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Peri-Tethyan neritic carbonate areas: distribution through time and driving factors

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Abstract

Neritic carbonates (NC) were one of the most prominent facies of the Peri-Tethyan domain. From the Moscovian to the end of Tertiary times, most parts of the area concerned were included in, or in the vicinity of, the intertropical domain, favourable to the deposition of NC. These optimal latitudinal conditions were strengthened by warm surface currents which globally ran from east westward in this part of the Tethyan realm. The settlement of NC was enhanced by the existence of huge shallow marine platforms on the southern and northern Peri-Tethyan margins and on isolated oceanic highs as well. Peri-Tethys atlas maps, explanatory notes and validation points have provided data on the main biological, sedimentological, geographical, and environmental features of NC. Areas covered by NC have been calculated from 20 maps encompassing the Moscovian to the Piacenzian/Gelasian, using an Image Analysis Optilab system. The latitudinal distribution and the total area covered by NC for each time slice have been plotted with reference to global factors driving the carbonate factory. Variations of areas through time have been analysed and discussed with respect to regional palaeogeographic conditions. Global factors driving the NC sedimentation in Peri-Tethyan areas have been successively examined. The dominant skeletal and non-skeletal mineralogy on carbonate deposition has been evaluated. Photozoan organisms have been dominant contributors; however, deposition of temperate Heterozoan carbonates in northern latitudes occurred during Artinskian, Wordian, Maastrichtian and Tertiary times. Adverse conditions of siliciclastic inputs on carbonate deposition settled at certain periods but many Peri-Tethyan NC areas faced without damage terrigenous belts. Sea level highstands generally allowed wide NC areas to form, but certain time intervals had about the same amount of area covered by NC, despite opposite – low vs high – eustatic stillstand. Latitudinal enlargement of NC areas was enhanced during Mesozoic and Early Cainozoic greenhouse regimes, while a latitudinal constriction occurred during Artinskian, Wordian and late Tertiary times, in relation to an icehouse mode. During early Jurassic, middle Cretaceous and early Tertiary times, ocean circulation seems to have controlled latitudinal shifts of the NC areas. Abrupt increases or reductions of areas covered by NC coincided with the onset of atmospheric-controlling magmatic events or of sudden oceanic events with climatic implications.

Keywords: Phanerozoic; neritic carbonate areas; palaeogeography; palaeoclimatology; Tethys

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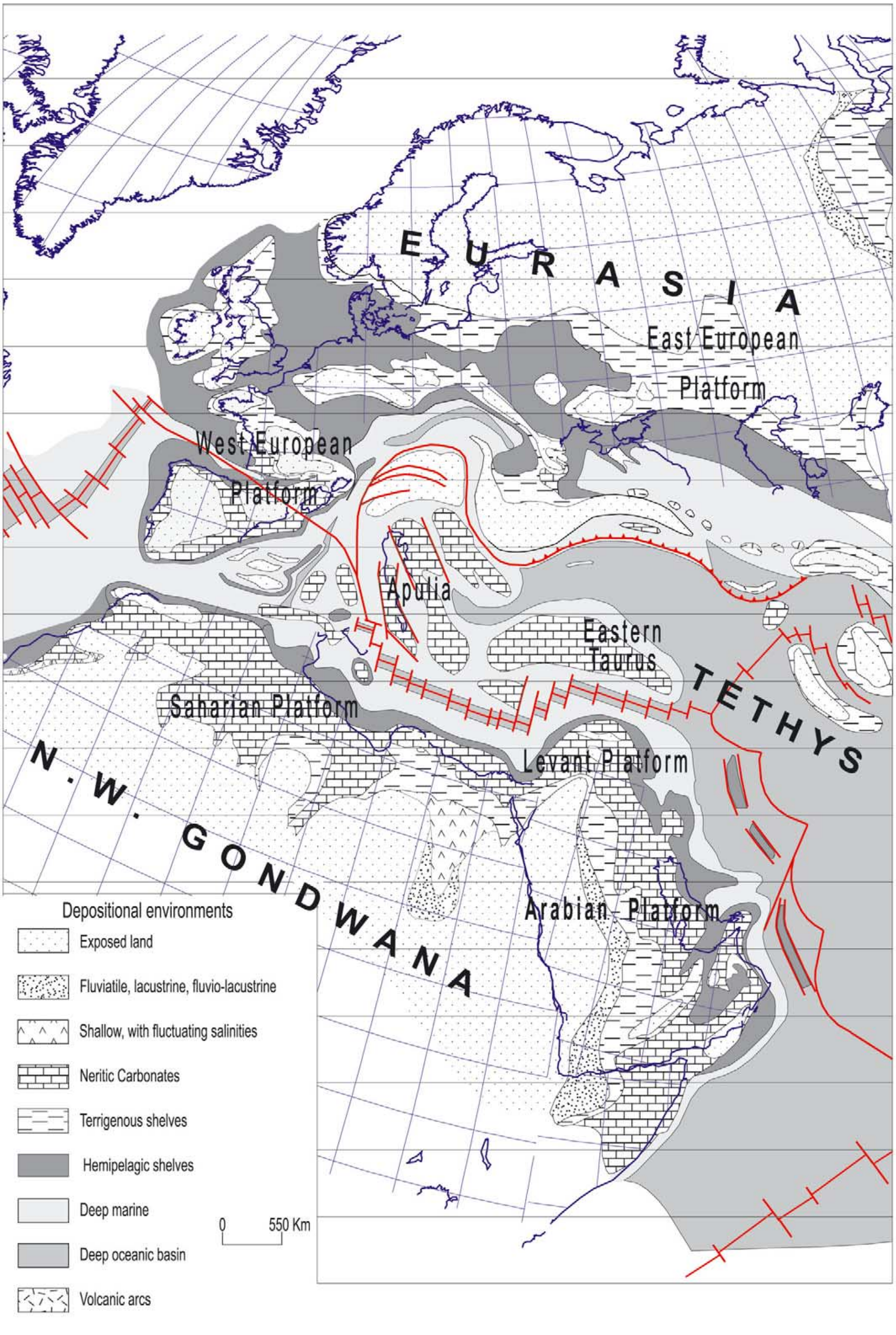
EURASIA
East European Platform
West European Platform
Apulia
Eastern Taurus
TETHYS
Saharian Platform
Levant Platform
N.W. GONDWANA
Arabian Platform
50°
40°
30°
20°
10°
0°
-10°
-20°
Depositional environments
Exposed land
Fluviatile, lacustrine, fluvio-lacustrine
Shallow, with fluctuating salinities
Neritic Carbonates
Terrigenous shelves
Hemipelagic shelves
Deep marine
Deep oceanic basin
Volcanic arcs
0
550 Km

1. Introduction

Neritic carbonates (NC), also called shallow marine carbonates, are defined here as deposits formed in the ocean environment between low tide level and approximatively the continental shelf edge. Obviously, the major biological content of NC is of benthic origin. They include facies originating from carbonate platforms or ramps, which have formed belts along continental margins, or were isolated on oceanic highs. In all cases, the biological factory (reefs and/or diverse benthic assemblages) plays a pre-eminent role in carbonate deposition and facies zonation.

The Peri-Tethyan domain appears a privileged palaeogeographic area for the setting up and the thriving of NC sedimentation. Indeed, this area was located in, or in the vicinity of, the intertropical domain, which offered favourable conditions for the deposition of reefal or perireefal carbonates. Likewise, latitudinal conditions were optimised by active warm surface currents which globally moved from east to west in this part of the Tethyan realm. Also, the settlement of NC was enhanced by the existence of huge shallow marine platforms on both sides of the Tethyan area: the southern margin of the Eurasian craton, and the northern margin of Gondwana. Moreover, carbonate facies developed on isolated highs drifted away through time from the northern Gondwana margin, such as the Apulian or Mega Lhasa (Ricou, 1994) intraoceanic platform areas.

The distribution through time of NC in the Peri-Tethyan domain was influenced by many physical, chemical and biological factors which will be analysed below.

However, like for the recent counterparts, the climatic factor had a pre-eminent effect on the composition of the biological carbonate factory, as well as on the latitudinal zonation of the carbonate facies on marine shelves. Peri-Tethyan NC consequently appear an important palaeoclimatic witness.

According to James (1997) on the basis of sea water temperature gradients, NC can be separated into two biological associations.

(1) A Heterozoan association composed of molluscs, bryozoans, echinoderms, foraminifera, rhodolites, linked to subtropical (18–22°C) to subpolar and cold (10–5°C) bottom water temperatures.

(2) A Photozoan association constituted of green algae, corals, rudists (in the Mesozoic), fusulinids (in the Palaeozoic), oolites, peloids, which correspond to tropical (>22°C) conditions.

In the shallow waters of the modern ocean, Photozoan carbonates occur widely in the intertropical domain (Habicht, 1979), in association with warm surface currents, while Heterozoan carbonates extend poleward from the limit of the tropical factory (about 30°) to polar latitudes; but it also occurs in the thermocline waters of the low latitudes (James, 1997; Schlager, 2000).

The latitudinal distribution and areas covered by recent neritic sediments containing more than 50% carbonates (Fairbridge, 1967) show a distinctly bimodal pattern with peaks (approximately 1.8 million km^2) centred at about 20°N and S and a strong constriction in the equatorial zone. Thus, estimates of total areas covered today by coral reefs only (Smith, 1978) provide much lower values, around 620 000 km^2. Surfaces covered by NC deposits dramatically decrease up to 30° latitude. Moreover, it is generally admitted (Habicht, 1979) that global climatic conditions (glacial vs non-glacial periods) play a role in the latitudinal extent of NC and reefs in recent seas. A constriction of the domain covered by these sedimentary systems toward the equator was generalised during glacial periods, while it extends latitudinally during interglacial or non-glacial periods.

In this paper we will analyse NC areal fluctuations in the Peri-Tethys domain, from the Moscovian to the Piacenzian/Gelasian, and we will suc-

Fig. 1. Late Cenomanian (94.7–93.5 Ma) palaeogeographical map of the Peri-Tethyan domain with main depositional environments and NC areas (modified from Philip et al., 2000).

cessively examine: (1) the methods used to calculate the areas covered by NC from the different maps of the Peri-Tethys atlas, and accuracy of the results; (2) the latitudinal distribution of NC and their total areal extent for each time slice represented by Peri-Tethyan maps; (3) their relationships with the global factors driving the NC factory; (4) the palaeogeographical and palaeoclimatic significance of Peri-Tethyan NC.

2. Methods and accuracies

The documents elaborated in the framework of the Peri-Tethys Programme have been used as sources of data relative to NC. Maps (at 1/10 000 000 scale at the palaeoequator) provide: (1) the latitudinal and geographical location of NC; (2) the NC area (both for each latitudinal belt and for the total covered domain); (3) the dominant facies (bioclastic limestones, oolites, bioherms, etc.); (4) the connections of the NC with neighbouring palaeoenvironments, basinward and landward.

Explanatory notes have given data on palaeogeographical conditions (eustasy, climate, tectonics or magmatic activity) of NC areas at each time slice. More precise data (such as sequences and systems tracts, surfaces of non-deposition or erosion, bio- and lithofacies) can be drawn from some available validation points of the Peri-Tethys Programme mapping, and from the compilation of published sections.

Areas covered by NC (expressed in millions of square kilometres) have been calculated using Image Analysis Optilab system X 2.01 on MC OS 8.5 with an error coefficient of about 2%. For reasons of homogeneity, only maps displaying the totality of NC belts (on pericratonic margins and on isolated Tethyan highs) have been taken into account for accurate comparisons. As a result, data have been extracted from only 20 maps, from the Moscovian to the Piacenzian/Gelasian. Calculation of the areas covered by NC (shown in a light blue colour on original Peri-Tethys maps) has been made for each 5° palaeolatitudinal belt where they are represented. On Peri-Tethys maps (Fig. 1), the interval ranging between two palaeolatitudes is constant and its value corresponds to 550 km in the vicinity of the palaeoequator, precisely the area where NC developed. The rectilinear projection systems used for mapping do not imply important distortions of areas in the domain considered which does not go much beyond 30° latitude.

The area covered by NC corresponds to the amount of light blue colour with respect to the total area of each latitudinal belt represented on the maps in the form of a rectangle.

A coefficient of overestimate has been introduced for latitudinal belts where areas covered by NC are not justified by validation points or known sections. In this case, calculated areas have arbitrarily been affected by a reduction coefficient. Thus, for each map, the areas covered by NC are quantified by an absolute value and a corrected value (Fig. 3). The difference between both values measures the amount (in per cent) of overestimated area covered by NC on each map.

The latitudinal distribution and the total area of NC for each time slice have been plotted with reference to global factors having driven the carbonate factory.

(1) The dominant marine skeleton mineralogy, calcite vs aragonite of the main hypercalcifying organism producers (Stanley and Hardie, 1998).

(2) The dominant non-skeletal carbonate mineralogy (of oolite particles for instance) (Sandberg, 1983).

(3) The climatic global trend (icehouse vs greenhouse conditions) as initially proposed by Fischer (1981), with modifications concerning the location of the boundaries between the dominant climatic systems during the time interval considered.

(4) The climatic global curve with special emphasis on ice sheet occurrences and episodes of possible cooling at low latitudes as suggested by Hallam (1985), Kemper (1987) and Price (1999) for the Mesozoic.

(5) The global long-term eustatic curve as recently traced by Hardenbol et al. (1998), with additional data from Golonka and Ford (2000) for the Late Palaeozoic.

(6) The global magmatic (e.g. traps, plumes and superplumes) or oceanic (e.g. CH_4 release) events

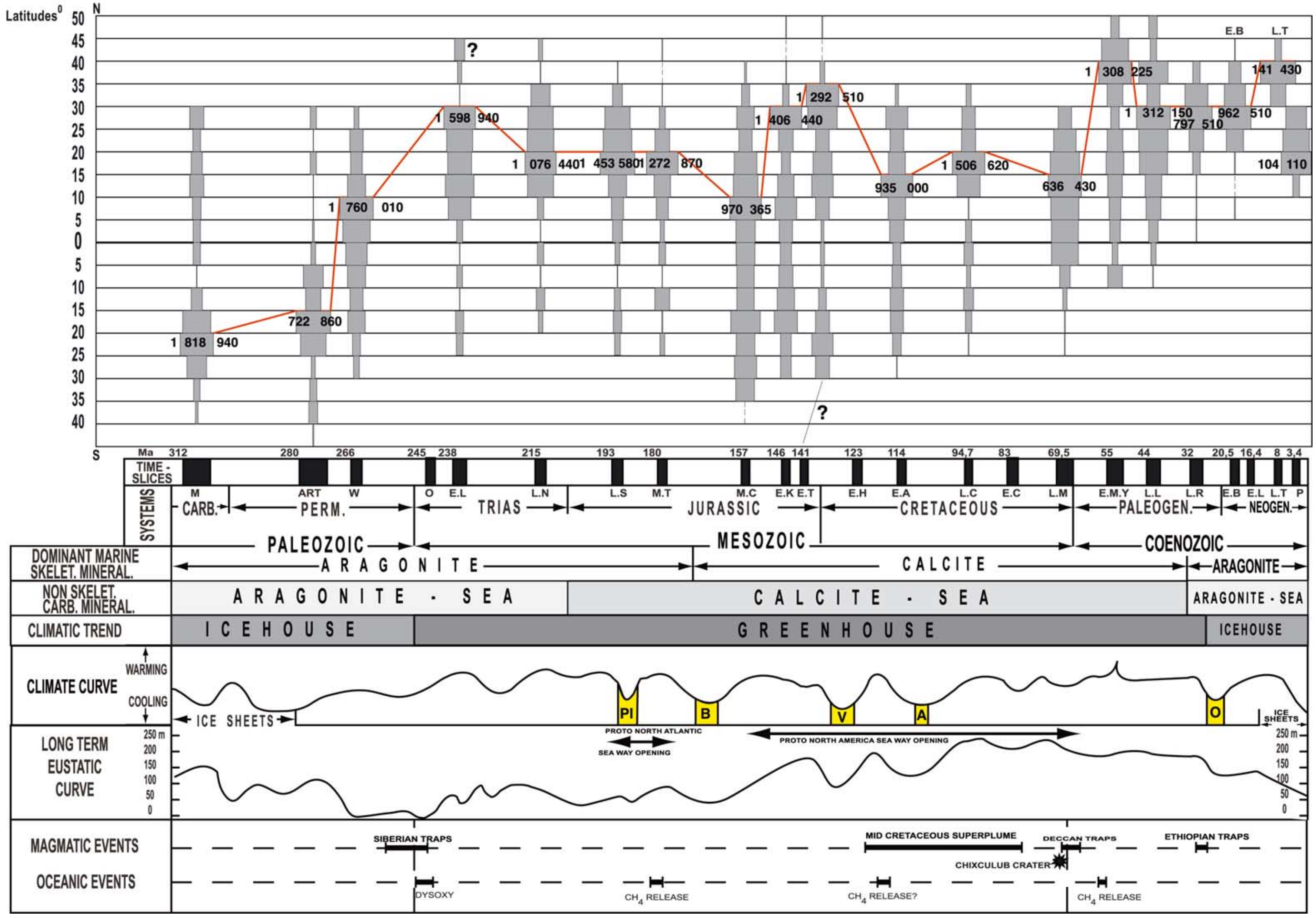

Fig. 2. Latitudinal areas covered by NC at the different time slices, plotted with reference to global driving factors. Abbreviations used for stages: M = Moscovian; Art = Artinskian; W = Wordian; O = Olenekian; E.L = Early Ladinian; L.N = Late Norian; L.S = Late Sinemurian; M.T = Middle Toarcian; M.C = Middle Callovian; E.K = Early Kimmeridgian; E.T = Early Tithonian; E.H = Early Hauterivian; E.A = Early Aptian; L.C = Late Cenomanian; E.C = Early Campanian; L.M = Late Maastrichtian; E.M.Y = Early Middle Ypresian; L.L = Late Lutetian; L.R = Late Rupelian; E.B = Early Burdigalian; E.L = Early Langhian; L.T = Late Tortonian; P = Piacenzian/Gelazian. Cooling events of the climatic curve: Pl = Pliensbachian; B = Bajocian–Bathonian; V = Valanginian; A = Late Aptian; O = Oligocene. Geochronological data from the Atlas Peri-Tethys (Dercourt et al., 2000). Numbers indicate the age of the lower boundary of each time slice.

able to have influenced the CO_2 content of both the ocean and the atmosphere and, consequently, the climate and the NC deposition.

3. Latitudinal distribution

The latitudinal distribution of the areas covered by NC at each time slice, from the Moscovian to the Piacenzian/Gelasian, i.e. a time span of 312 million years, is shown in Fig. 2. For each map, a number indicates the latitudinal location of the widest NC area in millions of square kilometres. Starting from this value, the diagram shows the amount of area covered by NC (see also the table giving the calculated data, Appendix A) for each 5° latitudinal belt with respect to the widest one.

Fig. 2 displays three prominent facts. Firstly, it is noticed that NC areas were reduced at the palaeoequator at different time slices. Secondly, two types of asymmetric distribution are distinguished: the first, as observed in the Moscovian and the Artinskian, displays maximum areas covered by NC in the southern hemisphere; the opposite type was provided by the period ranging between the Early Ladinian and the Middle Toarcian, and from the Late Maastrichtian to the Piacenzian/Gelasian. Thirdly, periods of balance between both hemispheres occurred in the Wordian, in the Late Jurassic, and in the Early Aptian.

3.1. Reduction of NC at the palaeoequator

The cause for this reduction seems to vary from time to time.

The Artinskian map (Vai et al., 2000b) displays a strong shortening of the Eastern European Basin (Chuvashov and Crasquin-Soleau, 2000) and a dramatic reduction of the areas covered by NC at the palaeoequator up to 25° north latitude. This seems due to a wide retreat of the sea in this territory and a settlement of shallow marine to coastal siliciclastic environments on the southern margin of the Eurasian craton (Vai et al., 2000b). Similarly, evaporitic belts were moved to the northern edge of the Baltic sea. These facies replaced a large part of the previous Russian and Arctic Moscovian carbonate platform.

In the Early Ladinian (Gaetani et al., 2000b) and in the Late Norian (Gaetani et al., 2000c), the areas covered by NC were largely developed in the northern hemisphere and reduced at the palaeoequator and in the southern hemisphere. In the Early Ladinian, evaporitic hypersaline environments developed around the palaeoequator on the eastern margin of the Arabian craton; this indicates that arid climatic conditions prevailed in this region. In the Late Norian, terrigenous inputs were probably responsible for carbonate platform shortening at the palaeoequator, east of the Arabian shield. Indeed, a very wide delta apron of siliciclastics flowing towards NNE was present, in which both braided river and alluvial meandering plain have been detected (Gaetani, 2000). Wet climatic conditions, providing siliciclastic deposits to the sea, are here supposed to have prevented carbonate deposition from thriving at the palaeoequator. Arid climatic conditions resulting in the development of a hypersaline basin, located between 0 and 10° north latitudes, and replacing partly NC, prevailed on the eastern margin of the Arabian craton during Middle Toarcian times (Thierry et al., 2000c).

The Early Tithonian map (Thierry et al., 2000e) also displays a significant reduction of carbonate platform areas around the palaeoequator, while these latter were well represented in northern and southern tropical realms. NC were replaced by the huge Arabian evaporitic basin which indicates arid conditions at the palaeoequator at this time.

During the Late Rupelian (Meulekamp et al., 2000c) up to the Piacenzian/Gelasian (Meulekamp et al., 2000d), the reduction of the areas covered by NC around the palaeoequator on the eastern part of the African craton, Somalian Plateau, seems to have been governed by siliciclastic deltaic inputs due probably to wet climatic conditions which prevailed throughout this period in this domain.

3.2. Shift of NC maximum development from the southern to the northern hemisphere

This change occurred around the Artinskian–Wordian transition. Afterwards, and particularly during the Early Ladinian–Middle Toarcian period, NC sedimentation dominated on the northern hemisphere. This fact was only due to the relative position of the huge Northern Gondwana shelf with respect to the palaeoequator. In the Moscovian and in the Artinskian, the shelf was located in the southern intertropical domain, while starting from the Early Ladinian, this shelf drifted away to the northern intertropical domain, following the northward drift of Pangaea. The Mega Lhasa Transit plate bearing NC deposits followed the same way. Thus, NC deposition on this shelf became a permanent feature by around the Palaeozoic–Mesozoic transition, due to constant intertropical conditions. This event was enhanced by the development of NC on the southern margin of the Eurasian craton.

3.3. Balance in the latitudinal NC deposition

In the Wordian (Gaetani et al., 2000a), Middle Callovian (Thierry et al., 2000d), Early Kimmeridgian (Thierry et al., 2000a,b), Early Tithonian (Thierry et al., 2000e), and Early Aptian (Masse et al., 2000) times, a relatively symmetric and significant distribution of carbonate platforms north and south of the palaeoequator up to 30 or even 35° latitude is noticed. Palaeoclimatic conditions inferred from this distribution imply a weak contrast in latitudinal belts during these time intervals, and similar climatic conditions, favourable to NC deposition.

4. Areas covered by NC

In Fig. 3 is plotted the total area covered by NC for each time slice in relation to the global factors mentioned above.

The maximum area covered by carbonates is 10.44 million km^2 in the Moscovian. The main results are as follows: (1) occurrence of periods of large development of areas covered by NC, such as in the Moscovian, in the Wordian or in the Late Lutetian; (2) occurrence of periods of moderate development such as in the Middle Toarcian or in the different stages of the Cretaceous; and (3) occurrence of periods of reduction, or extreme reduction, in the Artinskian, Late Rupelian or in the Neogene.

The reduction of areas covered by NC from the Moscovian to the Artinskian was due to a demise of the Russian carbonate platform and of the NC belt southeast of the Eurasian craton. Carbonate deposits were replaced by evaporitic or siliciclastic facies.

The large increase of NC areas in the Wordian can be interpreted mainly as the result of the settlement of a huge carbonate belt south of the Eurasian craton and, in addition, the development of a large carbonate platform on the Mega Lhasa transit block (Ricou, 1994).

The northeastward migration of the Mega Lhasa up to 35° north latitude, and its collision with the Eurasian plate in the Late Norian (Gaetani et al., 2000c), seems the only cause of the reduction of NC areas at this time when compared with the Early Ladinian.

The opening of the proto-Atlantic gateway in the Late Sinemurian (Thierry et al., 2000a) was a favourable palaeogeographic event which enhanced the thriving of NC in this newly created shallow marine area. In the Middle Toarcian (Thierry et al., 2000c) the reduction of NC areas resulted mainly from the demise of carbonate platforms all around the western European craton while the net increase of areas in the late Jurassic was attributable to a new development of NC belts in this region and in the peri-Caspian domain (e.g. in the Early Tithonian).

A limited demise of carbonate platforms in the southern margin of the Eurasian craton appears to cause the reduction of NC areas in the Early Aptian (Masse et al., 2000), despite the fact that shallow marine seas occupied this area.

The large development of NC areas in the Middle Ypresian (Meulekamp et al., 2000a) and in the Lutetian (Meulekamp et al., 2000b) must be interpreted as resulting from the growth of carbonate belts on the southeastern margin of the Eurasian craton, on the Black Sea and peri-Caspian regions.

A dramatic decrease of NC areas occurred in the Late Rupelian (Meulekamp et al., 2000b) and continued throughout the Neogene period. Carbonate platforms and belts migrated southward

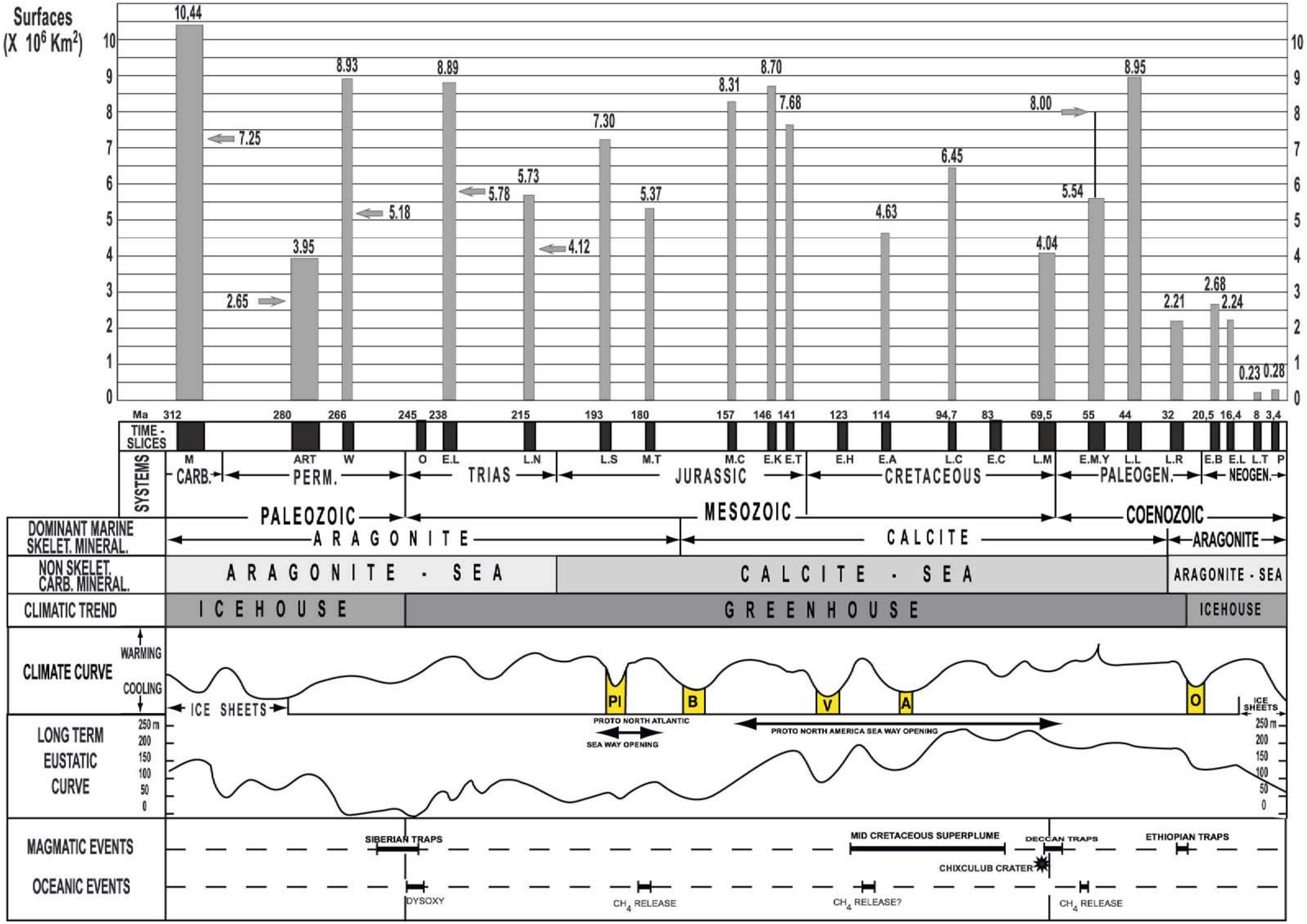

Fig. 3. Total areas covered by NC at the different time slices compared to global driving factors. Numbers indicated by arrows correspond to corrected area values (see text for explanations). Same abbreviations and symbols as in Fig. 2.

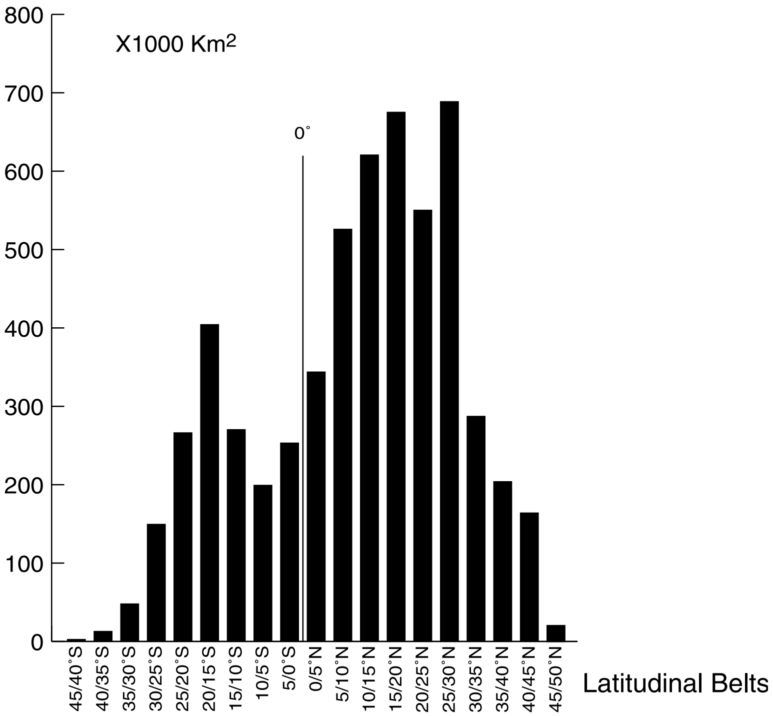

Fig. 4. Histogram of average area covered by NC in each latitudinal belt for the 20 studied time slices.

and were located on the northern and eastern margins of the African–Arabian shield.

The average area covered by NC has been calculated for the 20 maps examined and for each 5° latitudinal band (Fig. 4 and Appendix A).

The histogram is bimodal and strongly asymmetrical. It displays an average area maximum of development in tropical zones of the northern hemisphere, while a reduction appears in the equatorial zone and slightly less in tropical zones of the southern hemisphere.

Of particular interest is the average carbonate area maximum between 25 and 30° north latitude. This observation leads to a suspicion of the importance of Heterozoan producers during various periods, such as in the Artinskian and the Late Permian (Beauchamp and Desrochers, 1997) and in the Ypresian (Plaziat and Perrin, 1992) at these latitudes. Climatic conditions (excessive heating or drying?) and/or terrigenous inputs seem to have been inimical for carbonate producers in the equatorial zones.

5. Factors driving the NC sedimentation through time in Peri-Tethyan areas

5.1. Skeletal mineralogy

A look at the distribution of carbonate areas (Figs. 2 and 3), compared with the dominant marine skeletal mineralogy trend of hypercalcifying organisms (Stanley and Hardie, 1998), indicates that no influence of typical skeletal mineralogy could be invoked as a factor driving the rate of carbonate deposition. Whatever the dominant skeletal mineralogy was (aragonite or calcite dominant), carbonate production reached high values for all the considered time interval.

According to Stanley and Hardie (1998), fluctuations of the predominant skeletal type of mineralogy during the Phanerozoic aeon depended of the Mg/Ca ratio of the seawater, driven by changes in spreading rates along mid-oceanic ridges.

Thus, according to James (1997), seawater temperature also plays a role in the carbonate skeletal mineralogy of neritic organisms. For instance, the attribute of cool water carbonates is their predominantly calcite mineralogy. Accordingly, the dominant skeletal mineralogy of neritic organisms is not always easy to interpret in terms of climate instead of seawater chemistry.

Calcite-secreting organisms such as fusulinids, bryozoans, brachiopods, crinoids, cyanobacteria and sponges were the main biological components of NC during Moscovian and Wordian times. Aragonite-dominated organisms (phylloid algae, chaetetids, sphynctozoan and inozoan sponges, *Tubiphytes*) were major contributors of reef building during the Late Carboniferous and the Permian (Stanley and Hardie, 1998). This confirms that equable climatic conditions and high Mg/Ca ratios prevailed during these periods, which were favourable to aragonite-secreting organisms thriving in both northern and southern tropical domains. They were able to produce large amounts of carbonate deposits. An elevated Mg/Ca ratio could also have characterised early and middle Triassic seawater and favoured the evolution of aragonite faunas (Railsback and Anderson, 1987).

The onset of the calcareous plankton at the Triassic/Jurassic turn and the possible control of this ecosystem over oceanic calcium cycling seems not to have affected the budget of the NC deposition during the Jurassic, especially from the Callovian to the end of the system. In fact, much of the $CaCO_3$ extracted by the plankton came to rest in shallow water environments (Degens, 1989) and probably contributed to the outer platform carbonate sedimentation. However, a relative reduction of the NC budget is noticed in the Late Cretaceous (especially in the Late Maastrichtian), coincident with a widespread deposition of massive chalk deposits and a decline of aragonite corals as reef builders (Stanley and Hardie, 1998), while calcitic-dominant rudists flourished. As suggested by these authors, the pivotal fact of the ascendancy of rudists on aragonitic corals in the Late Cretaceous was probably a decrease in the Mg/Ca ratio of seawater which predominantly affected these latter. However, the hypothesis of an excess of CO_2 can also be considered, given that calcification rates of modern reef-building corals are depressed by increased levels of CO_2 (Gattuso et al., 1998).

Despite rudist extinction at the end of the Cretaceous and the failure of aragonitic reef corals to flourish until Oligocene times (Stanley and Hardie, 1998), NC were widespread during the Eocene. This was due to the strong development of rock-forming nummulitid foraminiferans in Peri-Tethyan carbonate platforms, possibly enhanced by warm temperatures at low latitudes (Pearson et al., 2001), a high level of atmospheric CO_2 and a low Mg/Ca ratio in seawater.

The onset of aragonitic coral reefs on a global scale at the Oligocene did not have a consistent influence on Peri-Tethyan NC deposition, due to the fact that the Peri-Tethyan domain was located at relatively high latitudes and underwent progressive cooling. These conditions favoured bryozoan and mollusc-rich NC deposition in the area concerned.

5.2. *Photozoan vs Heterozoan associations*

Photozoan associations, including scleractinian corals, stromatoporoids, chaetetids, green algae and other subordinate organisms, played a dominant role in the formation of Peri-Tethyan NC during the time interval considered (Kiessling et al., 1999).

Cretaceous rudist-bearing facies have generally been interpreted as Photozoan intertropical carbonates (Philip, 1972; Masse and Philip, 1981). The relevant arguments are based on the frequent association of rudists with hermatypic corals (Camoin et al., 1988; Scott et al., 1990; Skelton et al., 1997), stromatoporoids, large foraminifera, green algae, etc. Moreover, numerous genera of rudists (Kauffman, 1969; Philip, 1972; Vogel, 1975; Skelton and Wright, 1987), if not the whole group (Seilacher, 1998), have been suspected of having harboured symbiotic algae in their tissues. Palaeotemperatures inferred from the oxygen isotopic composition of Late Cretaceous rudist shells from Greece and Turkey (Steuber, 1996) range from 20.6°C to 36.1°C; these values are compatible with intertropical climatic zones. According to Steuber (1999), higher low-latitude sea surface temperatures than the present ones existed during the Late Cretaceous. Peri-Tethys palaeogeographic Cretaceous maps (e.g. Fig. 1) display: (1) a maximum area of development of NC ranging from 25° south latitude to 30° north latitude in the Early Aptian, and (2) a constriction toward the palaeoequator of these areas during the Late Cretaceous, especially the Maastrichtian. So, biological and palaeogeographical observations disagree with the interpretation of the Late Cretaceous rudist-bearing carbonates of Sardinia and south Italy (Carannante et al., 1997) as temperate associations. As shown by the palaeogeographic reconstructions, these regions were included within the intertropical realm between 20° and 30° north latitude during Late Cretaceous times and no indication of cooling can be detected from carbonate-associated facies. In contrast, rudist–coral–chaetetid build-ups, referred to as Photozoan associations, have been described in the lower Senonian of Sardinia (Philip and Allemann, 1982).

However, during some periods, true Heterozoan associations seem to have contributed to the formation of NC. Indeed, in the Late Palaeozoic, bryonoderm carbonates, dominated by bryozoans, echinoderms, brachiopods and siliceous sponges, were abundant in northwest Pangaea (Beauchamp and Desrochers, 1997). According to these authors this assemblage indicates a cool water regime. This regime could have prevailed in north latitudes (up to 25°N) during Artinskian and Wordian times, giving birth to very few NC deposits in Timan and northern Ural areas.

Likewise, probably Heterozoan bryozoan-rich carbonates (Zijlstra et al., 1996) deposited in the Uppermost Maastrichtian of the Limburg area were located up to 35°N at this time.

During the Ypresian, *Solenomeris* (Foraminifera) reefs developed at about 32° north latitude and have been interpreted (Plaziat and Perrin, 1992) as fitting with the border of the subtropical climatic belt. Accordingly, NC sedimentation, which developed between 35° and 45° north during the Early/Middle Ypresian in eastern Europe and western Asia (Meulekamp et al., 2000a), can be related to subtropical to temperate carbonates. Indeed, NC contain a diversified faunal association with molluscs, foraminifera (e.g. Nummulites), echinoids and scarce corals. Nummulitic limestones were also abundant during the Late Lutetian at these latitudes. The Burdigalian and Langhian NC, bearing a molluscan, echinodermal and bryozoan-rich association, developed between 35° and 40° north latitude and were probably deposited under subtropical to temperate seawater conditions.

5.3. Non-skeletal mineralogy

Referring to the non-skeletal mineralogy (Sandberg, 1983), Peri-Tethys maps indicate that wide areas were covered by NC, regardless of the dominant trend of the ocean chemistry: influencing either aragonite deposition or calcite deposition (Figs. 2 and 3). As re-emphasised by James (1997), calcite seas appear to have been common when the Earth was in greenhouse mode (high atmospheric CO_2 concentrations, e.g. the Mesozoic); conversely, aragonite seas typified icehouse periods when atmospheric CO_2 was low (Late Cainozoic, Late Palaeozoic). But Triassic times are considered aragonite seas, despite the fact that this period was of the greenhouse type.

The possibility of early aragonite dissolution in ancient calcite seas has been supported by observations from Middle Jurassic submarine cemented horizons in northwestern Europe, in which aragonite fossils have been dissolved out (Palmer et al., 1988). If it existed, this process did not affect the rate of deposition of Late Jurassic NC which were largely developed at these latitudes or, as a whole, the amount of deposition and preservation of NC during the Mesozoic, as the ocean was in calcitic mode.

5.4. Siliciclastic inputs

Regional to local environmental pressures can have significant impacts on reef growth patterns by modulating global changes (Montaggioni, 2000).

As recalled by James (1997), carbonate sediments, both Photozoan and Heterozoan in origin, accumulate in abundance where terrigenous clastic sedimentation is arrested. Excess of nutrients brought by increased detrital material can inhibit thriving of carbonate producers. Wet or glacial conditions and sea level lowstands are favourable to siliciclastic deposits on continental shelves and, consequently, to a lesser development of NC.

Wet conditions which provided large amounts of terrigenous clastics probably prevailed on the eastern margin of the Arabian–African shield around the palaeoequator in the Late Norian and in the Late Rupelian to the Piacenzian/Gelasian (see above). Thus, different time slices of the Peri-Tethys domain (e.g. Wordian, Early Aptian) show that NC faced elongated and permanent siliciclastic belts, without apparent damage. Probably, in this case, the corresponding shelves were subjected to meso- or oligotrophic conditions, and the rate of NC production was greater than the rate of terrigenous clastic inputs. Likewise, some important carbonate producers (e.g. hippuritid rudists, in the Late Cretaceous; Philip, 1972) were well adapted to resist terrigenous and/or nutrient inputs.

Mixed NC/terrigenous facies were also frequent at relatively high latitudes, on shelves developed between 40 and 50° north during the Early Ladinian, the Early/Middle Ypresian and the Late Lutetian.

5.5. *Eustasy*

NC deposits, and subsequently reefs, generally thrive on carbonate shelves and oceanic highs during periods of sea level highstands. Indeed, transgressions increase surfaces where benthic organisms develop, enhance equable climatic conditions and diminish terrigenous inputs; all these conditions are favourable to NC production and deposition. These considerations lead one to expect a large development of areas covered by NC in the studied domain during episodes of sea level highstand (most of the selected time slices) and an areal reduction during lowstand episodes.

This roughly occurred through the time span examined (Fig. 3). Indeed, periods of increasing area covered by NC (e.g. Moscovian, Early Ladinian, Early Kimmeridgian, Late Cenomanian, Late Lutetian) were coeval with sea level highstands, even if the amplitude of the rise was different from one period to another. Similarly, the prominent decrease of NC areas beginning in the Late Rupelian and ending in the Piacenzian/Gelasian was correlated with a global sea level fall during this period.

However, the net decrease of NC areas during the Artinskian is coeval with a sea level highstand as shown by the sea level curve in Golonka and Ford (2000). In this case, a climatic influence responsible for the reduction of NC areas is suspected (see below).

Another striking point is the similarity in the amount of area covered by NC, irrespective of the amplitude of the sea level highstand. As an example, the Late Norian (Gaetani et al., 2000c) and the Late Cenomanian (Philip et al., 2000) have about the same area covered by NC despite a low (100 m) vs high (250 m) eustatic stand, respectively. In this case, the predominance of a climatic factor can thus be suspected. Indeed, in the Late Cenomanian, cool or temperate conditions prevailed on the southern margin of Eurasian cratonic areas, preventing deposition of NC facies (Fig. 1), although an important flooding of shelves and a setting up of shallow marine conditions occurred.

Unfortunately, due to the selection of time slices, data are not available on the areas occupied by the NC during some significant sea level lowstands, such as the Palaeozoic/Mesozoic, Triassic/Jurassic, Jurassic/Cretaceous boundaries.

5.6. *Atmospheric and oceanic climatic factors*

5.6.1. *Atmospheric CO_2, icehouse vs greenhouse modes*

As a whole, the latitudinal enlargement of NC areas was enhanced by greenhouse modes which reduced the climatic contrast between low and high latitudes, whereas latitudinal constriction might be expected during icehouse modes. The alternation of icehouse and greenhouse modes which characterised Phanerozoic times (Figs. 2 and 3) is generally interpreted as influenced by the rate of CO_2 present in the atmosphere. Indeed, modelling of the level of atmospheric CO_2 (Berner, 1990) indicates that the CO_2 level was high during the Mesozoic, and low during the Permo–Carboniferous and the Late Cainozoic.

As shown by Peri-Tethyan maps, NC areas

(Fig. 3) were widespread during Mesozoic and Early Cainozoic greenhouse regimes, especially in the Late Jurassic and in the Eocene, while a dramatic reduction of NC areas occurred during Artinskian, Wordian and late Tertiary times, in relation to an icehouse mode.

A recent reconstruction of tropical sea surface temperatures throughout the Phanerozoic aeon (Veizer et al., 2000) indicates large oscillations, in phase with cold–warm cycles, thus sustaining the idea of climate variability as a global phenomenon. This reconstruction shows a marked decrease of $p\mathrm{CO}_2$ during Permo–Carboniferous glaciations and a negative anomaly (about 3°C) of the tropical surface palaeotemperature at the end of the Carboniferous.

If real, this temperature decrease did not affect the NC deposition in tropical zones as shown by the Moscovian map (Vai et al., 2000a), and the relatively large area (Fig. 3) covered by NC at this time.

Another decrease of tropical surface temperature was inferred by Veizer et al. (2000) at the end of the Jurassic and during the early Cretaceous (from 160 to 100 Ma). This assumption is, in part, in disagreement with our data which indicate a large development of NC in the late Jurassic (Fig. 3). However, temperature variation during the early Cretaceous and a relative cooling during the earliest Hauterivian could have existed in the northern hemisphere (Price et al., 2000), resulting in a reduction of NC, replaced by siliciclastic deposits. A global cooling is also inferred for the late Aptian (Kemper, 1987), possibly responsible for the Tethyan demise of carbonate platforms at this time.

As suggested by several authors (Frakes and Francis, 1988; Price, 1999), Mesozoic and especially Jurassic and Cretaceous times were not strictly in greenhouse mode. According to these authors, there is a record of high-latitude ice rafting during these periods, suggesting that ice was present on Earth. Based on this evidence, a number of episodes of cold or sub-freezing polar climates during the Bajocian–Bathonian, Tithonian–Volgian, Valanginian, Aptian and (with some uncertainties) during the Pliensbachian are recognised (Price, 1999) and correlated with coincidental falls of sea level and arid events (Figs. 2 and 3). According to Price (1999), glacial episodes were associated with periods of aridity, partly due to huge volumes of water being locked up in polar ice caps. If a reduction of NC areas in the Aptian can be considered to be influenced by unfavourable cooling conditions (see above), our results disagree with a hypothesis of cooling during the Tithonian at low latitudes as shown by the large development of NC at this time.

5.6.2. Magmatic events

Although a change from icehouse to greenhouse conditions operated at the Triassic/Jurassic transition as stressed by Fischer (1981), recent works (e.g. Golonka and Ford, 2000) admit that this change occurred at the Permian/Triassic boundary, consecutive to a catastrophic discharge of CO_2 into the atmosphere from the eruption of the Siberian traps. Areas and latitudinal distribution of NC deposits in the Early Ladinian and also in the Late Norian are in agreement with these conclusions. Indeed, the setting up of greenhouse conditions at the Palaeozoic/Mesozoic boundary could explain the northward latitudinal shift of maximum NC deposition during the Early Ladinian compared to the Wordian (Fig. 2).

It is also worth mentioning the onset of the mid-Cretaceous superplume around 120 Ma, which Larson and Erba (1999) have interpreted as responsible for increasing CO_2 in the atmosphere and for initiation of a global warming event. But, as shown by the Early Aptian map (Masse et al., 2000) (Fig. 3), there was no net increase of NC at this time. Thus, the warming could have initiated by: increasing rainfall at the equator and, consequently, terrigenous runoffs, especially in the southern margin; or an excess of temperature which would have resulted in a decay of NC producers.

Another global magmatic event is the appearance of the Ethiopian Afar plume head at the Earth's surface at approximately 30 Ma (Hofmann et al., 1997) and active over a period of 1 Myr or less. This magmatic event was coeval with the dramatic fall of NC deposition in the Late Rupelian (Fig. 3). This was also the time of a change to a colder and drier climate, of a major ice sheet advance in Antarctica, of the largest Tertiary sea level drop and of a significant extinction. Indeed, cooler winters at the Eocene/Oligocene boundary have recently been suggested from mean otolith oxygen isotope values (Ivany et al., 2000).

To summarise, in opposition to Siberian traps, the effect of the Ethiopian Afar eruption was not to increase the amount of CO_2 in the atmosphere but to inject massive, sulphur-rich aerosols and dust, which could have accelerated global cooling and aridity (Hofmann et al., 1997) and, consequently, resulted in decreasing NC deposition.

5.6.3. Ocean circulation

Ocean currents can contribute to poleward transport of heat from the intertropical domain and consequently to increases in the surface of oceanic sedimentary deposits linked to this domain. Such a mechanism was proposed by Shackleton and Boersma (1981) for explaining the unusual warmth of the Earth during the early Tertiary. According to these authors, a global geographical reconstruction for the past 50 Myr shows that sea surface temperature at high latitudes was about 10°C and at low latitudes around 20°C. Moreover, a recent work (Pearson et al., 2001) indicates that for the Late Cretaceous and Eocene epochs, tropical sea surface temperatures were at least 28–32°C. These values are more in line with the greenhouse conditions inferred for these periods and the results of climate models with increased CO_2. Indeed, tropical warming, inducing poleward heat flow, could be invoked for explaining the prominent northward latitudinal extent (up to 40° latitude) of NC deposits in the Early–Middle Ypresian (Fig. 2).

Fluctuations of Cretaceous tropical carbonate and reef boundaries have also been related to major thermal changes resulting from ocean heat transport (Johnson et al., 1996). These authors attributed the collapse of Caribbean middle Cretaceous rudistid ecosystems to the cooling of the tropics due to a poleward move of superheated surface waters. Thus, in the studied area, no significant constriction of tropical carbonates appears in the Late Cenomanian, and the demise of rudist carbonates in tropical zones took place in the early Turonian only (Philip and Airaud-Crumière, 1991) possibly due to a seawater cooling at this time (Kemper, 1987). The recovery of tropical neritic rudist carbonates occurred quickly in the Middle Late Turonian.

Compared to the Triassic, early Jurassic NC deposits were less developed in the northern latitudes. Unfortunately, the geographical extent of NC during the Pliensbachian and the Bajocian–Bathonian is not mapped. The relative northern constriction of NC during the early Jurassic (Fig. 2) could be due to a cooling of the northwestern part of the European domain, as a consequence of the opening of the proto-North-Atlantic seaway (Doré, 1991), rather than a global oceanic cooling. Furthermore, no evidence of a particular cooling event was recorded by NC in the area concerned during late Jurassic and early Aptian times, which appear to be periods of equable climate and low temperature gradient.

5.6.4. Oceanic events

A global oceanic event with climatic implications was recently typified (Weissert, 2000) by the methane release from gas hydrates in oceanic sediments after a global warming of the seawater, probably as a response to an increase of volcanic activity. Methane-derived CO_2 led to amplification of greenhouse climate during a short time (about 1 Myr). The biological carbonate pump showed a negative shift of $\delta^{13}C$ due to an excess of the light carbon. This hypothesis also implies that CO_2 increase led to a carbonate crisis by dissolution and leaching. Such a warming event due to methane release in the ocean and the atmosphere was recently evidenced by Dickens et al. (1995) for the Late Palaeocene–Eocene transition 55 Ma and by Hesselbo et al. (2000) for the Early Toarcian.

Indeed, the Middle Ypresian map (Meulekamp et al., 2000a), which spans a time interval from 55 to 51 Ma, shows an extreme northern occurrence (from 35° to 45°) of NC (Fig. 2). A diversified faunal association including corals, echinids, molluscs, foraminifera, nummulites, etc. is reported from these latitudes. It clearly seems that optimal warm climatic conditions prevailed at this time in these areas. Possibly a link could be established with the global and sudden heating reported at the Palaeocene–Eocene transition. However, a crisis of NC deposition is not observed at this time which would have resulted from dissolution and leaching by CO_2 excess.

Sudden seawater temperature increase was also inferred due to a methane release event in the Early Toarcian, about 180 Ma (Hesselbo et al., 2000). Consecutive changes in the global thermohaline circulation have also been supposed. As proposed by these authors, the supply of cool, nutrient-rich bottom waters of northern origin could explain the extraordinary nature of the organic enrichment in the northwestern European seaway. It might be possible that this palaeoenvironmental change also explains the demise of NC as recorded by the Middle (180–178 Ma) Toarcian map (Thierry et al., 2000c) precisely in these northwestern European areas (Fig. 2).

Moreover, the consequence of any sudden warming due to methane release is not univocal; modulated by palaeogeographical conditions, it could either enhance NC deposition or, on the contrary, indirectly inhibit it by increasing eutrophic influxes.

6. Discussion

6.1. Comparisons with recent counterparts

The values obtained for areas covered by NC for each time slice are not strictly comparable to those of their recent counterparts for different reasons. Firstly, the area mapped is not the exact picture of the real initial distribution. Indeed, in pericratonic margins, the boundaries of carbonate belts often result from an erosion landward, and are poorly defined basinward. Secondly, in the Tethyan domain, precise sizes of isolated carbonate platforms cannot be known with accuracy due to the fact that the areas in question have been deeply modified by alpine tectonics. A third point concerns the selection of the different time slices which privileged sea highstand settings in order to facilitate stratigraphic correlations.

But, from map to map the same types of uncertainties are reproduced and thus comparisons can be established between the relative values of areas covered by NC in a geographical domain which, approximately, remained constant throughout the considered period.

Areas covered today by intertropical NC between 0 and 200 m depth are evaluated at about 4.2 million km^2 by Smith (1978), and 3.93 million km^2 by Kleypas (1997). Taking into account the areas occupied by Heterozoan carbonates on shelves (e.g. Eucla shelf), the total surface might be evaluated at 5 million km^2. The highest values of NC areas recorded during, for instance, Moscovian, Early Kimmeridgian and Lutetian times could be mainly due to the existence of wider shelves than at present.

6.2. Reliability of the Peri-Tethyan NC

A question to be raised concerns the reliability of areas covered by Peri-Tethyan NC with respect to global carbonate deposits preserved within each time slice, as they have been quantified, for instance, at the scale of the entire Tethys (Philip et al., 1995). The answer must be modulated according to the period considered. Indeed, for late Palaeozoic and Triassic times, wide carbonate platforms thriving on South Asian cratonic areas or on the Northern American craton have not been taken into account. Similarly, huge carbonate platforms from Caribbean and Central American domains should be added, especially in the Cretaceous and in the Cainozoic.

Comparisons with data calculated for the entire Tethyan domain (Philip et al., 1995) can be established for various time slices. It appears that during Triassic and Jurassic times, the Peri-Tethyan regions were the main NC settings. Indeed, in the Late Norian, Peri-Tethyan NC represented about 84% of the global NC and in the Middle Toarcian 90%. During the Cretaceous, NC enlarged in the Caribbean and American provinces and, accordingly, the amount of Peri-Tethyan NC diminished. For instance, it reached 62% for the Early Aptian and 66% for the Late Cenomanian. During Tertiary times, Peri-Tethyan NC represented 88% of the global NC in the Lutetian and only 39% in the Late Rupelian. These remarks lead us to regard variations of areas calculated herein as reflecting a general climatic trend, but also peculiar palaeogeographical conditions of the domain considered.

6.3. Validity of NC area data

Due to a relative scarcity of validation points on north and northeast Gondwana, Mega Lhasa Block, and Praecaucasian orogenic belt areas, an overestimate of areas is inferred for the Moscovian, Artinskian, Wordian, Early Ladinian and Late Norian times. More realistic values could be obtained by withdrawing at least 50% of NC areas in the latitudinal bands where validation points are scarce or missing.

From this it results that, especially for the Moscovian, the Artinskian and the Wordian, the corrected surfaces (Fig. 3) are more in agreement with climatic and eustatic factors reconstructed for these periods. The slight increase of NC areas from the Wordian to the Ladinian seems due to global warming and a sea level rise.

An underestimate is noticed for the Early/Middle Ypresian due to a lack of data in the Tethys area. If this domain was taken into account, the total area of NC for this map might probably be close to that of the Lutetian map; this result does not disagree with climatic and eustatic conditions at this time.

7. Conclusions

(1) The history of the Peri-Tethyan NC has been reconstructed with reference to regional palaeogeographic conditions and to global driving factors of the NC factory. Twenty time slices, from the Moscovian to the Piacenzian/Gelasian, have been investigated with special emphasis on NC geographical location and latitudinal distribution.

(2) Peri-Tethyan areas represented the main sites for the NC sedimentation during Triassic, Jurassic and Palaeogene times. Warm equable climatic conditions and wide shelves favoured periods of large development of areas covered by NC. In contrast, periods of reduction of NC areas occurred when extreme climatic and palaeoenvironmental conditions prevailed in the intertropical domain (e.g. arid climate and hypersaline environment; wet climate and high terrigenous sedimentation; excessive heating), or when blocks and continents bearing NC drifted toward high latitudes.

(3) Through all the analysed time intervals, the average NC area maximum is found in the tropical zone of the northern hemisphere whereas, comparatively, a reduction existed in the equatorial zone and in the tropical zone of the southern hemisphere. The shifting of the NC maximum development between the southern and the northern hemisphere took place at the Palaeozoic–Mesozoic transition, as a consequence of the northward drift of Gondwana and Mega Lhasa blocks. This extension was amplified by the development of NC on the southern margin of the Eurasian craton.

(4) The mineralogy of skeletal or non-skeletal components seems not to have played any role in the control of the rate of carbonate deposition and distribution of NC areas. Regardless of the dominant mineralogy of skeletal and non-skeletal contributors, the carbonate production reached high values for all the time intervals considered, so much that climatic and palaeogeographical conditions were favourable. Photozoan associations appear to be the main contributors to the formation of Peri-Tethyan NC but, during various periods (Artinskian, Maastrichtian, Lutetian), Heterozoan producers have played a prominent role in high latitudes of the northern hemisphere.

(5) As a whole, sea level highstands enhanced the increase of NC areas on shelves, while sea level falls led to a decrease of these areas. But, occasionally (e.g. Cenomanian), unfavourable climatic conditions could prevent NC deposition on shelves, during a regime of highstand.

(6) Climatic variations at low latitudes, greenhouse vs icehouse modes and oceanic circulation influenced fluctuations of Peri-Tethyan NC areas. The distribution of NC allowed climatic events to be identified for the late Palaeozoic, the late Jurassic, the early Cretaceous, and the early Tertiary. The spreading of NC was also governed by global and sudden magmatic and oceanic events. The warm event, recorded at the Palaeocene–Eo-

TIME-SLICES	LATITUDINAL BELTS																			TOTAL AREA Km^2
	45/40°S	40/35°S	35/30°S	30/25°S	25/20°S	20/15°S	15/10°S	10/5°S	5/0°S	0/5°N	5/10°N	10/15°N	15/20°N	20/25°N	25/30°N	30/35°N	35/40°N	40/45°N	45/50°N	
MOSCOVIAN		86 430 ●	314 290 ●	1 178 580 ●	1 818 940 ●	1 693 230 ●	573 575	176 790	373 220 ●	461 610 ●	510 720	825 000	775 900	726 790	930 200					10 447 275
ARTINSKIAN	41 250 ●	176 790 ●	210 180 ●	121 790 ●	530 360 ●	722 860 ●	333 930	487 250	177 180 ●	310 070 ●	310 070 ●	310 070	88 590	44 295	88 590					3 953 275
WORDIAN				216 075 ●	278 930 ●	836 800 ●	738 580 ●	779 830 ●	1 001 790 ●	1 634 300 ●	1 760 010 ●	993 940 ●	461 610 ●	36 430	200 360					8 938 655
EARLY LADINIAN					319 790 ●	506 790 ●	98 215	216 075	90 360 ●	275 000 ●	1 119 650 ●	1 382 870 ●	1 127 510 ●	1 386 800 ●	1 598 940	98 215	186 610	483 220		8 890 045
LATE NORIAN						108 040 ●	337 860 ●	76 610 ●	241 610	92 320	153 215	933 040	1 076 440 ●	952 690 ●	903 580	667 860 ●	56 970	137 500		5 737 735
LATE SINEMURIAN					284 825	361 430	294 645	31 430	196 430	436 075	506 790	927 150	1 453 580	1 331 795	1 206 080	204 290	70 715			7 305 235
MIDDLE TOARCIAN					221 475	664 430	526 430	98 215	231 790	161 075	428 220	691 430	1 272 870	565 720	316 250	106 075		88 400		5 372 380
MIDDLE CALLOVIAN			442 950	654 110	624 650	881 970	512 680	542 150	463 575	516 610	970 365	805 360	699 290	383 040	459 650	253 400	102 140			8 311 940
EARLY KIMMERIDGIAN				392 860	388 930	1 005 720	783 750	550 000	471 430	565 720	915 360	699 290	573 575	605 000	1 406 440	290 720	39 290		13 750	8 701 835
EARLY TITHONIAN				354 360	707 150	618 750	263 220	129 640	137 500	157 150	593 220	738 580	707 150	475 360	1 261 080	1 292 510	227 860		23 570	7 687 100
EARLY APTIAN				74 640	22 000	280 890	353 575	271 075	165 000	408 575	502 860	935 000	485 180	369 290	667 860	98 215				4 634 160
LATE CENOMANIAN					88 590	326 075	373 220	263 215	345 720	310 360	753 020	1 050 900	1 506 620	636 430	608 930	192 500				6 455 580
LATE MAASTRICHTIAN					39 865	53 040	184 270	177 180	559 825	487 250	577 500	636 430	624 650	451 790	251 430					4 043 230
EARLY-MIDDLE YPRESIAN								165 000	445 900	608 930	663 930	612 860	671 790	273 040	90 360	475 360	308 225	1 149 120	80 540	5 545 055
LATE LUTETIAN								9 029	165 000	443 930	632 500	565 720	1 249 290	1 280 725	1 312 150	500 900	1 210 010	1 280 720	304 470	8 954 444
LATE RUPELIAN										7 860	35 360	47 140	196 430	388 930	797 510	581 430	165 000			2 219 660
EARLY BURDIGALIAN											66 790		66 790	500 900	962 510	671 790	343 750	76 610		2 689 140
EARLY LANGHIAN											25 535	223 930	341 790	479 290	636 430	271 075	231 790	21 610	11 790	2 243 240
LATE TORTONIAN																64 820	141 430	25 540		231 790
PIACENZIAN / GELASIAN												23 570	104 110	86 430	72 680					286 790
AVERAGE AREA Km^2	2 062.5	13 161	48 371	149 620	266 275	403 001	268 697	198 675	253 317	343 842	526 256	620 114	674 158	548 737	688 552	288 458	204 190	163 136	21 706	

cene transition, and interpreted as the result of methane release in the ocean and the atmosphere, seems to have contributed to the rapid increase of NC deposition at this time.

Further palaeogeographic mapping, focused on time slices not taken into account by the Peri-Tethys atlas, is required for a better understanding of the history of NC and the role of driving factors.

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Appendix A

Table of the calculated areas (in square kilometres) covered by NC at the different time slices in each latitudinal belt from 45° south to 50° north. Black points indicate overevaluated values (see text for explanations).

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