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Upper Cretaceous oceanic red beds (CORBs) in the Tethys: occurrences, lithofacies, age, and environments

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Abstract

A major change in oceanic sedimentation from mid-Cretaceous organic carbon-enriched deep-sea deposits to predominantly Upper Cretaceous oceanic red beds (CORBs), represented mainly by deep-sea red shales and marls, occurred during the Late Cretaceous and early Tertiary in the Tethys. A variety of earth processes such as organic carbon draw-down, tectonic, palaeoceanographic, eustatic and palaeoclimatic changes, or a combination of these could cause such a change, the main significance of which is that it demonstrates that the deep ocean basins ceased to be the preferential burial site for organic carbon. A compilation of available data on CORB occurrences, composition, and age indicate that: (1) CORBs are found in a broad geographic belt extending from the Caribbean across the central North Atlantic, southern and eastern Europe to Asia; with limited occurrences in the Indian ocean; (2) both the first and the last occurrences of CORBs are diachronous; (3) CORBs are of pelagic and hemipelagic origin and were deposited in a variety of environments from continental slope to deep oceanic basin, above and below the carbonate compensation depth (CCD); (4) total organic carbon (TOC) is mostly $<0.1\%$; haematite is relatively abundant, up to 10% in red shales; (5) the termination of CORB deposition in the Alps, Carpathians, and Himalayas was mostly a result of major tectonic events associated with intensification of continental plate migration and initial stages of collision of the Indian and Asian plates and the African and European continental plates. We suggest that changes in dissolved oxygen in the deep ocean were mainly the result of changes in the location and formation of deep water and changes in ocean circulation. It is more than probable that a score of different earth processes, including changes in climate, all acting in concert, were involved in such a major change in the deep-sea environment and location of the carbon reservoir.

Keywords: Oceanic red beds; Upper Cretaceous; Oxic environment; Tethys; Stratigraphy; Sedimentology

1. Introduction

The occurrence of Upper Cretaceous oceanic red beds (CORBs) has been known for at least 140 years, since Štur (1860) and Gümbel (1861) first described them from the Púchov beds in the Carpathians and the Nierental beds in the Eastern Alps. Biostratigraphic and sedimentological studies followed, particularly in Italy, Slovakia, Poland, and Austria (e.g., Birkenmajer, 1977; Premoli Silva, 1977; Butt, 1981; Premoli Silva and Sliter, 1994; Bak, 1998, 2000a,b). Minor attention has been

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paid until now to the Tethys, the wide distribution, correlation, and significance of the oxidation of these deposits for palaeoceanographic reconstructions, and their relationships to the distinctly different, underlying mid-Cretaceous black shales. The latter include organic carbon-enriched beds associated with Oceanic Anoxic Events (OAEs) (e.g., Schlanger and Jenkyns, 1976; Jenkyns, 1980). Recently, Late Cretaceous oceanic red beds were discovered in southern Tibet (Wang et al., 1999, 2000; Hu, 2002), which further confirmed their global extent.

In this paper we use the term CORBs (Cretaceous oceanic red beds) for those reddish sediments that were deposited in situ in marine environments. Therefore, the red colour is regarded as syndepositional and indicates that deposition occurred in a strongly oxic bottom environment. This definition of oceanic red beds does not include red sediments that were derived from the erosion of continental red beds (van Houten, 1964) and transported from continental to marine environments (Turner, 1980).

Modern deep-sea red clays (e.g., Glasby, 1991) are deposited under low productivity gyres, particularly in the Pacific Ocean. This prompts the question: Is the occurrence of Late Cretaceous pelagic red beds associated with changes in biotic productivity in the Tethys Ocean, eustasy, climate, or oceanic circulation? What is the triggering mechanism? Before we could begin to answer the latter question it was necessary to compile occurrences of CORBs, and their composition, biostratigraphy and depositional environment, in order to provide a basis for more specialized studies under the auspices of International Geological Correlation Programme Project 463. Despite many similarities in the development and characteristics of CORBs in the Tethys, there are enough differences for us to present the data by region before we attempt a synthesis of the results.

2. Stratigraphic framework

Compilation of CORB data faces several major problems. First, many CORBs were deposited below the CCD, so calcareous microfossils are absent and siliceous microfossils are rare. Therefore, it is difficult to use biostratigraphy for exact age determination. Second, the definition of microfossil zones in previous studies of CORBs results in different chronostratigraphic correlations. Here we apply the planktonic foraminiferal zones established by Premoli Silva and Sliter (1994), Robaszynski and Caron (1995) and Bralower et al. (1995), and the Cretaceous stratigraphic scale of Gradstein et al. (1995). Third, many CORB occurrences in the Alps, Carpathians and Himalayas are in parts of fault blocks and nappes that are tectonically disconnected from their original depositional sites and even from their original geographic positions.

3. CORBs in the Tethys

3.1. North Atlantic

Upper Cretaceous–Palaeocene pelagic red beds in the North Atlantic basins (Fig. 1, Locality 1) (Jansa et al., 1979) are varicoloured, locally zeolitic, non-calcareous claystone. They form the Plantagenet Formation, which is a relatively thin, but widespread unit that overlies black claystone of the mid-Cretaceous Hatteras Formation (Jansa et al., 1979). This formation is 92.3 m thick at its type locality, DSDP Site 386. These CORB claystone beds are up to 10–20 cm thick and vary in colour from dusky yellowish brown to moderate brown to dusky dark red with some light greenish grey beds. The main minerals are illite and montmorillonite (60–ca. 80%) and, in order of decreasing abundance, quartz, disordered cristobalite, and feldspars. Zeolites (clinoptilolite, phillipsite) form 6–20%. Iron and manganese oxides including micronodules occur in minor amounts. Rare primitive agglutinated foraminifera and poorly preserved radiolarians are present. Thin, irregular lamination is the only sedimentary structure in the formation.

The transitional zone between the Plantagenet Formation and the underlying Hatteras Formation is interlaminated red and green-grey claystone centimetres to a few metres thick (Fig. 2A). The top of the Plantagenet Formation grades into the overlying Palaeogene Bermuda Rise Formation, which comprises siliceous clay and chert.

The earliest Turonian–Palaeocene age of the Plantagenet Formation is not constrained by microfossils, but is bracketed by the ages of the underlying and overlying strata (Jansa et al., 1979; de Graciansky et al., 1987). The lack of calcareous microfossils indicates that deposition occurred below the CCD, and the presence of iron oxides and agglutinate foraminifers suggest an oxygenated depositional environment on the ocean floor (Jansa et al., 1979; de Graciansky et al., 1987). The average accumulation rate for the Plantagenet red beds was less than 2 mm/ka. The composition and depositional environment of the Plantagenet Formation in the central North Atlantic was similar to modern red clays of the deep Pacific Ocean (Glasby, 1991), which were also deposited below the CCD at similar low sedimentation rates.

3.2. Subbetic Zone, Spain

Cretaceous hemipelagic red beds crop out extensively in the External Zone of the Betic Cordillera in southern

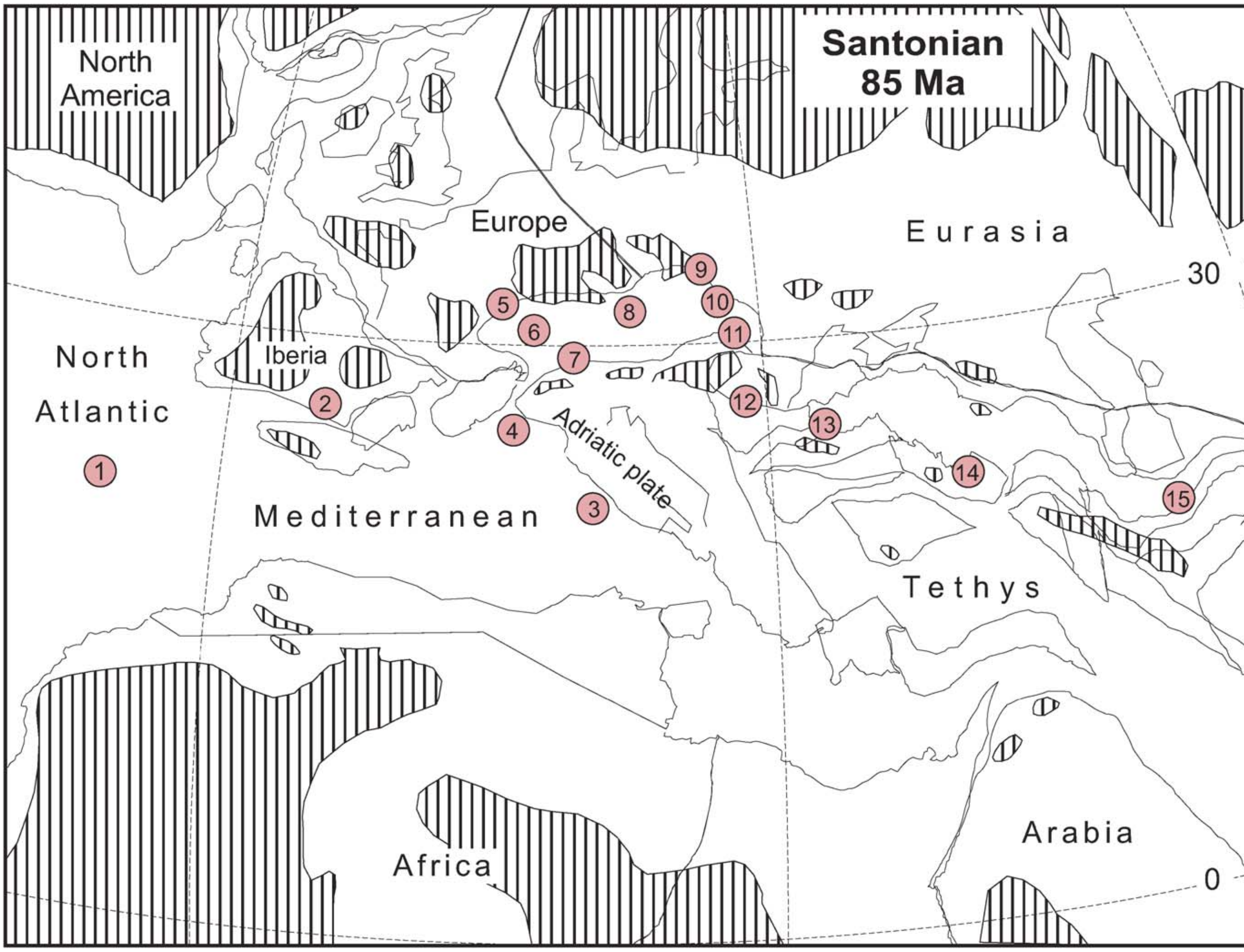


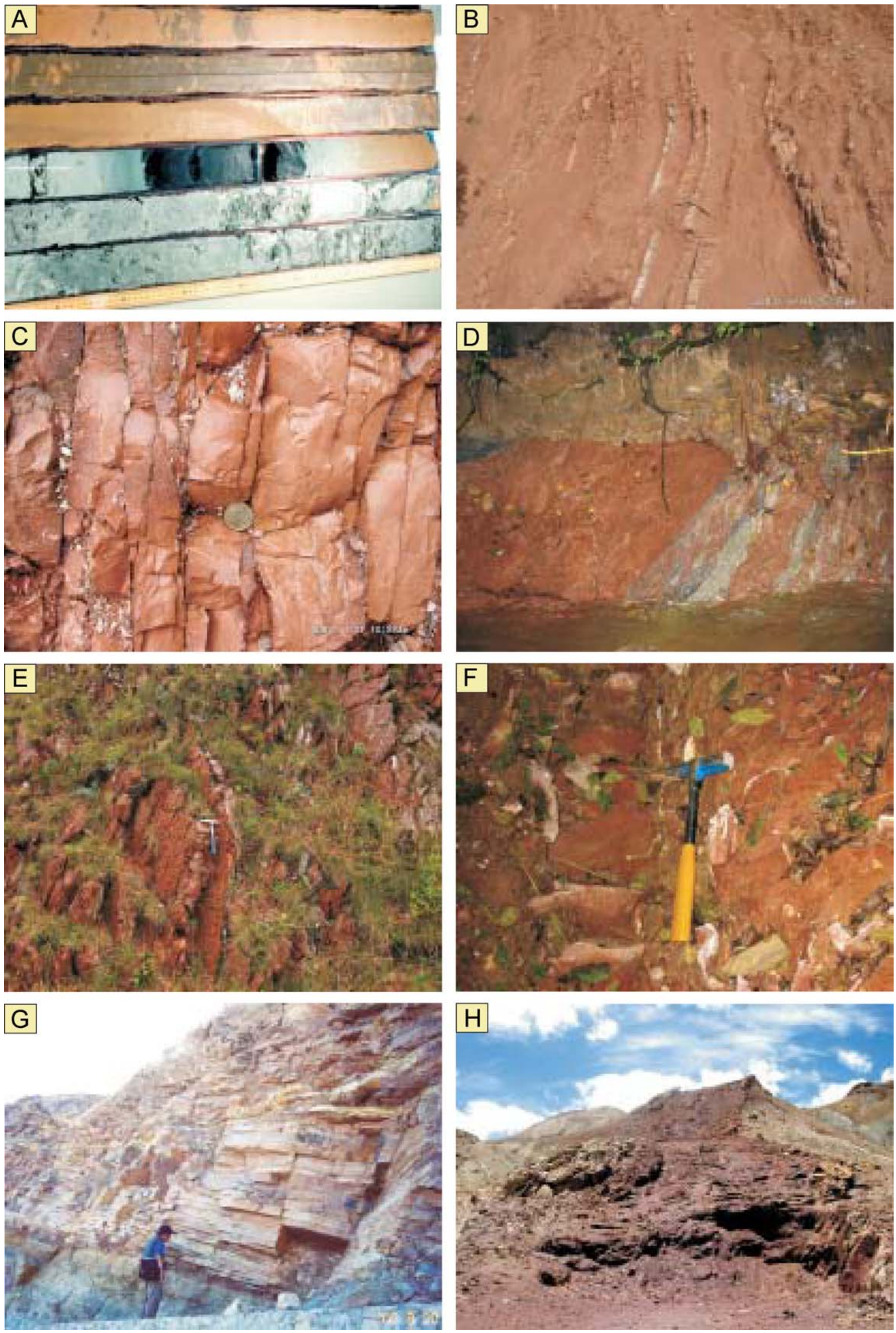
Fig. 1. Palaeographic map of western Tethys (85 Ma, Santonian) showing the localities of CORBs discussed in the text. Palaeographic map after Voigt et al. (1999). Localities: 1, central North Atlantic; 2, Subbetic Zone, southern Spain; 3, Umbria-Marche Basin, Italy; 4, Southern Alps, Italy; 5, Helvetic Zone, Austrian Alps; 6, Rhenodanubian Flysch Zone (Penninic Zone); 7, Northern Calcareous Alps (Austroalpine Zone); 8, Slovakian Western Carpathians; 9, Pieniny Klippen Belt (Polish Carpathians); 10, Manine Basin (Polish Inner Carpathians); 11, Polish Outer Carpathians; 12, south-east Hungary; 13, Romanian East Carpathians; 14, Eastern Pontides, Turkey; 15, Caucasus.

Spain (Fig. 1, Locality 2). They were recently described in detail by Vera and Molina (1999). The ‘‘red beds’’ crop out for about 600 km in a belt orientated west-south-west–east-north-east. They were named Couches Rouges by Fallot (1928) and formally named Capas Rojas by Vera (1984). Stratigraphically, Capas Rojas spans the Cenomanian–Turonian to Early Eocene (Vera et al., 1982). Lithologically they comprise marly limestones, marlstones and calcareous shales that are pink to light reddish in colour and locally intercalated with carbonate turbidites (Fig. 2B). The thickness of the formation varies between 100 and 600 m. The fauna consists of isolated rudists, echinoids and abundant foraminifera and nannofossils. In some of the beds planktonic foraminifera comprise 80% of the rock. The sedimentation rate for Capas Rojas in different areas of the Subbetics varies from 1 to 12 mm/ka (Vera et al., 1982). The presence of *Zoophycus*, *Planolites* and *Chondrites* ichnofacies led Vera and Molina (1999) to suggest that deposition occurred on the continental margin in water depths of between 200 and 1000 m. The authors noted above have suggested that the Capas Rojas deposits are similar to those of the Scaglia Rossa in Apennines.

3.3. Umbria-Marche Basin, central Italy

CORBs occur in the Cretaceous Scaglia Bianca and Scaglia Rossa formations in the Umbria-Marche Basin (Fig. 1, Locality 3). The biostratigraphy and magnetostratigraphy of several sections have been well-documented (Alvarez et al., 1977; Arthur and Fischer, 1977; Premoli Silva, 1977; Premoli Silva and Sliter, 1994).

The Albian–Cenomanian Scaglia Bianca consists predominantly of siliceous, light grey to white biomicritic limestone about 60 m thick (Premoli Silva, 1977;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Premoli Silva and Sliter, 1994). Limestone beds average 25 cm thick and alternate with shale beds 2–3 cm thick. Discontinuous chert beds are greenish grey, red-brown, and dark grey to black and occur at intervals of 15 to 50 cm. A chemostratigraphic marker, the Bonarelli Horizon (OAE2), which is globally traceable, occurs near the top of this formation. This 1-m-thick bed consists of cherty black shale with more than 23% organic carbon (Arthur and Premoli Silva, 1982). Below the Bonarelli bed the Scaglia Bianca has a 10-m-thick interval of intercalated pink limestone, grey limestone, and rare greenish grey marl, which encloses pinkish grey chert nodules. This interval is a widely distributed marker in the Umbria-Marche Basin (Coccioni and Galeotti, 2003).

The overlying Scaglia Rossa Formation, 345 m thick in the Bottaccione section (Premoli Silva and Sliter, 1994), comprises predominantly pinkish red marly limestone beds with shale interbeds (Fig. 2C). Total organic carbon (TOC) of this red limestone is extremely low, only 0.01–ca. 0.07% (Arthur and Fischer, 1977). Alvarez and Montanari (1988) divided the Scaglia Rossa into a lower member characterized by red to pink to yellow-grey limestone and interbedded green-grey to red-brown chert beds. The upper member lacks chert and is predominantly composed of pink to reddish-brown limestone. The uppermost Cretaceous bed in the Umbria-Marche Basin is a white bleached zone, about 20–50 cm thick, that directly underlies the Cretaceous/Tertiary (K/T) boundary (Lowrie et al., 1990).

The age of the Scaglia Bianca Formation in the Umbria-Marche Basin is well constrained by calcareous planktonic foraminifera (Renz, 1936; Arthur and Fischer, 1977; Premoli Silva and Sliter, 1994). The lower CORB interval spans the lower–middle Cenomanian in the uppermost *Rotalipora brotzeni* Zone, the *R. reicheli* Zone and the lowermost part of the *R. cushmani* Zone (Fig. 3) (Premoli Silva and Sliter, 1994). The lowest CORB interval in the overlying Scaglia Rossa Formation appears 4 m above the Bonarelli Horizon, in the lowermost part of the early Turonian *Helvetoglobotruncana helvetica* Zone at the Bottaccione section (Arthur and Fischer, 1977; Premoli Silva and Sliter, 1994). The Scaglia Rossa lithofacies extends to the uppermost Eocene (Premoli Silva, 1977) (Fig. 3). Based on this biostratigraphic control the overall mean sediment accumulation rate for the Cenomanian–Maastrichtian stratigraphic section was 9.2 mm/ka, uncorrected for compaction (Fig. 3). Rates of individual stages vary from 6.8 mm/ka for the Maastrichtian to 18.3 mm/ka for the Santonian (Fig. 3). As confirmation, graphic correlation analysis of the Cenomanian–Turonian interval in the Cismon section gives a mean rate of 8.9 mm/ka (R. Scott, pers. comm. 2004). These sedimentation rates are typical for pelagic environments (Jenkyns, 1986). The Upper Cretaceous sedimentary strata in the Umbria-Marche Basin were deposited at depths of 1500–2500 m in an open Tethyan ocean setting (Kuhnt, 1990), as indicated by sediment composition, lack of terrigenous input, and enclosed nannofossils and planktonic foraminifera (Arthur, 1976; Arthur and Fischer, 1977). In the eastern part of the basin, close to the Adriatic margin, turbidite beds in the Scaglia Rossa suggest deposition on or near the continental rise (Wezel, 1979; Stow et al., 1984).

3.4. Southern Alps, Italy

In northern Italy near Lake Garda, the Scaglia Rossa Formation, the same facies as in the Umbria-Marche Basin, ranges in age from middle Turonian to Eocene and is about 160 m thick (Fig. 1, Locality 4) (Lehner et al., 1987; Luciani, 1989). It is predominantly marlstone, but locally, reddish calcareous shale and limestone turbidite beds are intercalated. The top of the Scaglia Rossa is a hardground unconformably overlain by Eocene shallow-water limestone. The hiatus is diachronous, spanning the late Turonian–Ypresian (Bosellini and Luciani, 1985; Luciani, 1989) and represents the erosional base of a wide submarine canyon.

3.5. Austrian Alps

Upper Cretaceous oceanic red beds are exposed in the three major tectonic zones of the Eastern Alps that extend from the southern margin of the European Plate (Helvetic domain) to the elongate deep Penninic Ocean (Rhenodanubian Flysch Zone) and to the Austroalpine microplate to the south, which includes the Northern Calcareous Alps (Fig. 1) (Wagreich, 1995, 2002).

The Helvetic Zone. In the Ultrahelvetic zone of Upper Austria, CORBs occur in the Albian–Eocene "Buntmergelserie" (variegated shales) (Prey, 1952; Egger et al., 2000) (Fig. 1, Locality 5). These range in age from Turonian to Campanian (Kennedy and Summesberger, 1999; Wagreich, 2002) and are comprised of red marl, red limestone and limestone-marl

Fig. 2. Selected photographs of the CORBs. A, DSDP Leg 103, Site 641, North Atlantic (drill core), showing dark grey non-calcareous claystones of Cenomanian age overlain by organic rich "Bonarelli Horizon" (C/T boundary), in turn overlain by reddish pelagic clays of the Plantagenet Formation (Late Cretaceous). B, the Valdepeñas de Jaen section, southern Spain, Upper Cretaceous. C, the Scaglia Rossa at the Bottaccione section (Gubbio, central Italy), latest Cretaceous. D, the "Buntmergelserie" in the Rehkogelgraben section (Upper Austria), Coniacian–early Campanian. E, the Kysucke section (Slovakia), Cenomanian. F, the Dursztyn section, Pieniny Klippen Belt (southern Poland), middle Cenomanian–Campanian. G, Upper Cretaceous red pelagic limestones resting unconformably on the volcanic rocks on the East Amasra section, Turkey. H, the Chuangde section (southern Tibet), Santonian–early Campanian.

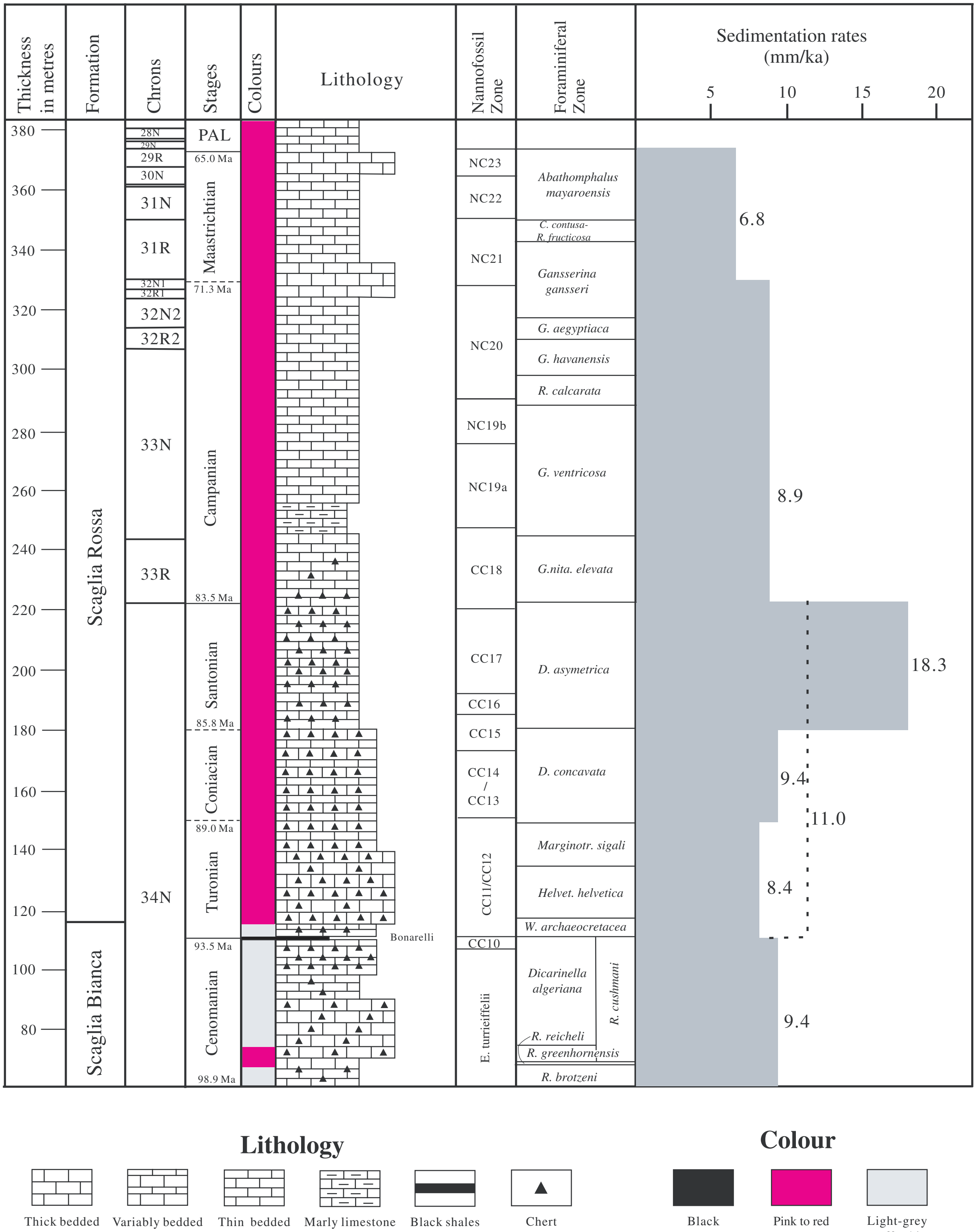

Fig. 3. The Bottaccione section: lithology, biostratigraphy (foraminiferal and nannofossil zones) and sedimentation rate, compiled from data in Premoli Silva and Sliter (1994).

successions. The CORBs are rich in planktonic foraminifera; inoceramid shells, ammonites and echinoids are rare (Fraaye and Summesberger, 1999; Kennedy and Summesberger, 1999). CORBs in the Buntmergelserie of the Ultrahelvetic Gresten Klippen Zone are mainly carbonate-poor shale rich in "flysch type" benthic foraminifera, and were deposited to the south on the deeper parts of the European continental slope.

Rhenodanubian Flysch Zone, *Penninic Zone*. Three intervals of non-calcareous, variegated reddish shale, each a few metres thick, are intercalated with Upper Cretaceous siliciclastic turbidites (Fig. 1, Locality 6; Fig. 2D). Thin sandstone intercalations display Bouma C, D and E bedding types, indicating distal turbidites. All three CORB intervals are interpreted to be the result of very low sedimentation rates in a deep flysch basin below the local CCD. Another CORB interval in the Coniacian–Campanian Kaumberg Formation of the Laab Flysch Nappe near Vienna consists of red and green deep-sea clays with thin, basin-plain turbidites (Faupl, 1976). These carbonate-free red pelites are hemipelagic basin-plain clays of the Penninic Ocean. Flysch-type agglutinated foraminifera characterize the microfauna. Alternating red and green colours have been interpreted to be the result of different redox levels at or near the sea bottom (Faupl, 1976).

Northern Calcareous Alps, *Austroalpine Zone*. The tectonic evolution of the northern active margin of the Austroalpine microplate strongly influenced CORB deposition in the Turonian–Campanian Nierental Formation of the Upper Gosau Group (Fig. 1, Locality 7). Up to 400 m of interbedded syntectonic breccias and turbidites, reddish, thin to medium bedded, bioturbated calcareous marlstone and calcareous shale with minor sandstone beds comprise the Nierental Formation (Krenmayr, 1996). A thin succession of CORBs is late Turonian in age. These (hemi)pelagic marly limestones, marlstones and shales interfinger with turbidite and coarse mass-flow deposits of small submarine fans. Carbonate content varies between 50 and 85%. Planktonic foraminifera, calcareous nannofossils and inoceramid fragments are present. A *Zoophycos* ichnofacies is common. The Nierental Formation was deposited on the continental slope above the CCD (Krenmayr, 1996). The sediment accumulation rate of the CORBs is estimated at 25 mm/ka.

3.6. Slovakia, Western Carpathians

CORBs are widespread in the Coniacian–lower Campanian Púchov Marl of the Western Carpathians in Slovakia (Štur, 1860; Michalik et al., 2002) (Fig. 1, Locality 8). In the westernmost central Carpathians CORBs occur in the Košariská Formation (approximately equivalent to the Púchov Marl). The 50-m-thick sequence is characterized by variegated, mostly red marl containing a rich foraminiferal fauna dominated by planktonic forms of the *Globotruncana arca* Zone (Salaj and Gašparíková, 1983). The nannoplankton *Broinsonia parca* Zone confirms an early Campanian age (Bystrická et al., 1983). The underlying Hurbanova Valley Formation is a flysch sequence of alternating graded calcareous sandstone, sandy marl and sandy limestone. The overlying upper Campanian and Maastrichtian Podbradlo Formation is a thick sequence of grey-green marl intercalated with calcarenite sandstone, sandy *Orbitoides* limestone and conglomerate.

The Púchov Marl is also widely distributed in the Slovakian Pieniny Klippen Belt (Michalik et al., 2002) (Fig. 2E). A major diachronous hiatus spanning the Early to mid-Cretaceous separates the Púchov Marl from the underlying Jurassic–Cretaceous carbonate platform deposits. In the Czorsztyn Unit, CORBs directly overlie Jurassic limestone. In the Pieniny and Kysnca units, the Lower Cretaceous Maiolica facies with the lower Aptian Selli level at the top underlies CORBs (Michalik et al., 2002). The Púchov Marl is overlain by flysch of the Jarmuta Formation.

The upper Cenomanian –lowermost Turonian interval of channel-fill conglomerate, inter-channel sandstone and hemipelagic claystone are interpreted to be deep-sea fan deposits in the Široká section (Michalik et al., 2002). Intercalated brick-red marl yielded a planktonic microfauna of marginotruncanids, dicarinellids and hedbergellids. *Dicarinella imbricata* suggests an early Turonian age for the red marls (Salaj and Gašparíková, 1983). The overlying sequence of sandstones and claystones of the Snežnica Formation was deposited during the late Turonian (*Dicarinella primitiva* Zone). Siliciclastic deposition diminished during the early Coniacian and was replaced by the Púchov Marl, which here is 100–150 m thick. A rich planktonic foraminiferal fauna of the *Dicarinella concavata* Zone, the *D. asymetrica* Zone and the *Globotruncanita elevata* Zone indicates a Coniacian–early Campanian age (Salaj and Gašparíková, 1983; Michalik et al., 2002). Benthic calcareous species are represented by rare specimens of *Eponides sibiricus* and *E. frankei*.

3.7. Polish Carpathians

Upper Cretaceous pelagic red beds occur in southern Poland in two major tectonic provinces: the Polish Inner Carpathians including the Pieniny Klippen Belt (Fig. 1, Localities 10 and 11) and the Polish Outer Carpathians (Fig. 1, Locality 9).

Pieniny Klippen Belt. The Pieniny Klippen Belt occupies a major axial suture zone in the Carpathian fold belt and separates the Inner and Outer Carpathians. In the Polish Pieniny Klippen Belt variegated and red calcareous pelagic facies occur in the Jaworki Formation (Birkenmajer, 1977; Bak, 1998, 2000a,b; and references therein) (Fig. 2F), and are similar to CORBs exposed in the Klippen Belt of Slovakia (Fig. 1, Locality 10). The Jaworki Formation is divided into three lithostratigraphic units: the Skalski Marl, Pustelnia Marl and Macelowa Marl members (Birkenmajer, 1977) (Fig. 4A).

The Skalski Marl Member is 2–10 m thick and composed of green, grey, pink, and cherry-red marls

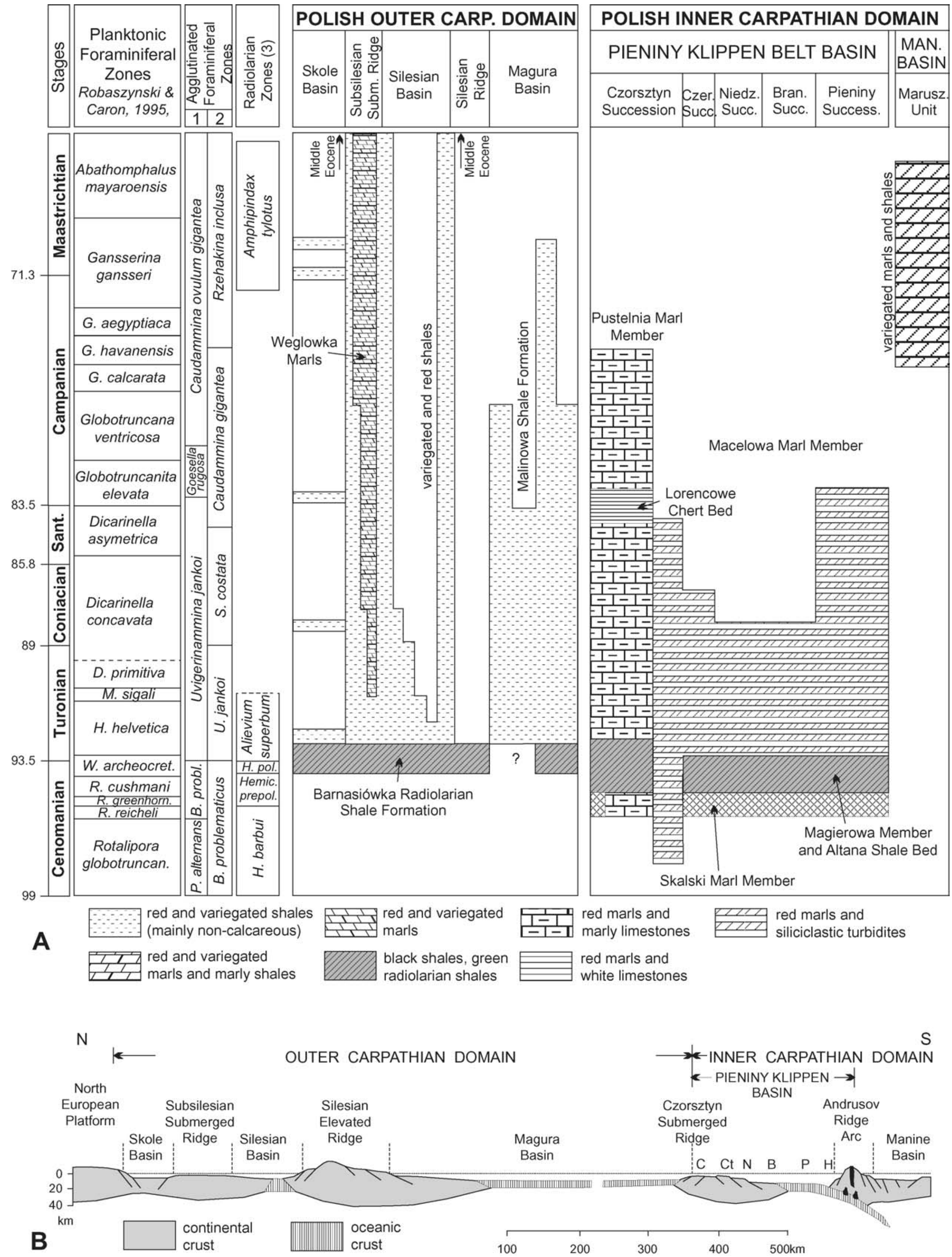

Fig. 4. A, stratigraphical column for the Upper Cretaceous in the Polish Carpathians, showing stratigraphical distribution and ages of the CORBs in the Outer and Inner Carpathian domains, including the Outer (flysch) Carpathians, Pieniny Klippen Belt and Maruszyna Unit (compiled from Bak, 1998, 2000a,b, 2002); for tectonic successions, see B, palinspastic position of the Polish Outer and Inner Carpathian basins during the Late Cretaceous (revised after Birkenmajer, 1986; Oszczypko, 1999). Pieniny Klippen Belt successions/units: C, Czorsztyn Ridge; Ct, Czertezik; N, Niedzica; B, Branisko; P, Pieniny; H, Haligovce; AR, Andrusov Exotic Ridge; Ma, Manine Basin. Agglutinated foraminiferal zones: 1, after Geroch and Nowak (1984), zone boundaries after Bak (2000a,b); 2, after Olszewska (1997). Radiolarian zones: 3, after Bak (1999, 2000a,b); *H. pol.*, *Hemicryptocapsa polyhedra*; *Hemic. prepol.*, *Hemicyptocapsa prepolyhedra*.

and marly limestones. It corresponds to the middle–upper Cenomanian pelagic foraminiferal (*Hedbergella-Rotalipora-Praeglobotruncana*)-radiolarian microfacies (Alexandrowicz, 1966). Planktonic foraminifera and radiolaria are significant components of these rocks (8–19% and 1–11%, respectively).

The Pustelnia Marl Member is 30–40 m thick and comprises strongly bioturbated brick-red marls devoid of any clastic intercalations (Fig. 2F). Light green colours appear locally, especially at the base of the unit. Planktonic foraminifers are 15–20% of the grains; however, in the Santonian–Campanian part of the section, agglutinated and calcareous benthic foraminifera dominate. Inoceramid calcite prisms are locally abundant. The 3-m-thick Lorencowe Chert Bed is near the upper Santonian/lower Campanian boundary in the Pustelnia Marl. Contrary to its name, this bed consists of light green, thin-bedded limestone intercalated with brick-red marly limestone and marl (Fig. 4A). Large marginotruncanids and globotruncanids are the main component of limestone beds. Numerous hardgrounds indicate condensation and extremely low sedimentation rates.

The Macelowa Marl Member is 10–50 m thick and comprises cherry-red marl and calcareous mudstone intercalated with thin-bedded, grey to greyish blue, calcareous siltstone and sandstone. Carbonate content of the red beds ranges widely from 16 to 75%. Greyish red calcareous mudstones usually occur in beds 8–14 cm thick, and are particularly common in the Turonian–Coniacian part of this member. Foraminifers constitute up to 20% of the marls and marly limestones, and are dominated by the deep-water agglutinated foraminiferal assemblages. A low-diversity assemblage of trace fossils in the marl is dominated by *Planolites* and *Zoophycos* (Bak, 1995). The microfauna suggests deposition on the continental slope and central furrow of the Klippen Basin (Bak, 2000a,b). Grey to bluish, thin-bedded (1–3 cm) sandy mudstones and sandstones deposited by turbidity current are common in the upper part of the unit.

CORB deposition in the Pieniny Basin began on the Czorsztyn submerged ridge in the early Cenomanian (*Rotalipora globotruncanoides* Zone) and expanded into the whole of the basin during the middle and late Cenomanian (*Rotalipora reicheli–Rotalipora cushmani* zones) (Fig. 4A). Sedimentation of red and variegated muds was interrupted during the late Cenomanian–early Turonian by deposition of muds (now represented by a black shale facies) during OAE2. CORB deposition resumed during the Turonian (*Helvetoglobotruncana helvetica* Zone) and continued into the middle Campanian (*Globotruncanella havanensis* Zone) (Bak, 2002). However, in the shallowest part of the basin on the Czorstyn Ridge (Fig. 4), turbidites ended CORB deposition.

Well-oxygenated oligotrophic conditions on the sea floor are suggested by a low-diversity benthic foraminiferal assemblage, dominated by shallow and deep infaunal agglutinated taxa (Bak, 2000a,b), and by a low-diversity trace fossil assemblage having few depth tiers (Bak, 1995). CORB sediment accumulation rate in the Klippen Basin was 1–4 mm/ka on the Czorsztyn Ridge, and 8–23 mm/ka in deeper parts of the basin. The calcareous/agglutinated foraminiferal ratio, the trace fossil assemblage, and the calcium carbonate content suggest that deposition occurred at lower bathyal depths near the foraminiferal lysocline (Bak, 2002).

Maruszyna Succession, central Carpathians. CORBs are also present in the Maruszyna Succession/tectonic terrane of the Inner Carpathian province along the southern boundary fault of the Pieniny Klippen Belt (Fig. 1, Locality 11). This succession was deposited in a narrow back-arc basin, located 50–100 km from the shoreline during the Late Cretaceous–Eocene (Birkenmajer, 1986; Fig. 4B). The Campanian–Maastrichtian succession consists of hard, light-coloured marly limestone overlain by soft, variegated marl about 20 m thick (Birkenmajer and Jednorowska, 1983; Kostka, 1993). The dominance of calcareous benthic foraminifers and the high ratio of planktonic/benthic foraminifers (about 0.9) suggest that these sediments were deposited in an open marine, bathyal environment (Kostka, 1993).

Polish Outer Carpathians. The Upper Jurassic–Miocene "flysch Carpathians" are over 6 km thick, exposed in a series of imbricated nappes (Fig. 1, Locality 9). These flysch deposits accumulated in several elongated deep-marine basins in the western Tethys realm (Fig. 4B). The red and green shales are characteristic lithologies of the flysch; most either contain little or no carbonate (e.g., the Weglowka Marl).

CORB biostratigraphy in the Outer Carpathians is based mainly on deep-water foraminifera (Geroch and Nowak, 1984; Olszewska, 1997) and radiolaria (Bak, 1999, 2000a,b). Sedimentation of variegated facies began during the early Turonian (radiolarian *Alievum superbum* Zone). In all Outer Carpathian subbasins, lower Turonian variegated shale directly overlies the uppermost Cenomanian–lowermost Turonian green and black radiolarian shales of the Barnasiówka Radiolarian Shale Formation (Bak et al., 2001) (Fig. 4A). The duration of CORB sedimentation varied in different subbasins (Fig. 4A) and was terminated by the influx of terrigenous turbidites (Geroch et al., 1967). In the Magura Subbasin it continued into the early Maastrichtian (Oszczypko et al., 1990), and in the Subsilesian and Silesian subbasins CORB deposition terminated in the Eocene. In the Skole Subbasin, on the northern margin of the Outer Carpathian Basin, variegated shale intervals up to 10 m thick are interbedded in lower Turonian–Maastrichtian calcareous and siliciclastic turbidites (Kotlarczyk, 1978). The thickness of variegated shale varies from basin to basin. It is 10–200 m thick in the Magura Subbasin (Malinowa Shale Formation; Birkenmajer, 1977; Oszczypko et al., 1990), about 100 m thick in the Silesian Subbasin, and more than 600 m thick in the Subsilesian Subbasin (Weglowka Marls). The latter sediments were deposited along the crest of a submarine ridge during the Turonian–middle Eocene.

Small specimens of siliceous-walled, deep-water, agglutinated foraminifers (DWAF) are the only microfauna in the non-calcareous variegated shales in the Magura and Silesian subbasins (Geroch et al., 1967; Malata and Oszczypko, 1990; Bak, 2000a). Most of these taxa characterize the abyssal Late Cretaceous realm below the CCD. Deep-water CORB sedimentation in these subbasins is also confirmed by the *Nereites* ichnofacies, which includes abundant *Agrichnia*, *Fodinichnia* and *Pascichnia* (Leszczynski and Uchman, 1993; Bak, 2000a).

The dominant red colours of the variegated shales, their moderately diversified benthic foraminiferal assemblage, and trace fossils indicate that the original sediment was poor in organic matter and that deposition occurred in a highly oxygenated environment. This is confirmed by abundant epi- and infaunal foraminiferal morphotypes. That oxygen content fluctuated in interstitial waters is also documented by *Chondrites*, which are more frequent in grey-green shales (Leszczynski and Uchman, 1993; Bak, 2000a,b). These fodinichnial burrows were produced by organisms that preferred oxygen-poor, chemically reducing, interstitial conditions.

3.8. South-east Hungary

In south-east Hungary (Fig. 1, Locality 12), Turonian CORBs occur in the red globotruncanid-rich Vékény Marl (Balla and Bodrogi, 1993), which is the Hungarian equivalent of the lower part of the Púchov Marl in the western Carpathians. The development of the Turonian–Senonian "Púchov Marl" facies in Hungary is restricted to the Szolnok Flysch zone (Csontos et al., 2002).

The Vékény Marl, exposed in small isolated, exotic bodies, is heavily sheared and brecciated, and consists of red nodular and thinly laminated pelagic marl and calcareous marl. The rocks yield a rich planktonic and poor benthic foraminiferal fauna; radiolarians and ostracods are sporadic, and *Inoceramus* prisms, fish teeth and echinoid detritus are extremely scarce (Balla and Bodrogi, 1993). The red marl is composed of 5% haematite and 3% goethite (Balla and Bodrogi, 1993).

3.9. Romanian East Carpathians

Upper Cretaceous reddish pelagic beds are widespread in the southern part of the Carpathians and form a post-tectonic cover on the Outer Dacides tectonic unit (Melinte, 2002) (Fig. 1, Locality 13). The most extensive marine red bed unit is the Campanian–Maastrichtian Gura Belie Formation, which is composed of red calcareous marls intercalated with white and green calcareous marls. The thickness of the formation increases from west to east, from 80 to 200 m. It contains the belemnites *Belemnitella mucronata* and *B. carpathica* as well as Campanian–Maastrichtian planktonic foraminiferal assemblages (Ion et al., 1997). The calcareous nannofloras in the formation are assigned to the late Campanian–Maastrichtian CC21–26 nannozones. As in Italy, CORBs in the western part of the East Carpathians extend into the Palaeogene (Melinte, 1999), but in the eastern part deposition of marine red beds ended in the late Maastrichtian.

3.10. Eastern Pontides, Turkey

In the Eastern Pontides, Turkey, reddish limestone and argillaceous limestone form a marker horizon along the Black Sea coast called the Kapanboğazi Formation (upper Cenomanian–lower Campanian) (Görür et al., 1993; Fig. 1, Locality 14; Fig. 2G). This CORB limestone is a biomicrite rich in planktonic foraminifera with subordinate thin-shelled bivalve fragments, radiolaria, and echinoderm fragments. The foraminifera are mainly globotruncanidae, globigerinidae, and heterohelicidae. The reddish limestone was deposited in water 500–1000 m deep (Görür et al., 1993). On average it is 30 m thick (Görür et al., 1993) and separates two main episodes of volcanism associated with the formation of a volcanic arc and opening of the western Black Sea back-arc basin (Tüysüz, 2002; Fig. 2G). Calcium carbonate content of the limestone ranges from 63 to 84% and haematite from 0.5 to 3.0 wt. % (Eren and Kadir, 1999). The acid insoluble components are quartz, illite and haematite, with minor amounts of chlorite, feldspar, kaolinite and anatase (Eren and Kadir, 2001).

In the Kilop area, a hardground surface is the contact between Lower Cretaceous shallow water limestone and Upper Cretaceous red limestone (Eren and Tasli, 2002); the hiatus spans the Aptian–Santonian. The red pelagic carbonates were deposited immediately after the onset of late Santonian spreading, when widespread subsidence occurred in this region (Tüysüz, 2002).

3.11. Northern Peri-Tethys (Caucasus and central Asia)

CORBs are widespread in the southern part of northeast Peri-Tethys, extending from the Carpathians to Central Asia in Crimea, Georgia, Armenia and Turkmenia (Fig. 1, Locality 15; Scherbinina, 2002; Tur, 2002).

In the Crimea, Coniacian Púchov-type sediments are present. In Cis-Caucasia, pink to reddish brown CORBs are widespread in the upper Turonian–Santonian limestones and marls. On the southern slope of the Greater Caucasus in central Georgia, upper Turonian, red, pink and white limestones up to 90 m thick grade into Coniacian–lower Campanian red and green marls (Scherbinina, 2002; Gambashidze, 2002). In the western Caucasus, a pink to brick-red carbonate flysch-like succession ranges in age from Cenomanian to Santonian, and Campanian–Maastrichtian limestones are predominantly white and rarely pink coloured. In the Lesser Caucasus of Armenia CORBs are mainly late Turonian and late Coniacian–early Santonian.

In north Caucasia and western Turkmenia CORBs range in age from late Turonian to early Maastrichtian but are best developed in the Coniacian–Santonian interval (Tur, 2002). In the Prae-Caucasus, reddish and grey marls and limestones are about 80 m thick; they span the lower Coniacian–lower Santonian, but may extend into the Campanian. In the Tuarkyr Basin of north-west Turkmenia, several beds of reddish marls and limestone span the Coniacian–Campanian. On the northern slope of the north-west Caucasus, red marl beds are present in upper Turonian (?) flysch. Pink limestone and red to brown marl beds also occur in Maastrichtian strata.

In the western Kopet-Dag Basin of south-west Turkmenia, upper Turonian–lower Maastrichtian red and green marls 40–180 m thick grade eastward into grey marls and limestones (Scherbinina, 2002). Lower Coniacian red marl is in the deepest part of the basin and Santonian–Maastrichtian strata extend over the entire area.

3.12. Ladakh-Zanskar Himalayas

South of the Indus Suture Zone in the Karamba and Lamayuru complexes, Ladakh Himalaya, Cretaceous volcanogenic sediments are overlain by thin to medium bedded, pink to grey pelagic carbonates 25 m thick (Robertson and Degnan, 1993; Robertson and Sharp, 1998). The planktonic foraminifera *Globotruncana* sp. and *Heterohelix* sp., indicate a Late Cretaceous (Campanian) age (Robertson and Sharp, 1998). This pelagic deposition was terminated by alkaline volcanism. Post-Campanian deposits are missing in the Karamba and Lamayuru complexes, as result of thrusting induced by the initial collision of the Indian and Eurasian continental plates (Robertson and Sharp, 1998).

Upper Cretaceous multicoloured pelagic marly limestones (grey, red, green) of the Fatu La Formation crops out widely in the Zanskar Himalaya (Gaetani et al., 1986; Premoli Silva et al., 1991; Garzanti, 1993). The formation is about 100–300 m thick and rich in planktonic foraminifera. It was dated as early Turonian–early Campanian on the basis of occurrences of planktonic foraminifera by Premoli Silva et al. (1991), who considered this multicoloured limestone to have been deposited in a deep, open shelf/slope environment under oxygenated conditions. The formation is partially synchronous with the Chuangde Formation (see below) and the Scaglia Rossa.

3.13. Tibet Himalayas

Mid-Cretaceous strata deposited on the deep northern margin of the Indian continental plate are represented by the Gyabula and Chuangde formations in the Gyangze area. Here, the grey to dark grey shales of the Gyabula Formation are overlain by reddish-coloured shale intercalated with pink pelagic marlstone, limestone and radiolarian cherts of the Chuangde Formation, which is about 30 m thick (Fig. 2H) (Wang et al., 2000, 2001; Hu, 2002). The red shales of the latter formation are composed of clay minerals dominated by illite, with minor chlorite and haematite and trace amounts of very fine silt-size quartz, pyrite, and mica. The red marlstone/marly limestone beds are composed of nannomicrite with locally preserved nannofossils and variable amounts of planktonic foraminifera. The formation contains very little organic carbon (TOC 0.01–0.14%). It is dated as Santonian–early Campanian based on the planktonic foraminifera *Globotruncana linneiana*, *G. lapparenti*, *G. ventricosa*, *Globotruncanita elevata*, *G. stuarti*, *G. stuartiformis*, *Dicarinella asymetrica*, *D. concavata*, *Marginotruncana pseudolinneian*, *M. schneegansi*, *M. sinuosa* and *Rosita fornicata*, and on nannofossils (Hu, 2002; Wan and Li, 2002). The sedimentation of the red facies took place under highly oxygenated bottom conditions, a conclusion that is supported by the red colour, the high iron trioxide content, a negative Cerium anomaly at the base of the red sequence, and very low TOC (Hu, 2002).

The contact between the Chuangde Formation and the overlying Zongzhuo Formation is sharp. The light greenish grey, thin-bedded shale of the latter contains slump-deformed intraclasts of reddish marlstone, some of which enclose pieces of contorted red shale. The marlstones represent recurring slumps from the upper part of the continental slope into the adjacent deep oceanic basin.

4. Discussion

The initial aim of this study was to arrive at the process or processes that resulted in a major change from a dysoxic to an oxic deep-sea bottom environment in Late Cretaceous oceans. We therefore compiled published data and added new data from our field studies on the regional distribution and composition of such facies, which, from previous limited data, were assumed to be synchronous Tethys-wide. However, our major finding is that this is not the case. Below we summarize some of the most important and common features of CORBs.

Regional distribution. Upper Cretaceous oceanic red beds extend west from the Himalayas in the east to the Caucasus, Turkey, the Carpathians, Alps and Apennines, Spain, the central North Atlantic and the Caribbean (Fig. 1). They were deposited in mid-latitudes of both the northern and southern Tethys. Evidence for the southern latitude distribution is the occurrence of CORBs in the Himalayas (Fig. 1) and the South Atlantic. The former were deposited near the northern margin of the Indian continental block, located at about 10–20° south palaeolatitude (Patzelt et al., 1996). This suggests that CORBs were deposited predominantly in Tethyan subequatorial and perhaps also in equatorial climatic belts. They are not present in latitudes north of the Tethys. They are found in variety of basinal settings, from deep open ocean basin, such as the central North Atlantic, to a wide variety of mostly narrow, elongate basins, ''troughs'' and back-arc basins in the Alps-Carpathians and eastern Pontides (Table 1).

Composition. CORBs are predominantly reddish coloured shales, marlstones and limestones, and less commonly radiolarian chert (Table 1). The TOC in CORBs is very low, commonly less than 0.1% in weight (Table 1). Haematite is relatively abundant in the red shales and limestones of southern Tibet (up to 12.5 and 5.6% respectively; Hu, 2002) and Italy (up to 9.15% and 0.9% respectively; Arthur and Fischer, 1977) and in red limestone in Turkey (up to 3.0%; Eren and Kadir, 1999).

Sedimentation rates. CORB sedimentation rates uncorrected for compaction are typical of deep-water environments (Jenkyns, 1986). They range from 1–3 mm/ka in the deep North Atlantic Basin (Jansa et al., 1979) to 6–26 mm/ka for the Nierental Formation in Austria (Krenmayr, 1996) (Table 1). The higher sedimentation rates are generally in turbidites or marls deposited above the CCD.

Depositional environment. CORBs are deep-water, pelagic to hemipelagic deposits laid down in environments ranging from deep oceanic basins below the CCD, to deep continental margins, intra-oceanic ridges and volcanic arcs (Table 1) where deposition was mostly above the CCD. In the slope/rise environmental setting CORBs are predominantly reddish calcareous marls and limestones, commonly intercalated with calcareous and/or terrigenous turbidite beds, such as in the Scaglia Rossa, Capas Rojas, and Nierental formations (Table 1).

Age. One of the most characteristic features of CORBs, in addition to their colour, is that they are predominantly of Late Cretaceous age, although some are as young as Early Eocene. Initiation and end of oxic deposition was not synchronous between various basins. The oldest Late Cretaceous red beds are early Cenomanian in the Italian Scaglia Bianca Formation (Figs. 3, 5) and the Silesian Subbasin of the Outer Carpathians. However, the majority of CORB developments post-date Cenomanian–Turonian black shales, such as the Bonarelli Horizon (OAE2). The Turonian–Campanian time interval was the most favourable for CORB deposition, as documented by their occurrence in geographically distant regions such as southern Poland, Hungary, Turkey, and southern Tibet (Fig. 5).

Tectonics. Tectonic activity may have played a role in the deposition of CORBs (Fig. 5). For example, in southern Tibet, CORB deposition was terminated by olistostromes emplaced during collision of the Indian and Lhasa continental blocks (Liu and Einsele, 1996; Hu, 2002). In the Carpathians and Pieniny Klippen Belt of Poland, Slovakia, the Czech Republic and Austria, Late Cretaceous thrust-folding and the onset of continental collision resulted in high terrigenous turbidite input that variably, and in some locations completely, overwhelmed pelagic deposition.

Red colouration. The red colour of CORBs is the result of a change in redox conditions on the ocean floor, recognized by the presence of finely disseminated ferric oxides, normally in the form of haematite (Turner, 1980), which formed during early diagenesis (Channell et al., 1982; Eren and Kadir, 1999, 2001; Hu, 2002). Oxidation took place at or near the sediment-water interface by oxygen-rich bottom waters. The occurrence of CORBs in shallower oceanic basins, such as the Umbria-Marche Basin in Italy, and/or onlap continental margins indicate that in places intermediate waters were also highly oxygenated.

Potential causes. The data presented in this study document a major change in Cretaceous oceanic sedimentation from predominantly organic carbon-rich muds during the Aptian–Cenomanian (Schlanger and Jenkyns, 1976; Jenkyns, 1980) to carbon-poor CORBs during the remainder of the Late Cretaceous, when deep and intermediate waters became rich in oxygen, but at different times and places. Such diachroneity points to a complex process because it indicates local or regional modification of an ''oxic process'' of at least hemiglobal extent. Arthur et al. (1988) suggested that the change resulted from CO_2 draw-down owing to extended burial of organic carbon in oceanic basins. However, if that were the case, we would expect to find the initiation of CORB deposition to be globally synchronous because it would have been climatically forced. Similarly, if the change were triggered by a eustatic sea-level rise, which could have resulted in a decrease in supply of nutrients into the ocean and decreased bioproductivity, it should have been basin-wide. However, if it were the result of changes in ocean circulation, these would have been on a global scale as well as on local scales.

Despite the diachronous initiation of CORB deposition, we consider it extremely important that they

Table 1
Comparison of the typical characteristics of the CORBs from selected areas in the world

Area	North Atlantic	Spain	Italy	Austria	Outer Carpathian Basin	Pieniny Klippen Basin	Inner Carpathian Basin	Turkey	Tibet
Name	Plantagenet Formation	Capas Rojas	Scaglia Rossa	Nierental Formation	Malinowa Shale Fm Weglowka Marls Variegated Shale	Skalski Marl Mb Pustelnia Marl Mb Puchov Marls Macelowa Marl Mb	Kosariska Fm Variegated Marls Vekeny Marl	Kapanboğazi Formation	Chuangde Formation
Colour	varicoloured, yellow-olive, pink, red	red, white	red, pink, white	red, grey, white	variegated, red	variegated, red	variegated, red	red	red
Thickness	92.3 m	100–600 m	200–400 m	400 m	10–200 m	30–60 m	20–50 m	40 m	about 30 m
Age	early Turonian–Palaeocene	Cenomanian–Middle Eocene	early Cenomanian–Middle Eocene	late Santonian–Palaeocene	early Cenomanian–early Maastrichtian (to Middle Eocene on submerged ridges)	early Cenomanian–middle Campanian	Turonian (Campanian)–Eocene	late Cenomanian-Campanian	Santonian – Campanian
Lithology	mudstone	limestone, marlstone, shale	limestone, marlstone, shale, chert	shale, marlstone	shale, marlstone with siliciclastic turbidite intercalations	marlstone, limestone	marlstone, limestone	limestone, marlstone	shale, marlstone, chert
Sedimentation rate	1–3 mm/ka	1–12 mm/ka	5–12 mm/ka	6–26 mm/ka	—	1–4 mm/ka on outer shelf, 8 ~ 23 cm/ka on slope and central furrow	2–4 mm/ka	—	2–10 mm/ka
TOC(%)	0.3%	—	0.07–0.17%	—	—	—	—	—	0.01–0.14%
CCD	below	above	above	above to near	below (except for submerged ridges)	above	above	above	near
Turbidity current	none	frequent	frequent	frequent	frequent	few	few	few	few
Red beds in strata	all	all except for turbidite	all except for turbidite	frequent, except for turbidite	frequent except for turbidite	all except for turbidite	all except for turbidite	all	all
Sedimentary environment	deep basin below CCD	pelagic basin to slope	pelagic basin to slope	(hemi)pelagic slope basins	deep-water below CCD, hemipelagic	pelagic (ridge and central furrow) to hemipelagic (slope facies)	pelagic	pelagic	pelagic slope to basin

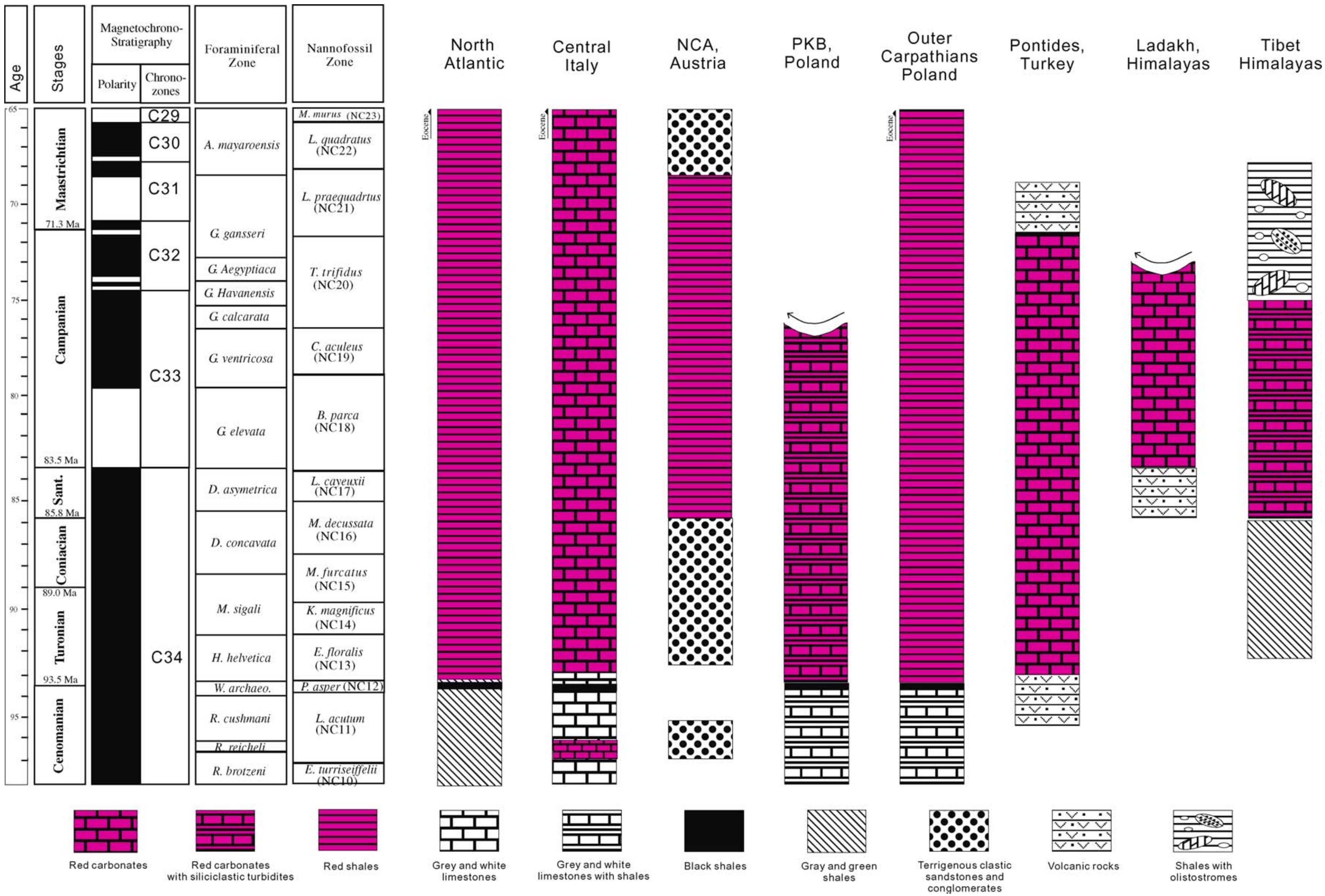

Fig. 5. Integrated stratigraphic distribution of the CORBs showing their ages and relationships with overlying and underlying strata. The chronostratigraphic scale is from Gradstein et al. (1995); the foraminiferal and calcareous nannofossil zones are after Bralower et al. (1995). For localities, see Fig. 1.

dominated Turonian–Campanian oceanic environments in mid- and possibly low palaeolatitudes, and therefore represent a hemiglobal, if not global oceanographic event.

What other Late Cretaceous earth processes could have led to the development of highly oxygenated bottom conditions in the world oceans? The data also suggest that it could have been changes in deep-water production, bioproductivity and oxygen content of the atmosphere (Haupt and Seidov, 2001; Frank and Arthur, 1999). Oxidation of organic carbon during Late Cretaceous could have had a significant affect on both the carbon and oxygen reservoirs in the oceans and atmosphere (Garrels and Perry, 1974; Arthur et al., 1988).

That the general onset of a change in redox bottom conditions is broadly synchronous with initial stages of global cooling, as suggested by $\delta^{18}O$ data (Clarke and Jenkyns, 1999; Voigt and Wiese, 2000; Norris et al., 2002), and provides some support for a climate-triggering mechanism, such as colder high latitudes, which could have led to an increase in bottom-water formation, with bottom waters being more oxygen–rich because the solubility of oxygen increases with decreasing water temperature. However, diachronous initiation and termination of pelagic red bed deposition argues against climatic control alone, and points to strong local or regional overriding influences, probably related to tectonics and its influence on oceanic circulation. It is not coincidental that the deep-sea oxic period is broadly synchronous with major changes in global tectonics, the formation of major mountain chains, such as the Himalayas and Alps, and closure of the Tethys Ocean. Another hypothesis that would better explain the occurrence of Late Cretaceous pelagic red beds is that oceanic circulation may have been very different from the present, as indicated by ocean/atmosphere model studies (Otto-Bliesner et al., 2002). The model indicates that during the Cretaceous, as a result of a different global temperature regime and basin physiography, the overturning cell reached the basin floor at 4000–5000 m. By contrast, in modern oceans the base of the overturning cell is around 3500 m. Therefore, oxygenated surface waters would reach abyssal depths in Late Cretaceous oceans. The apparent concentration of pelagic red beds at mid-palaeolatitudes could indicate that during the Late Cretaceous bottom waters were formed by down-welling in mid-palaeolatitudes; therefore, oceanic circulation could have been very different from that of the Holocene. Although such a hypothesis would explain most of observed features, the difficulty is that oxygen isotope data from planktonic foraminifers suggest cooling of Late Cretaceous surface waters in the western Tethys instead of increasing evaporation (Clarke and Jenkyns, 1999; Voigt and Wiese, 2000; Norris et al., 2002).

5. Conclusions

New data from field work in Europe and Tibet complement published data on global occurrences, composition, palaeontology, and the tectonic setting of Late Cretaceous oceanic red beds (CORBs). Our synthesis led to some surprises, e.g., that the change from dysoxic to oxic conditions in the Tethys was not a time-synchronous event. Oxic oceanic bottom conditions appeared briefly earlier, during the Cenomanian, Albian, and even Aptian (see Hu et al., 2003). However, the main occurrence of CORBs was during Turonian–early Campanian; locally CORB deposition continued into the Early Eocene in the central North Atlantic, Spain and the Italian Apennines.

CORBs were deposited in mid- to low palaeolatitudes on both sides of the Tethys, because they can be found exposed in the Himalayas, the Caucasus, Turkey, and the Carpathians, Alps and Apennines, as well as in deep-sea cores in the central North Atlantic, Caribbean, and South Atlantic. They are found in the wide variety of oceanic settings, from deep-ocean in the central North Atlantic to shallower Alpine-Carpathian-Pieniny pelagic basins. They are characterized by low sedimentation rates of several mm/ka to several cm/ka; therefore, there is also a eustatic component in the origin of CORBs. In Eastern Europe they were deposited during a period of tectonic upheaval expressed by the Cretaceous Eo-Alpine Orogeny and the Cenozoic formation of the Himalayan mountain chain; therefore, associated changes in oceanic circulation and/or palaeoclimate may have played a critical role.

Even though a variety of hypotheses have been proposed to explain the origin of Late Cretaceous pelagic red beds, none is able to satisfactorily explain their diachronous appearance and why in some areas of the western Tethys such environmental conditions continued into the Eocene whereas elsewhere CORB deposition was terminated in the Coniacian. It is very likely that several different Earth processes working in concert were involved in the origin of deep-sea pelagic red beds, and that in different areas, or even in the same area but at various times, different processes operated. Only further research, including the application of a variety of geochemical proxies, may advance our understanding of this unique history of the world's oceans and the conditions that led to changes in the location of global carbon reservoir.

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