cretaceous of Western Interior, U.S.A. *In*: J.S. SCHLEE (*Ed.*), Interregional unconformities and hydrocarbon accumulation. *American Association of Petroleum Geologists Memoir*, **36**, 7-35.

— 1986. Relationship of unconformities, tectonics and sea-level changes in the Cretaceous of the Western Interior, United States. *In*: J.A. PETERSON (*Ed.*), Paleotectonics and sedimentation in the Rocky Mountain region. *American Association of Petroleum Geologists Memoir*, **41**, 397-422.

WIEDMANN, J. & SCHNEIDER, H.L. 1979. Cephalopoden und Alter der Cenoman-Transgression von Mülheim-Broich, SW-Westfalen. *In*: J. WIEDMANN (*Ed.*), Aspekte der Kreide

Europas. International Union of Geological Sciences (A) 6, 645-680.

WORSSAM, B.C. & TAYLOR, J.H. 1969. Geology of the country around Cambridge. *Geological Survey England and Wales Memoir*, **188**, 1-159.

WRIGHT, C.W. & KENNEDY, W.J. 1987. The Ammonoidea of the Lower Chalk, part 2. *Monographs Palaeontographical Society Publication*, **573**, 127-218.

— & — 1996. The Ammonoidea of the Lower Chalk, part 5. *Monographs Palaeontographical Society Publication*, **601**, 320-403.

WRIGHT, C.W., KENNEDY, W.J. & HANCOCK, J.M. 1984. The Ammonoidea of the Lower Chalk: Introduction. *Monographs Palaeontographical Society Publication*, **567**, 1-37.

YOUNG, K. 1986. Cretaceous, marine inundations of the San Marcos Platform, Texas. *Cretaceous Research*, **7**, 117-140.

Manuscript submitted: 10th August 2003
Revised version accepted: 20th December 2003