CRETACEOUS OCEANIC RED BEDS (CORBS) IN THE AUSTRIAN EASTERN ALPS: PASSIVE-MARGIN VS. ACTIVE-MARGIN DEPOSITIONAL SETTINGS

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Abstract: CORBs are described from a north–south transect from the passive European margin with the Helvetic–Ultrahelvetic shelf and continental slope through the Alpine Tethys, including the Rhenodanubian Flysch Zone into the southern, tectonically active margin of the Austro-Alpine microplate, including the Northern Calcareous Alps. In the Helvetic (shelf) and Ultrahelvetic (slope) part of the European margin, the proportion of CORBs in the Upper Cretaceous successions increases significantly with increasing water depth and increasing pelagic character. In the Ultrahelvetic units of Upper Austria (Rehkogelgraben, Buchberg), CORBs define a continuous red interval from the Lower Turonian to the Lower Campanian. The onset of CORB deposition in the Ultrahelvetic Zone corresponds to a major change in paleoceanographic conditions from anoxic during the Late Cenomanian OAE 2 to highly oxic during the Early to Middle Turonian. In the Rhenodanubian Flysch, hemipelagic red and green shales alternate with turbiditic siltstones and minor sandstones in the Upper Aptian–Lower Cenomanian Lower Varicolored Marls, the Coniacian–Lower Campanian Seisenburg Formation, and the uppermost Campanian Perneck Formation. CORBs in the Rhenodanubian Flysch are controlled mainly by tectonic events and sea-level changes, and occur during times of transgressions, low clastic input, and low turbidite frequencies. In the Austro-Alpine Northern Calcareous Alps, CORBs occur from the Santonian onwards in the upper parts of transgressive sequences of the Gosau Group, e.g., in the Tiefenbach and the Dalsenalm sections. In areas where clastic input was low, CORB deposition continued up into the Maastrichtian. Based on these data a peak of oceanic red beds is inferred for the middle Santonian–Early Campanian time interval. Prerequisites for CORB sedimentation are low clastic input, low sedimentation rates, and increasing paleo–water depth. CORBs can be classified as a variation of three end members: clayey CORBs, consisting mainly of terrigenous clay minerals; calcareous CORBs, mainly pelagic limestones; and siliceous CORBs, consisting mainly of biogenic SiO_2.

Key words: CORBs, Eastern Alps, Austria,Ultrahelvetics, Gosau Group, Turonian

INTRODUCTION

Cretaceous oceanic red beds (CORBs) are present in the three major tectonic units of the Eastern Alps of Austria and of Bavaria (Germany) (Fig. 1). These tectonic zones represent different paleogeographic domains of the northwestern Tethys (Fig. 2): (1) the Helvetic domain, including Helvetic and Ultrahelvetic tectonic units and, to the east, the Gresten Klippen Zone; (2) the Penninic domain, including the Rhenodanubian Flysch Zone and metamorphic complexes exposed in tectonic windows; and (3) the Austro–Alpine domain, including the Northern Calcareous Alps (NCA).

These paleogeographic domains are arranged in a north–south transect from the passive European margin (Helvetic–Ultrahelvetic domain) through the deep-water Alpine Tethys (Stampfli et al., 2002; Stampfli and Borel, 2004) to the southern, tectonically active margin of the Austro-Alpine microplate on the northern margin of the Adriatic plate (Channell et al., 1992). These units were situated at a latitude about 30° to 35° north in a tropical to subtropical climatic zone (Wagreich and Faupl, 1994),

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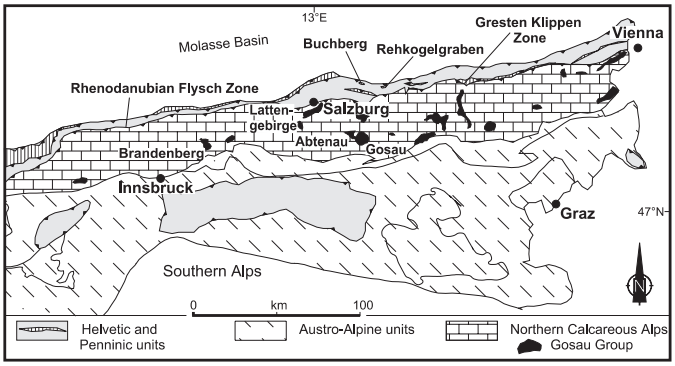

FIG. 1.—Schematic geological map of the Eastern Alps including major tectonic zones and outcrop areas mentioned in the text.

on the northern margin of the large Tethys realm (Fig. 2). During the Cretaceous, a shelf to upper-slope succession accumulated along the Helvetic sector of the European passive margin. Deep-water strata characterize the Ultrahelvetic units and the Gresten Klippen Zone, originally situated to the south of the Helvetic realm, at the continental slope of the European Plate (Figs. 2, 3). The partly oceanic Penninic units developed as part of the Alpine Tethys due to transtension and spreading between the European foreland–Helvetic zones and the Austro-Alpine microplate during Jurassic and Cretaceous times. Early Cretaceous turbidite sedimentation began in the deep-water northern Penninic Rhenodanubian Flysch Zone. The NCA formed part of the northern, active margin of the Austro-Alpine microplate, which was characterized by southward oblique subduction of the southern part of the Penninic Ocean. Late Cretaceous subsidence due to strike-slip faulting controlled deposition of an accretionary complex (Wagreich and Krenmayr, 2005). In general, the area of the NCA deepened northward and received increasing input from rising metamorphic complexes to the south (Butt, 1981; Wagreich and Faupl, 1994).

Various types of CORBs (Cretaceous oceanic red beds; Hu et al., 2005; Hu et al., 2006) were deposited, especially in Late Cretaceous times, in these strongly differing paleogeographic and depositional settings. These varied from the wide Helvetic shelf and continental slope to deep-water basins below the calcite compensation depth (CCD) of the Alpine Tethys to the tectonically active basins of the NCA in the south. This paper describes the stratigraphy of these Upper Cretaceous CORBs, gives an overview of CORB facies, and discusses various features and controlling factors. Standard biostratigraphic study of foraminifera and nannofossils are the data for chronostratigraphic interpretations by two methods, age interpolation of biozones and graphic correlation with the MIDK42 data base (for explanations see Scott, this volume).

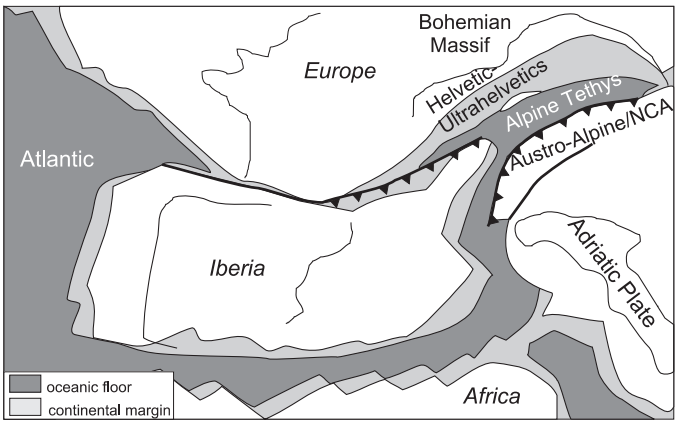

FIG. 2.—Schematic paleogeographic map for the Maastrichtian (69 Ma) of the western Tethys, simplified from Stampfli et al. (2002) and Stampfli and Borel (2004). NCA—Northern Calcareous Alps; Alpine Tethys includes Penninic oceanic realm.

PASSIVE-MARGIN CORBs (HELVETIC–ULTRAHELVETIC UNITS)

The Helvetic and Ultrahelvetic units of the Eastern Alps of Austria and Bavaria record sedimentation at the northern continental margin of the Alpine Tethys, i.e., the shelf and continental slope to the north of the Penninic Ocean (e.g., Faupl and Wagreich, 2000; Stampfli et al., 2002). Whereas shelf deposits (Helvetic units) are widespread, in particular in western Austria, the slope deposits of this passive margin are rarely preserved and often strongly tectonized due to polyphase Alpine orogeny. The Ultrahelvetic units are preserved in highly tectonized slices (Ultrahelvetic tectonic windows; Prey, 1983) in the Rhenodanubian Flysch Zone (Egger et al., 2000).

In general, the proportion of Upper Cretaceous CORBs increases with increasing water depth and increasing pelagic character from the Helvetic neritic shelf marls and limestones to the Ultrahelvetic bathyal continental slope (Fig. 3). CORBs are present in the Säntis Nappe of the Helvetic realm in westernmost Austria (Föllmi, 1989). A Lower Cretaceous carbonate shelf succession is overlain by a condensed interval of glauconite-rich deposits (Garschella Formation) and, higher up, by Upper Cretaceous, outer-shelf to upper-bathyal, pelagic gray limestones of the Seewen Formation. A few tens of centimeters of thin red micritic, globotruncanid limestones are present in the Turonian and Santonian (Föllmi, 1989). In the pelagic successions of the bathyal Ultrahelvetic realm (Liebenstein Nappe of western Austria, Ultrahelvetic units east of Salzburg), red intervals increase in number and thickness in the pelagic successions. CORBs constitute a continuous red marlstone–limestone interval from the Turonian to the Lower Campanian in the Buchberg and Rehkogelgraben sections (Fig. 4).

Farther downslope, carbonate-rich cyclic limestone–marl deposits grade into the carbonate-poor strata of the Ultrahelvetic Gresten Klippen Zone (Fig. 5B). Upper Cretaceous strata indicate increasing water depths to the southeast near or below the local CCD. Consequently, Albian to Eocene strata of the Gresten Klippen Zone are mainly carbonate-poor marls to claystones and shales rich in deep-water agglutinated foraminifera, and with minor amounts of planktic foraminifera. CORB intervals start in the Cenomanian, predominate in the Upper Turonian to Campanian, and are common in the Upper Paleocene to Eocene (Widder, 1988).

Bathyal CORBs at Rehkogelgraben and Buchberg

Several sections display CORBs in the Ultrahelvetic units of Upper Austria east of Salzburg, including Rehkogelgraben (Fig. 5A), Buchberg, Gschliefgraben, and Oberhehenfeld (Prey, 1983; Wagreich et al., 2008). These strata are referred to as "Buntmergelserie", an informal lithostratigraphic unit (Prey, 1952) comprising Aptian or Albian to Eocene shales, marlstones, and marly limestones. Based mainly on planktic foraminifera and nannofossils, a composite section can be reconstructed that includes (1) Albian–Cenomanian dark gray marls and dark to light

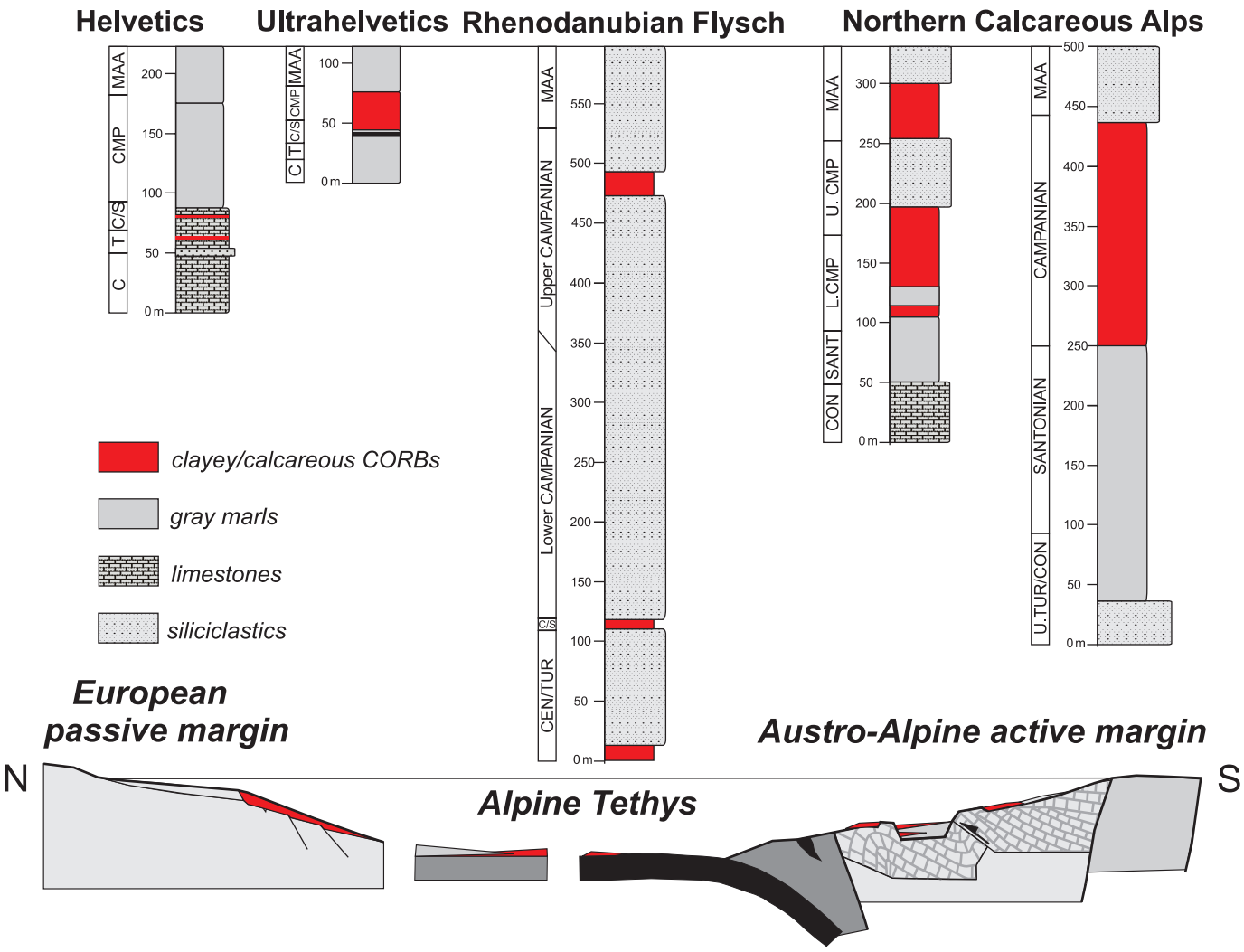

FIG. 3.—Schematic Campanian paleogeographic and paleotectonic transect through the Eastern Alps indicating major areas of CORB deposition and representative profiles of the Upper Cretaceous of the Helvetics of western Austria (after Föllmi, 1989), the Ultrahelvetics east of Salzburg (after Kroh and Jagt, 2004, and Neuhuber et al., 2007), the Rhenodanubian Flysch (composite section modified from Egger, 1992, and Wagreich et al., 2006), and the Gosau Group of the Salzburg–Lattengebirge area (composite section of Wagreich and Krenmayr, 1993, Krenmayr, 1999, and Wagreich, 2003) and Abtenau (Wagreich and Krenmayr, 2005). C—Cenomanian, T—Turonian, Con—Coniacian, San—Santonian, C/S—Coniacian to Santonian, Cmp—Campanian, Maa—Maastrichtian.

gray limestones, (2) Upper Cenomanian medium-gray marls and white limestones, (3) Upper Cenomanian to Cenomanian–Turonian-boundary black shales, (4) Lower Turonian white to light gray limestones, (5) Lower to Middle Turonian to Santonian reddish marl–limestone cycles (Figs. 5A, C, D), (6) Lower Campanian red marlstones (Fig. 5B), (7) Upper Campanian gray marlstones with ammonites and other macrofossils (e.g., Kennedy and Summesberger, 1984, 1999, Tröger et al., 1999; Kroh and Jagt, 2004), and (8) dark gray marls of Maastrichtian to Paleogene age, and Eocene limestones and sandstones (Fig. 4).

The Buchberg section is in a small Ultrahelvetic tectonic sliver in the Penninic Rhenodanubian Flysch, west of Lake Attersee (Fig. 1) (map sheet Mondsee, ÖK 65, 1:50,000 Geological Map of the Republic of Austria; coordinates WGS 84: 13° 31' 45" E; 47° 56' 04" N). The section exposes a continuous Cenomanian–Turonian succession of limestones, marly limestones, and marlstones (Fig. 6). The Cenomanian part of the succession is partly covered. Light gray limestone beds with dark gray bioturbation mottles alternate with medium and dark gray spotty marls in the lower part of the section. The Cenomanian–Turonian transition is in the overlying covered interval, about three meters thick. Above, the section is continuously exposed to its top, where Ultrahelvetic rocks are truncated by overthrust strata of the Rhenodanubian Flysch.

The Rehkogelgraben section (Kollmann and Summesberger, 1982) also belongs to an Ultrahelvetic tectonic slice east of Gmunden (Upper Austria, Fig. 1). A Cenomanian–Turonian boundary section (coordinates WGS 84: 013° 55' 30" E, 47° 56' 08" N; Wagreich et al., 2008) includes distinctive black shale intervals that, up-section, grade into marly limestones and red marls, which can be correlated to the Buchberg section. Above Upper Cenomanian–Lower Turonian strata, a CORB succession composed of limestone–marl rhythms is present (Fig. 5A).

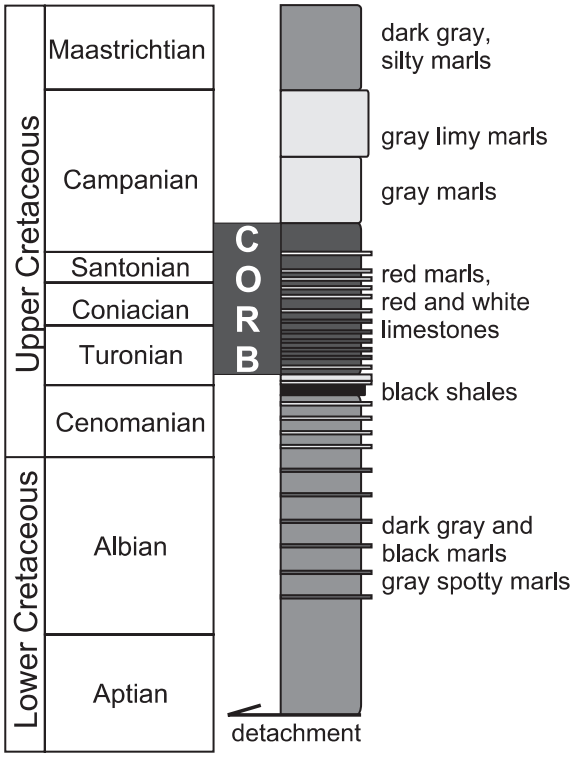

FIG. 4.—Composite chronostratigraphic section of the Ultrahelvetic Rehkogelgraben–Greisenbach and the Buchberg area according to Rögl in Kollmann and Summesberger (1982), Egger at al. (2000), and Wagreich et al. (2008), showing stratigraphic position of CORB interval from the Lower Turonian to the Lower Campanian.

In both sections, Upper Cenomanian strata including black shales grade upward into light gray Lower Turonian pelagic limestones. This interval is a few meters thick and is overlain by a cyclic marl–marly limestone succession in which red coloration increases up to the Middle Turonian, where red color is pervasive. Biostratigraphy indicates that the transition into CORBs is in the lower part of the *Helvetoglobotruncana helvetica* Zone and nannofossil zones CC11/UC7 defined by the first occurrence of *Quadrum gartneri* (Fig. 6). Also the presence of the radiolarian species *Pseudodictyomitra pseudomacrocephala*, *Crucella cachensis,* and *Alievium superbum* (Luo Hui, personal communication, 2005) in the lower part of the section indicates an Early Turonian age. The top of the Buchberg section was dated to the Middle Turonian nannofossil zone CC12/UC8a based on the first occurrence of *Eiffellithus eximius* and to the *Marginotruncana sigali* Zone characterized by common occurrence of large marginotruncanids above the LO of *H. helvetica*. The age of 89.55 Ma in the Upper Turonian is projected by graphic correlation. The transition into CORBs is four alternating gray to red limestone–marl cycles (Fig. 6, between 2 m and 3 m). In the lower part of the transitional interval, the red color is restricted to marl beds only, whereas at the top of the interval both marls and limestones are red. The beds tend to be more bioturbated at the top of the transitional interval. Red marls and bioturbated red marly limestones prevail in the upper two CORB intervals of the Buchberg section (Neuhuber et al., 2007; Wendler et al., this volume).

CORBs are continuous from the Middle Turonian up to the Lower Campanian *Globotruncanita elevata* Zone and nannofossil zone CC17/UC13. Above, in the Lower Campanian, the red color fades out and light gray marlstones start to prevail. Cyclic calcareous CORBs are typical of the Middle Turonian to Santonian time interval. Both red marl–light gray limestone cycles and red marl–red limestone cycles occur. The consistent presence of *Dicarinella asymetrica* in red–white rhythms in the Rehkogelgraben section indicates a Santonian age (*Dicarinella asymetrica* Zone; e.g., Caron, 1985; Melinte and Lamolda, 2007). Foraminiferal assemblages are dominated by planktic foraminifera, which constitute some 90 to 95% of the total fauna. The occurrence of the nannofossil *Lucianorhabdus cayeuxii* places the profile in the Santonian nannozone CC16 according to the Sissingh (1977) and Perch-Nielsen (1985) zonation, and UC11c (Upper Coniacian to Lower Santonian) according to the Burnett (1998) zonation.

The Rehkogelgraben section displays red marls and white to light gray limestones that alternate regularly (Fig. 5A); carbonate content varies between 44% and 91%. The organic-carbon content is generally very low and varies between 0.029% and 0.168%. Bed thickness ranges between 10 and 40 cm. A rough estimate of the sediment accumulation rate from profile thickness of about 11 m and assuming the total coverage of CC16 (about 0.6 Myr according to Ogg et al., 2004) is 18.8 mm/kyr. For the CC16 zone, calculation of time content of about 33 discrete limestone beds suggests that each bed represents about 18 kyr in duration, although the range of frequencies from 18 to 114 kyr calculated by different methods reveals a high degree of uncertainty. This cyclicity likely corresponds to Milankovitch-driven orbital control on limestone–marl rhythmicity, and the lower frequency corresponds most probably to the precession of the Earth's axis (19,000 and 23,000 year cycles, e.g., Herbert et al., 1999). Graphic correlation of the Rehkogelgraben section suggests that zone CC16 is incomplete, and calculates a rate of 28.5 mm/kyr. By contrast, the sediment accumulation rate of the Cenomanian–Turonian transition is about 1 mm/kyr (Wagreich et al. (2008).

Interpretation

The Ultrahelvetic units record Late Cretaceous pelagic sedimentation along the passive margin of Europa (Fig. 3), and thus provide a sedimentary archive for paleoceanographic events in the northwestern Tethys that were not influenced by local tectonism. The onset of CORB deposition in the Ultrahelvetic units corresponded to a major change in paleoceanographic conditions from anoxic during the Late Cenomanian OAE 2 to oxic during the Early to Middle Turonian. In contrast, the end of CORB deposition in the Ultrahelvetic realm during the Early Campanian was controlled mainly by increasing clastic input and shallowing of the basin, as a distant effect of Alpine orogeny. CORB sedimentation was continuous from the Early to Middle Turonian onwards, and resulted in typical slope-type carbonate CORB facies varying rhythmically between marls and limestones. The Gresten Klippen Zone gives evidence that CORB sedimentation was also continuous in space from depths above to below the CCD. Consequently, large parts of the European passive margin from outer shelf to bathyal depths below the CCD were characterized by red, oxic, fine-grained sedimentation during the Turonian to Campanian.

DEEP-CLASTIC-BASIN CORBs BELOW THE CCD (RHENODANUBIAN FLYSCH ZONE)

The Rhenodanubian Flysch (Barremian–Ypresian) of the Eastern Alps was deposited in an abyssal environment at the

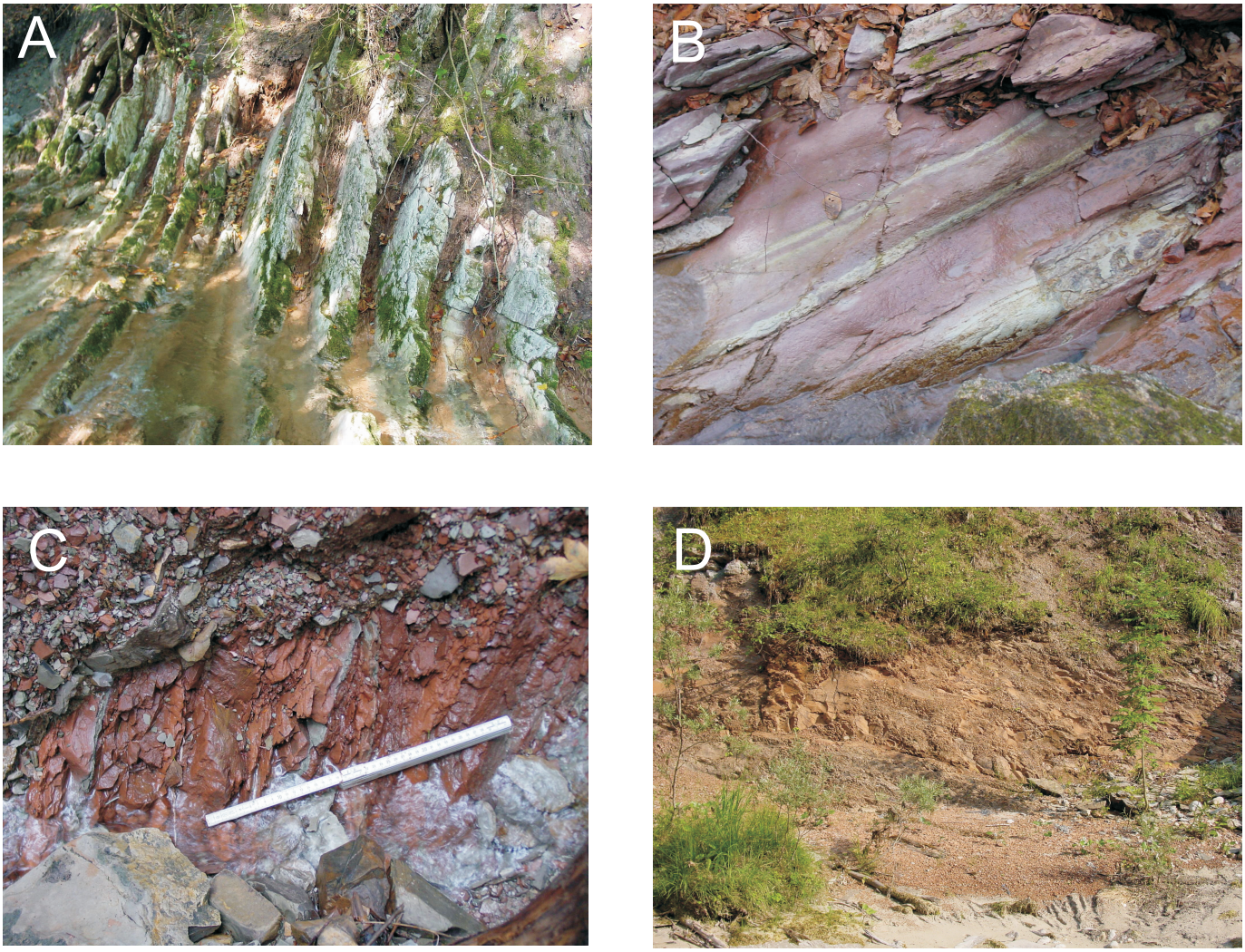

FIG. 5.—Photographs of various CORB facies of the Eastern Alps. **A)** Cyclic Santonian CORBs of the Rehkogelgraben with white to light gray protruding limestone beds and red marl interbeds. **B)** Marly Campanian CORBs of the Gresten Klippen Zone, showing greenish-gray interlayers. **C)** Dark red claystones and thin turbidites (gray to light red) of the Coniacian–Santonian Seisenburg Formation of the Rhenodanubian Flysch, deposited below the calcite compensation depth. **D)** Santonian marlstone CORBs of the Tiefenbach section near Brandenberg, Gosau Group of the Northern Calcareous Alps.

continental rise and in deep basins south of the European Helvetic shelf in the Alpine Tethys (Fig. 3) (e.g., Butt, 1981; Egger et al., 2002). Paleodepths are estimated below the local CCD, between 3000 and 5000 m below sea level (Butt, 1981). The succession displays alternating siliciclastic-dominated and carbonate-rich turbidite deposits. Paleocurrents and the pattern of sedimentation suggest that deposition occurred on a flat, elongate, gently inclined abyssal basin plain and was not disturbed by syndepositional tectonic deformation (Hesse, 1982, 1995). Postdepositional thrusting and wrenching have largely destroyed the original basin configuration and its relation to source areas.

In Austria, three formations consist mainly of hemipelagic red and green shales alternating with turbiditic siltstones and minor sandstones; the formations comprise the Upper Aptian–Lower Cenomanian Lower Varicolored Marls (Variegiated shales), the Coniacian–Lower Campanian Seisenburg Formation, and the uppermost Campanian Perneck Formation (Egger, 2006).

Late Albian–Early Cenomanian

In the Rhenodanubian Flysch Zone the lowermost interval of red shales (Lower Varicolored Marls–Untere Bunte Schiefer) has been dated as latest Albian to Early Cenomanian based on integrated biostratigraphic data (Kirsch, 2003; Wagreich et al., 2006). In an interval 18 m thick of alternating red and gray claystones and marlstones with minor sandstones, dinoflagellate cyst assemblages indicate the *Litosphaeridium siphoniphorum* Zone. The concurrent presence of *Litosphaeridium siphoniphorum* and *Ovoidinium verrucosum* in all samples correlates with the lower part of this zone. Based on foraminifera, the red beds can be assigned to the topmost *Rotalipora appenninica* Zone and the *Rotalipora globotruncanoides* Zone by the presence of small morphotypes of the index taxa. Nannofossils indicate standard zone CC9/UC0 throughout the red interval, defined by the first occurrence of *Eiffellithus turriseiffelii*, and zone UC1, defined by the first occurrence of *Corollithion kennedyi* above the red shales.

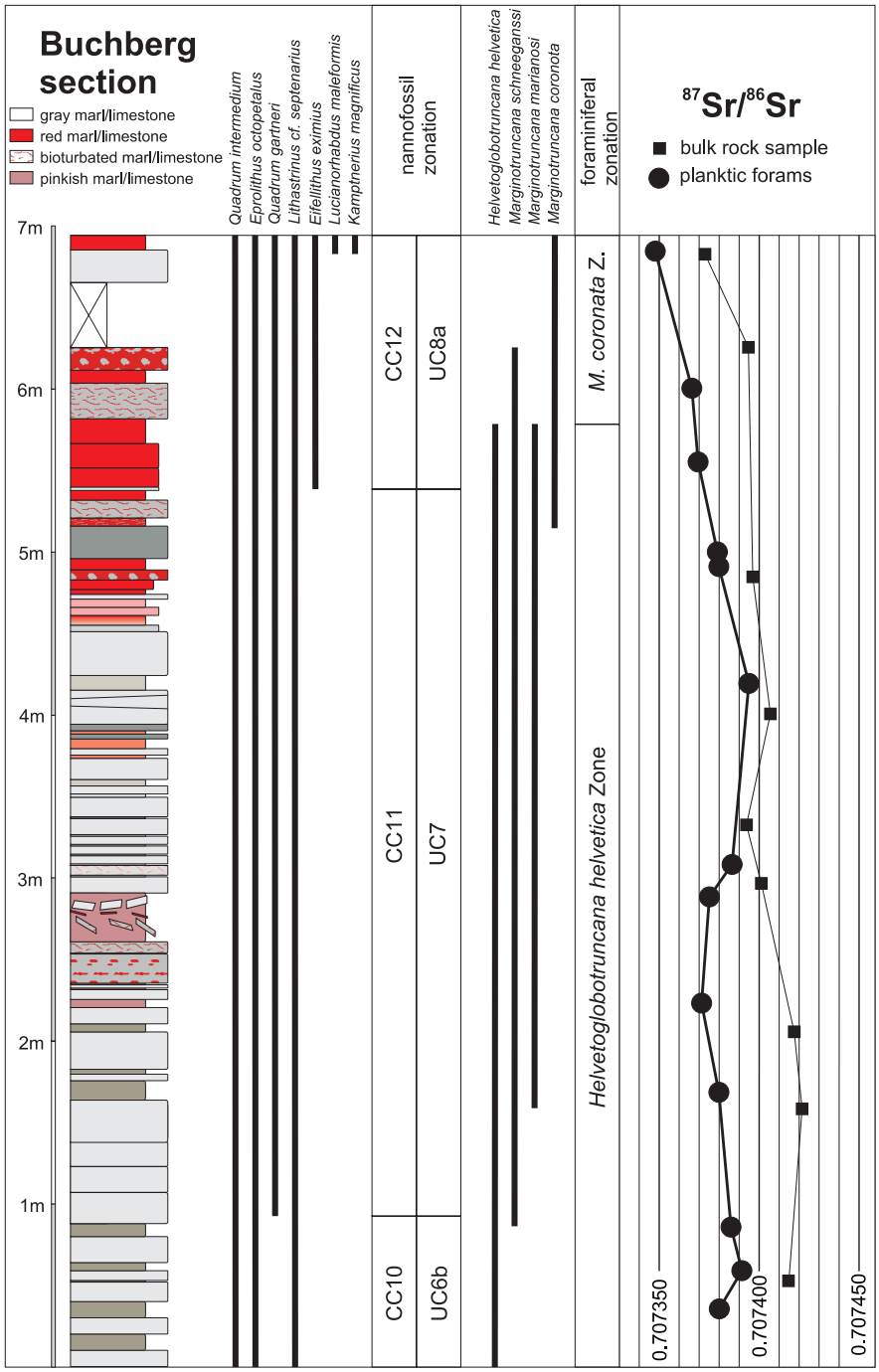

FIG. 6.—The Ultrahelvetic Buchberg section, showing the Lower to Middle Turonian transition from the Bonarelli level below the base of the profile to CORBs. Ranges of nannofossil and planktic foraminifera markers are indicated; nannofossil zonations are after Perch-Nielsen (1985) and Burnett (1998), foraminiferal zonation after Caron (1985), strontium isotope data of bulk rock and planktic foraminifers.

Sediment accumulation rates are around 13 mm/kyr in Bavaria (Egger and Schwerd, 2008) to a maximum of 27 mm/kyr; graphic correlation results in a sediment accumulation rate for the Austrian section (Wagreich et al., 2006) of 12 mm/kyr. The rather regional extent of this CORB interval, which seems to be very rare or absent outside the Alpine–Carpathian mountain belt, suggests that deposition of these red claystones and marlstones was controlled mainly by flysch-basin geometry and low turbidite input.

Coniacian–Santonian

The red-colored, fine-grained Seisenburg Formation of the Austrian Rhenodanubian Flysch overlies the Cenomanian–Turo-

nian sandstone-rich turbidite succession of the Reiselsberg Formation along a sharp contact. In the lower part, up to 5 m of red hemipelagic mudstone without any turbidite layers are developed (Fig. 5C). This part of the section represents the Upper Coniacian to Upper Santonian interval (Egger, 1993) and is characterized by low sediment accumulation rates of about 1.5 mm/kyr. Farther up in the section, thin-bedded turbidites alternate with red and green hemipelagites. This 20-m-thick succession has been dated as Zone CC18b (Lower Campanian) by the presence of *Broinsonia parca constricta* and is overlain by a few tens of meters of carbonate flysch. In Bavaria, an interval up to 30 m in thickness of thin-bedded turbidites with abundant intercalations of varicolored mudstone is present (Egger and Schwerd, 2008). Deposition of the Seisenburg Formation was interpreted to be a consequence of widespread Late Turonian–Coniacian transgression onto the shelves bordering the basin, which caused a decrease in terrigenous input into the basin and initiated a dearth of siliciclastic turbidite sedimentation (Egger and Schwerd, 2008). Low clastic input, in turn, led to widespread deposition of hemipelagic mudstones that interfinger with calcareous turbidite fans prograding from the west.

Late Campanian

The Perneck Formation is composed of red claystones in the eastern part of the Rhenodanubian Flysch (see Egger, 1995, for a review), which is exposed in a large number of outcrops between Vienna and southwest of Munich (Egger and Schwerd, 2008). Numerous outcrops in this area with nannoplankton assemblages including *Uniplanarius trifidus* (Zone CC22) indicate that the red claystone facies accumulated synchronously over a distance of at least 300 km. The base of the Perneck Formation has been dated northeast of Salzburg as middle Campanian Zone CC21 by the presence of *Uniplanarius sissinghii*.

Thin-bedded siltstone–shale couplets of the Perneck Formation are confined to the northern part of the Rhenodanubian Flysch basin. There, these couplets are intercalated between lime-muddy turbidite deposits of the Röthenbach Subgroup below and, above, predominantly siliciclastic turbidites of the Altlengbach Formation (Egger, 1995). The percentage of hemipelagites versus turbidites is much higher in the Perneck Formation than in the underlying and overlying formations. Towards the south the thickness of the Perneck Formation decreases and, finally, it is completely replaced by the Röthenbach Subgroup.

Clay-mineral assemblages of the hemipelagites of the Perneck Formation change from east to west. Hemipelagic shales of the eastern sections are dominated by illite (79%–90%) and chlorite (10%–21%). Farther west, smectite (26%–66%) is the prevalent clay mineral, followed by illite (11%–67%), kaolinite (3%–15%), and chlorite (0%–15%). Each clay-mineral assemblage is similar to those of associated turbidites; this points to different clastic input systems. Clay-mineral assemblages suggest that the source area in the eastern part had steep relief, resulting in pronounced mechanical erosion that affected even the parent rocks. The comparatively high percentages of smectite and kaolinite in the western section indicate enhanced chemical weathering and soil formation in an area of low relief.

The widespread dearth of turbidite sedimentation indicates a synchronous event that affected the Alpine Tethys (Egger, 2003, and unpublished data). This can be interpreted either as a consequence of increased hemipelagic sedimentation rate or as a result of a decrease in the frequency of turbidity currents that entered the basin. The remarkable association of hemipelagic shales (with indications of enhanced continental erosion) with thin-bedded fine-grained turbidites suggests a decrease of siliciclastic input. We assume that this facies association was produced by uplift of the source areas and a consequent shift of the basin axis towards the south, bringing the former basin plain into a slope position (depositional setting of the Perneck Formation). Farther south, sedimentation of carbonate flysch continued without significant breaks.

Interpretation

In general, the occurrence of CORBs in the Rhenodanubian Flysch was controlled tectonically by low clastic input and low turbidite frequencies, as expected for a flysch basin with a tectonically active hinterland to the south. CORBs are gradational to coeval turbidite successions and thus have mainly regional significance, generally reflecting a tectonically induced change in basin configuration and source areas. The Coniacian to Early Campanian (nannofossil zones CC14 to CC18) Seisenburg Formation event, however, seems to have been an effect of the high relative sea level during this period, which caused a decrease in siliciclastic sediment supply and initiated a dearth of turbidite sedimentation.

ACTIVE-MARGIN CORBs (NORTHERN CALCAREOUS ALPS)

CORBs on the northern active margin of the Austro-Alpine microplate are present in the fillings of the Gosau basins of the Northern Calcareous Alps (Wagreich and Krenmayr, 2005). Deposition of CORBs started at the transition from the lower to the upper part of the Gosau Group (Wagreich and Faupl, 1994). The upper part of the Gosau Group comprises deep-water deposits, such as a marly slope facies with common slump deposits (Nierental Formation; Krenmayr, 1999) and a broad variety of deep-water clastics deposited above and below the local CCD. Facies distribution and paleocurrent data of the upper Gosau Subgroup indicate a pronounced fault-controlled relief of a tectonically active, overall north-facing paleoslope. Subsidence of the Gosau basins was by subcrustal tectonic erosion, eliminating parts of an accretionary structure along the northern, by this time active, margin of the Austro-Alpine plate (Wagreich, 1993). Transitional sections from gray to red fine-grained strata were investigated in (1) the Tiefenbach section (WGS84 011° 53' 35" E, 47° 30' 00" N) near Brandenberg east of Innsbruck (Sanders, 1998), and (2) the Dalsenalm section (WGS84 012° 52' 25" E; 47° 40' 00" N) in Bavaria west of Salzburg (Wagreich, 2003). Both sections record a deepening from neritic to bathyal depths and a transition from gray to red marls, and thus CORBs are distinctly related to inferred changes in paleo–water depths.

Santonian Tiefenbach Section

The Santonian Tiefenbach section consists mainly of carbonate–lithic arenite, sandy marl, gray marl, and red marl. Three depositional cycles (Fig. 7) (Sanders, 1998) have been recognized, B4 33 m thick, B5 22.5 m thick, and B6 more than 25 m thick. The dark red-brown marl CORB facies is more than 10 m thick in the middle of cycle B5, and overlies gray-colored marl with large inoceramids. A significant debris flow and slump horizon is present above the red-brown marl and probably reworked the top of this CORB interval, marking the transition to the upper, turbidite-dominated part of the section. The Early Santonian age of cycle B4 and the lower part of cycle B5 below the red beds is indicated by an assemblage of ammonites including *Texanites quinquenodosus* and by inoceramids (Tröger and Summesberger,

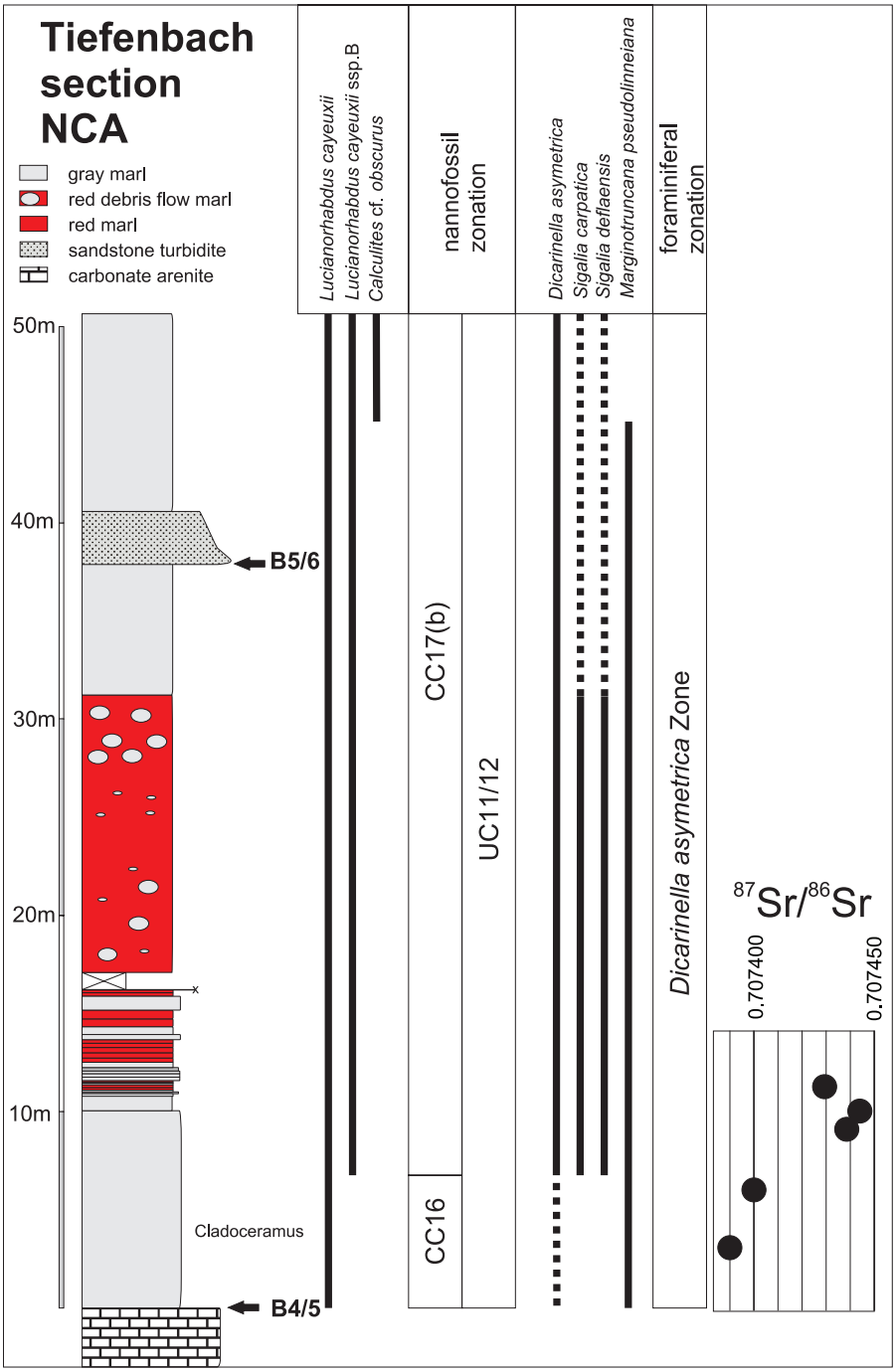

FIG. 7.—Tiefenbach section near Brandenberg, Gosau Group of the Northern Calcareous Alps (Sanders, 1998), showing lithology, sequence boundaries SB4/5 and SB5/6, and selected data of foraminifers, nannofossils, and strontium isotope data from the gray–red transition.

1994). The Santonian *Dicarinella asymetrica* Zone spans cycles B5 and B6. The *Sigalia carpatica* Zone ranges into the lower part of cycle B5. The numbers of planktic foraminifer specimens increase up section into the CORB facies and the numbers of benthics decrease, which suggests increasing offshore conditions and a likely increase in paleobathymetry. The local nannofossil subzone CC17b, defined by first occurrence of *Lucianorhabdus cayeuxii* ssp. B (*sensu* Wagreich, 1992), is also recognized in the section. Small nannoconids, including *Nannoconus truitti*, are present in significant amounts together with abundant inoceramids in gray marl in the lower part of cycle B5 below the red-brown marl. The nannoconids disappear completely in the CORB facies, possibly due to environmental changes, such as deepening or less carbonate and/or loss by dissolution. Results of graphic correlation indicate an age of 88.85 to 83.30 Ma for the section, and the rate of sediment accumulation is about 20 mm/kyr .

Lower Campanian Schmiedsippl Section

CORBs of the Gosau Group were deposited in deep water following progressive deepening of the basin (Wagreich and Krenmayr, 2005). In the Schmiedsippl section at Gosau the depositional area deepened from shallow neritic to bathyal depths during the Lower Campanian transgression (*asymetrica–elevata* Zone) (Wagreich and Neuhuber, 2005). Here sandy to silty, gray bioturbated neritic marls and marlstones are overlain by marly limestones of bathyal water depths. Geochemistry indicates that the influence of marine-derived Ca is close to zero between 0 and 5 m and increases significantly up section. The decrease in K/Al up section is interpreted as a shift towards more humid conditions during two pulses of sea-level change resulting in CORB sedimentation at the top of the section.

Lower Campanian Dalsenalm Section

The Dalsenalm (Lattengebirge) section on the eastern bank of the Röthelbach (WGS84 012° 52' 25" E; 47° 40' 00" N) spans the interval from the Grabenbach Formation to the transition into the Nierental Formation (Fig. 8) (Krenmayr, 1999; Wagreich, 2003). The Grabenbach Formation comprises soft, medium gray bioturbated marls (carbonate contents of 35 to 50%), rich in planktic foraminifera, (plankton/(plankton+benthic) ratios 0.40 to 0.75; see also Butt, 1981). The benthic foraminiferal assemblages suggest a deepening-upward trend in the section. Macrofossils are rare and include some bivalves, gastropods, and solitary corals. Intercalations of tempestite sandstones are present in the lower part, whereas graded turbidite beds appear in the upper part of the section, marking the transition into the Nierental Formation (Krenmayr, 1999). The gray marls of this interval display higher carbonate contents of 52–65%. Foraminiferal assemblages are dominated by planktic foraminifers with percentages above 90% of the total foraminiferal assemblage (Butt, 1981). CORBs start about 10 m above the first turbidite bed about 53 m above the base of the section. Red, strongly bioturbated silty marls have carbonate contents from 59 to 77% in the first red interval of a total thickness of about 14 m. Thin turbidite beds (< 8 cm) are present in that interval. The 3 m transition from gray to red colors is gradual, starting with pale-red, mottled layers. Marly limestones with persistent red colors above this transitional interval display total abundances of 3–10% planktic foraminifera in thin sections (foraminiferal wackestones).

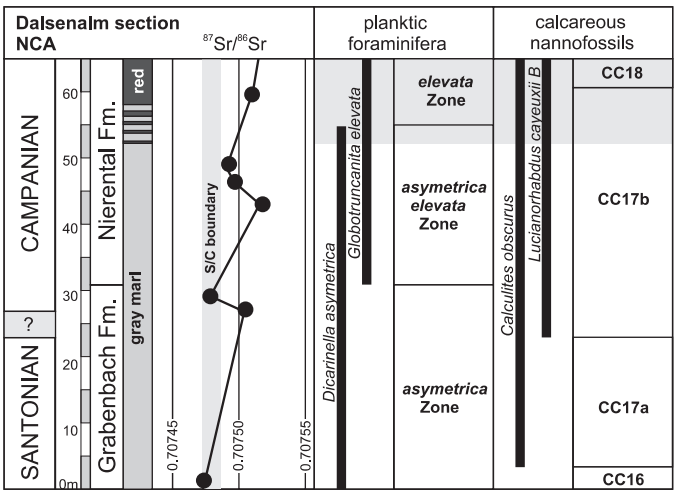

FIG. 8.—Overview section of the Dalsenalm outcrop, Lattengebirge (Germany) southwest of Salzburg, Gosau group, NCA, showing transition into CORBs, planktic foraminifer and nannofossil zonations and key taxa, and strontium isotope curve (modified from Wagreich, 2003). S/C boundary—strontium isotope value of the Santonian–Campanian boundary according to Gale et al. (1995).

A Late Santonian to Early Campanian age of the upper part of the section is indicated by nannofossils of the nannofossil standard zone CC17 (defined by the first occurrence of *Calculites obscurus*). According to the zonation of Burnett (1998), this corresponds to the UC11c and UC12 zones. The planktic foraminifers *Dicarinella asymetrica*, *Sigalia carpatica*, and *Sigalia decoratissima* are present, indicating the Santonian *D. asymetrica* Zone. CORBs start in the *asymetrica–elevata* Zone above the FO of *Globotruncanita elevata*. This narrow concurrent range zone is placed either into the Upper Santonian or into the lowermost Campanian (e.g., Robaszynski et al., 1984; Wagreich, 1992). The first occurrence of *G. elevata* is recognized within the nannofossil subzone CC17b a few meters above the first occurrence of *Lucianorhabdus cayeuxii* ssp. B (*sensu* Wagreich, 1992) which defines a regional nannofossil zone around the Santonian–Campanian boundary (Wagreich, 1992). Using strontium isotope stratigraphy the Santonian–Campanian boundary could be placed about 30 m below the first CORB interval (Wagreich, 2003). Graphic correlation of this section with the MIDK42 data base projects the base Campanian between 43 and 44 m.

The Dalsenalm section deepens rapidly from neritic shelf depths of about 50–150 m to about 500–1000 m water depth at the onset of CORB deposition (Butt, 1981). The amount of pelagic carbonate, mainly nannofossils and planktic foraminifers, increases significantly up section, whereas the terrigenous silt and clay fractions decrease. CORBs are clearly related to increasing water depth, as proven by foraminifer assemblages and increasing carbonate content. However, the facies change gradually and subtly from gray to red marl to marly limestones over a distance of several meters, which testifies to a gradual change to more oxygenated conditions.

Interpretation

In general, CORBs of the Gosau Group of the NCA reflect local current systems affected by complex slope-basin morphology and low siliciclastic sediment input. Marked intrabasinal lithofacies variations over short lateral distances, diachronous CORB intervals, and red-colored, slumped marls intercalated with gray-colored turbidite successions indicate that CORBs were not single, short-time events but represented the normal pelagic and hemipelagic background sedimentation in the slope-basins of the Gosau Group (Wagreich and Krenmayr, 2005).

The onset of CORB sedimentation is a transition from gray into red marls and is associated with a significant increase in water depth from gray shelf marls into red bathyal marls or marly limestones. This is proven by macrofauna, increasing amounts of planktic foraminifera up to 95% of the total foraminifera assemblages (Butt, 1981; Krenmayr, 1999; Wagreich and Neuhuber, 2005) and decreasing terrigenous input (see below). Although only brief time spans of about 500 kyr up to a maximum of 1 Myr for these transitions are inferred, the gradational character at Tiefenbach and Dalsenalm also argues against a single CORB event but suggests gradual changes in paleoceanographic conditions from gray to red deposition.

The Tiefenbach section was interpreted as recording a sediment–water interface above the CCD and oxic bottom waters. These conditions were suitable for a diverse community of benthic

foraminifera (Scott et al., 2003). The overlying water column supported an abundant and diverse pelagic community. The mineralogy of the CORB marl facies indicates reduced input of coarse terrigenous clastics. The approximate rate of sediment accumulation is comparable to rates of sedimentation of modern hemipelagic sediments.

MINERALOGY OF ACTIVE-MARGIN AND PASSIVE-MARGIN CORBs IN THE SANTONIAN–CAMPANIAN TETHYS

The mineral composition of Santonian to lowermost Campanian sections from passive-margin (Ultrahelvetics of Rehkogelgraben) and active-margin (Gosau Group, NCA, Schmiedsippl, and Tiefenbach) CORBs were compared by semi-quantitative X-ray diffractometry (XRD) analysis and organic-carbon (TOC) contents of 48 samples (for methods, see Neuhuber et al., 2007).

The mineral composition of the Schmiedsippl profile (for description, see Wagreich and Neuhuber, 2005) comprises mainly calcite and dolomite followed by quartz, sheet silicates, and feldspar (Table 1). The calcite content increases in the lower part of the profile, whereas it stays fairly constant at the top part, where dolomite increases relatively. The same minerals are present in the Tiefenbach section but in greatly different amounts compared to the Schmiedsippl section. Here, the calcite content decreases significantly towards the top of the profile. The amount of sheet silicates is higher than the dolomite content (Table 1). Calcite and sheet silicates dominate the Ultrahelvetic Rehkogelgraben section. Low amounts of quartz and feldspar (plagioclase) are identified. Plagioclase increases relatively at the top of the profile. The content of organic carbon in Rehkogelgraben and Tiefenbach is around 0.1%. The Schmiedsippl profile shows a gradual decrease from 0.5 to 0.15% TOC (Wagreich and Neuhuber, 2005).

The NCA region has significant dolomite content, as opposed to the Ultrahelvetic realm (Table 1), where no dolomites were deposited. The dolomite most likely originates from eroded Triassic dolomites that were exposed at the Austro-Alpine microplate. In contrast, the Rehkogelgraben was deposited in a distal position on the passive margin without any influence of the southern dolomite sources. The sheet-silicate content in the Rehkogel section is similar to that of the Gosau section of Brandenberg whereas its content is visibly lower in the Schmiedsippl section.

Carbonate production was highest at the passive margin at the Rehkogelgraben, due to the high planktic admixture. The sheet-silicate input was highest in the Tiefenbach section. Clay minerals identified in the Rehkogelgraben are illite, chlorite, kaolinite, smectite, and irregular mixed-layer clays, where smectites are by far the most abundant phase. The average plagioclase content is lowest in the Rehkogelgraben section, which is in accordance with its distal setting. The low organic-carbon content in all three profiles indicates a rapid recycling of TOC in oxic water with either an almost entire respiration of organic carbon in the water column and during early diagenesis or a primary oligotrophic environment.

AGE DISTRIBUTION OF CORB INTERVALS

For a survey of ages of CORBs in the Eastern Alps, the nannofossil zones of Perch-Nielsen (1985) were used as a measure of time, with the arbitrary (and naturally biased, see, e.g., Ogg et al., 2004) assumption that nannozones represent roughly equal time intervals. The more modern zonation of Burnett (1998) was not used, although there are some principal inconsistencies of the Perch-Nielsen (1985) zonation, especially in the Turonian–Santonian, because most correlation data are still published in this scheme. All sections having a CORB interval within one CC zone have been counted as 1. This analysis (Fig. 9) indicates a major CORB time of Late Santonian to early Early Campanian (CC17–CC19) with a modal high score in CC18. The Eastern Alps data base is definitely biased due to tectonism resulting in Turonian subaerial emergence and late transgression and subsidence of large parts of the NCA (Wagreich, 1993; Wagreich and Faupl, 1994), which favored CORB deposition only from the Santonian onwards. Globally, the peak time of CORB deposition was from the Turonian to the Santonian (Wang and Hu, 2005; Wang et al., this volume), from CC12 to CC19 (92–79 Ma according to the time scale of Ogg et al., 2004), but no significant short-term (1 nannozone) event can be defined either in the Eastern Alps or from the global distribution of CORBs.

CONTROLS ON CORB DEPOSITION

CORB deposition in different paleogeographic settings and different types of basins in the Alps was controlled by several crucial factors. Based on the Eastern Alps CORB data and published surveys and discussions (Hu et al., 2005; Hu et al., 2006; Wang and Hu, 2005; Wang et al., 2005) some inferences can be made about controlling factors and premises for sedimentation of Upper Cretaceous oceanic red beds.

Clastic Control

Comparing the occurrences and stratigraphy of CORBs shows straightforwardly a strong dependence of CORBs on sedimentary environments and especially on input of coarse clastic turbidites. Active-margin basins and deep-water flysch troughs can develop prominent CORB intervals as the main type of pelagic background sedimentation only during times of low clastic input in pelagic and hemipelagic settings (Wagreich and

TABLE. 1.—Mineralogy of investigated CORB sections from active-margin and passive-margin settings.

	Austro–Alpine active margin				Ultrahelvetic passive margin	
	Schmiedsippl (n = 12)		Brandenberg (n = 4)		Rehkogel (n = 32)	
	mean	stdev	mean	stdev	mean	stdev
quartz	8.0	1.4	4.8	1.0	1.7	0.9
sheet silicates	5.0	1.4	30.0	2.4	23.0	11.0
plagioclase	4.9	2.5	1.0	0.8	0.3	0.5
dolomite	30.3	5.9	19.0	10.0		
calcite	51.8	6.4	45.8	12.4	75.0	12.1

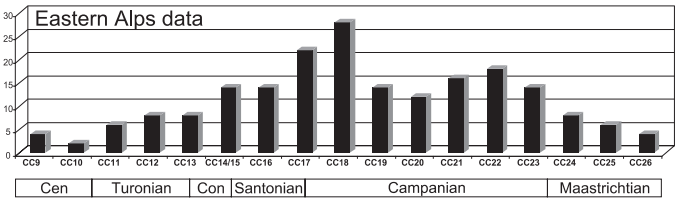

FIG. 9.—Age distribution of CORBs of the Eastern Alps (19 sites).

Krenmayr, 2005). This clastic control, where high input is probably related to tectonism in the source areas (e.g., Egger et al., 2002), is applicable both to the small slope-basins of the NCA above the calcite compensation depth and to the extensive flysch setting below the calcite compensation depth. Calcareous CORB types (marls, limestones) dominate the former and clayey CORB types (claystones, shales) the latter setting. However, no direct stratigraphic correlation between the NCA CORBs with the flysch CORBs is possible, although these depositional areas must have been in contact with each other during the Late Cretaceous (e.g., Faupl and Wagreich, 2000). CORB intervals in the flysch basin (Upper Albian to Lower Cenomanian, Coniacian–Santonian, and Upper Campanian) do not correspond to significant CORB intervals in the NCA (starting from the Upper Santonian to the Maastrichtian). Only during a short time span in the early Late Campanian (nannozone CC22) were both the NCA and parts of the flysch basin blanketed by CORBs, but the Ultrahelvetics display mainly gray marls during this time. There, CORB deposition ended already in the Early Campanian and was affected again by increasing clastic input and shallowing of the basin as indicated by an increase in terrigenous silt and sand particles, decreasing planktic foraminifera, and the presence of a Late Campanian neritic macrofauna.

Low Sedimentation Rates

Low sedimentation rates are another factor controlling CORB deposition (Wang et al., 2005), probably related indirectly to the clastic control, inasmuch as high clastic input may also influence pelagic to hemipelagic sedimentation rates. Sediment accumulation rates (calculated both from biostratigraphic datums taken mainly from the time scale of Ogg et al., 2004, and from graphic-correlation experiments, e.g., Scott et al., 2004) for the different CORB settings range between 2.5 to 12 mm/kyr for the Ultrahelvetics, 1.5 mm/kyr (Coniacian–Santonian) to 27 mm/kyr (including prominent turbidite beds) for the Flysch Zone, and 17 to 42 mm/kyr for the NCA active margin. A tendency for CORBs to predominate in times of lower sediment accumulation rates in the Austrian settings is remarkable. In the Gosau area the sediment accumulation rate of the gray part of the transition to CORB is around 42 mm/kyr, whereas the long-term CORB interval of the Postalm section has a mean sediment accumulation rate of around 26 mm/kyr (Wagreich and Krenmayr, 2005). Extremely low sediment accumulation rates are calculated for the Coniacian–Santonian red shales of the flysch basin, which are similar in magnitude to reported rates for deep-sea pelagic red clays (e.g., Gleason et al., 2002; 0.45 mm/kyr). However, the presence of turbidites in the section commonly distorts the calculations significantly. Pelagic sedimentation in the Ultrahelvetics shows conspicuously low sediment accumulation rates as low as 1.5 mm/kyr in the red CORB interval from the Middle Turonian to the Lower Campanian, but no significant changes in rates from gray to red intervals have been detected so far.

Paleo–Water Depth

Great paleo–water depth of the depositional area is another significant factor controlling CORBs. This is exemplified both by the Helvetic–Ultrahelvetic and the NCA successions. In the Helvetic–Ultrahelvetic passive-margin setting, only decimeter-thick red intervals occur in the normally gray Turonian–Santonian pelagic limestones of the outer shelf (Seewen Limestone; Föllmi, 1989), whereas the upper to middle bathyal successions of the Ultrahelvetics are characterized by a continuous carbonate–marl CORB interval from the Middle Turonian to the Lower Campanian. Farther downslope in the range of the calcite compensation lysocline, red marls and shales extend even into the Paleogene (Widder, 1988). The NCA transgressive successions such as at Dalsenalm and Tiefenbach, although differing strongly in their higher terrigenous input, also indicate a preferential occurrence of CORBs only after considerable deepening into bathyal depths of probably several hundred meters water depth. This is in accordance with observations by deep-sea drilling (e.g., Walvis Ridge, off Brazil), where cyclic gray-white carbonate–marl sedimentation starts at paleodepths of 400–600 m, and only deeper sites (> 1000 m water depth) show interbedded white carbonates and reddish marly beds (Herbert et al., 1999).

Eustatic Sea-Level Changes

The CORB record from the basins of the Eastern Alps indicates no direct relationship to eustatic sea-level maxima or minima (Fig. 10; Miller et al., 2005a; Miller et al., 2005b). Although the exact timing of short-term (third-order) sea-level changes is still debated, both the Turonian CORBs of the Ultrahelvetics and the NCA and flysch CORBs do not indicate direct sea-level control. The diachronous, red (hemi)pelagic intervals of the Nierental Formation of the NCA suggest that, if siliciclastic input is controlled mainly by tectonics; eustatic sea-level changes play a minor role in the development of CORBs (Wagreich and Krenmayr, 2005). Only for the Coniacian–Santonian CORBs of the Rhenodanubian Flysch can a sea-level control be inferred (Egger and Schwerd, 2008). However, eustatic sea-level rise after the Late Turonian lowstand may have been enhanced by tectonism affecting at least the NCA, and thus a combined eustatic–tectonic control via regulation of clastic input may be more likely. Eustatic control is also improbable considering the magnitudes of sea-level changes, with a maximum of about 120 m for the Late Cretaceous (Miller et al., 2005a; Miller et al., 2005b) versus the magnitude of tectonic subsidence of at least several hundreds of meters recorded in the gray-to-red transitions of the NCA and the Atlantic (Herbert et al., 1999).

Climate Change

Climate change may be one of the drivers of CORB sedimentation in the Late Cretaceous, when the climate–ocean system changed dramatically from mid-Cretaceous anoxia to Late Cretaceous oxic sedimentation (e.g., Arthur et al., 1988; Leckie et al., 2002). Essentially, climate cooling (Hu et al., 2006) increased the probability and amount of formation of oxygenated deep waters due to cool polar regions and ephemeral ice sheets (Stoll and Schrag, 2000; Miller et al., 2005a; Miller et al., 2005b). Thus the whole structure of ocean circulation changed (Hay et al., 2005a; Hay et al., 2005b). Inferred Early Cretaceous cool periods coincide with some of the CORB horizons, thus suggesting a causal link of climate and CORB deposition (Wagreich, this volume). During the Late Cretaceous a general cooling trend from extreme greenhouse conditions (hothouse of Wilson et al., 2002) at the onset of,

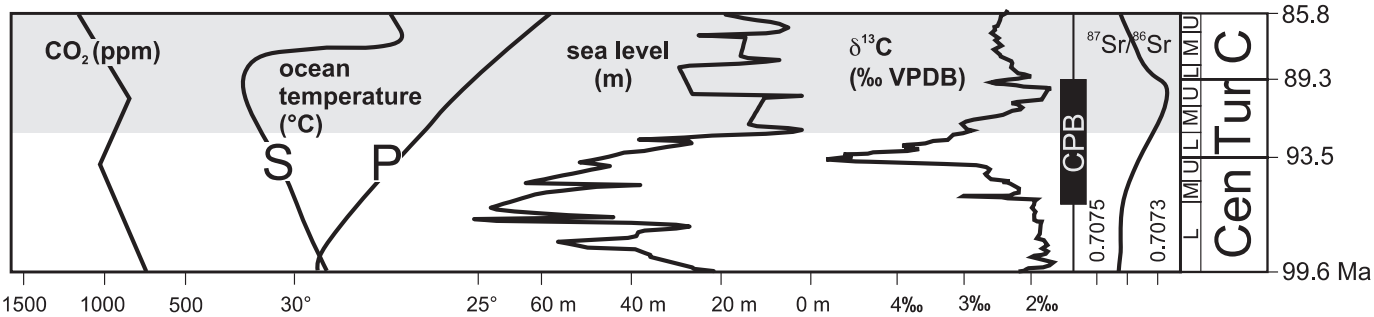

FIG. 10.—Cenomanian–Coniacian curves of parameters and proxies; main CORB interval is shaded. $^{87}Sr/^{86}Sr$ isotope ratio according to McArthur et al. (2001) and McArthur and Howarth (2004); CPB—estimated time of formation of Caribbean plateau basalts (Jones and Jenkyns, 2001; Erba, 2004); $\delta^{13}C$ curve (Jarvis et al., 2006); best estimate of sea-level record (Miller et al., 2005a); ocean temperatures (P—Pucéat et al., 2003; S—Steuber et al., 2005); CO_2 estimate of Royer (2006); time scale of Ogg et al. (2004).

or during, OAE 2 in Late Cenomanian times to the Coniacian is evident (e.g., Pucéat et al., 2003). This coincidence suggests the relation between cooling and CORBs. However, the details of the temperature curve (and related parameters like CO_2; Royer, 2006) are still far from settled. Regarding temperature during OAE 2 and the subsequent onset of CORBs in the course of the Turonian, controversial interpretations exist. The high-precision and/or high-resolution oxygen isotope records from fish enamel (Pucéat et al., 2003) suggest general cooling from the Turonian to the Campanian. Voigt (2000) suggests an extreme cool period in the Late Turonian; however, Steuber et al. (2005) conclude warming during the Turonian with a Cretaceous peak mean annual sea-surface temperature around 32°C of the Tethys in the Late Turonian followed by dramatic Early Coniacian cooling by 6°C. Wilson et al. (2002) posit a Cretaceous Thermal Maximum in the Middle and Late Turonian. Such controversies hinder the establishment of a straightforward correlation of CORBs with global temperature for the Late Cretaceous (see also Wang et al., 2005).

ONSET OF CORBs—AN EARLY TO MIDDLE TURONIAN GLOBAL EVENT?

The onset of CORB deposition in the clastic basins of the NCA and the Rhenodanubian Flysch resulted from establishment of suitable pelagic conditions, low clastic input, i.e., low turbidite frequencies, low sedimentation rates compared to underlying strata, and increasing water depths. All of these factors are related to tectonism in these orogenic basins, and thus a tectonic control on CORB deposition, both the onset and the termination, in these settings is evident. No widespread single CORB event can be identified. These settings testify that CORBs in such settings are a normal type of background basinal deposit (Wagreich and Krenmayr, 2005), especially in the Late Cretaceous, when oceans seem to have been generally more oxic than the OAE oceans of the mid-Cretaceous (Kaiho, 1994).

In contrast, the onset of CORB deposition in the Ultrahelvetic Zone, a pelagic slope setting remote from Alpine orogeny during the Late Cretaceous, seems to correspond to a major CORB level or event recognized not only in the Tethys (e.g., Hu et al., 2005; Hu et al., 2006) but also in the Atlantic, Indian, and Pacific oceans (Hu et al., 2005; Wang and Hu, 2005). Detailed inventories of this change (Hu et al., 2005, Vispi Quarry, Umbria, Italy; Neuhuber et al., 2007, Ultrahelvetics, Austria) from the extreme anoxia of OAE 2 (Bonarelli level) to the red and presumably highly oxic CORBs indicate a time span of no more than 1.5 Myr (Hu et al., 2006; calculated with a mean sediment accumulation rate of 7.4 mm/kyr) to 1.1–1.5 Myr (Buchberg, Neuhuber et al., 2007; calculated from carbon isotope stratigraphy and biostratigraphy) in the Early to Middle Turonian for red colors to become dominant. In detail, the first reddish or pinkish beds occur at 590 kyr in Italy or about 700 kyr in Austria following OAE 2. In the eastern Atlantic, CORB deposition began about 670 kyr following OAE 2 in ODP 641A (Scott, this volume).

Coeval changes suggest a widespread or even global change in the climate–ocean system as the primary cause for the end of global OAE 2 (e.g., Leckie et al., 2002). The coeval onset of red oxic sedimentation both in deep ocean basins like the North Atlantic and in the basinal and slope environments above the CCD of the Tethys probably was linked to this change. Geochemical and isotope evidence from the Ultrahelvetic Buchberg section suggests that paleoceanographic conditions changed gradually from anoxic during the latest Cenomanian OAE 2 to oxic during the Early to Middle Turonian, representing an episode of more oligotrophic conditions after the eutrophic OAE 2. A gradual nutrient depletion (most likely phosphate depletion in the surface waters) resulted in enhanced oligotrophy, which ultimately led to the formation of CORBs. From the onset of the first red bed a decreased availability of nutrients is shown by phosphorus, by nutrient-indicative trace elements like barium, and an increase in bottom-water oxygenation indicated by Pb and Zn. A precessional (ca. 20 kyr) or obliquity forcing on primary production is suggested by the total carbonate content. In addition, principal-component analysis indicates also a decrease in hydrothermal activity (Neuhuber et al., 2007).

The alternations between red and gray marls or limestones have been interpreted as reflecting intermittent changes in oxygen content of the bottom water during the transitional period. This is also inferred from the changing vertical distribution patterns of benthic foraminifera in relation to the sediment color. Very high abundance of species, which are typical of increased flux rates of organic matter to the sea floor and slightly reduced oxygen levels, such as the benthic foraminifera *Tappanina laciniosa* (Kuhnt and Wiedmann, 1995; Friedrich and Erbacher, 2006), occur just before the changes from gray to red colors (Wendler et al., 2006, this volume).

The formation of red beds thus is most likely associated with a general shift towards oligotrophic and more oxic conditions in basins with black shale deposits that eventually resulted in enrichment of thiophile elements in the entire basin. A gradual nutrient depletion during sea-level highstand might be the cause of significantly diminished nutrient availability. The widespread occurrence of this transition from black shale to CORBs in the

Turonian calls for a global change in the ocean–climate system during the Early to Middle Turonian, related not only to the end of organic-carbon-rich, anoxia-related deposition but also to a process continuing into the overlying strata for more than one million years. A long-term cooling trend during this time span is inferred by Pucéat et al. (2003), and short-term cooling is suggested due to carbon burial and massive CO_2 drawdown by OAE 2 (e.g., Arthur et al., 1988). The change to lighter carbon isotope values (Fig. 10) during the Turonian supports the idea of increasingly oligotrophic conditions, although the ultimate reason for this is unclear. This may reflect a change to generally lower plankton bioproductivity after OAE 2 extinction, and subsequently less organic-carbon burial and/or climate cooling from extreme greenhouse conditions can be invoked. However, strontium isotope data and dating of large igneous provinces, e.g., the Caribbean plateau basalts and parts of the Ontong–Java plateau (Jones and Jenkyns, 2001; McArthur and Howarth, 2004) indicate that peak magmatic input was reached later in Late Turonian times (Fig. 10) and also argue against strong cooling during the Turonian. Also, no plankton events can be defined during this time, e.g., the Turonian to Coniacian is regarded as a time interval of stasis of plankton foraminifera without significant extinction and radiation (Premoli Silva and Sliter, 1999).

Low productivity and highly oxygenated bottom waters have already been indicated especially for Santonian–Campanian times on the basis of low organic-matter contents, cerium contents, and benthic foraminiferal assemblages (Kaiho, 1994; Wang et al., 2005). These bottom waters resulted in widespread postdepositional (early diagenetic) oxic conditions in deposited sediments of oceanic basins and slopes. Considering the stratigraphic data presented here and by Hu et al. (2006), this interval began already shortly (ca. 500 kyr) after the end of OAE 2, during the Early Turonian. Decreasing carbon isotope values (Fig. 10) from OAE 2 may indicate the tendency to oligotrophic conditions during the Turonian. Subsequent small-sized positive peaks of the carbon isotope curve (Stoll and Schrag, 2000; Erba, 2004; Jarvis et al., 2006) may be an artefact of the special case of an anoxic equatorial Atlantic Ocean during times of worldwide oxic oceans (see Wagreich, this volume).

TYPES OF CORBs

CORBs are defined as red to pink to brown fine-grained sedimentary rocks of Cretaceous age deposited in hemipelagic and pelagic, deeper marine environments; they include limestones, marls, shales, and cherts (Hu et al., 2005). CORBs comprise deep-water red claystones deposited below the CCD, e.g., in the northern Atlantic (Hu et al., 2005), red hemipelagic and pelagic carbonates of the Tethys (Hu et al., 2005; Hu et al., 2006; Wagreich and Krenmayr, 2005), and red cherts and radiolarites (e.g., Neumann and Wagreich, this volume). Consequently, these CORBs can be classified into three lithological groups, and a ternary classification diagram can be constructed with the following end members (Fig. 11; turbidites not included): (1) clayey CORBs, consisting mainly of clay minerals, comparable to recent red (or brownish) pelagic clays; (2) calcareous CORBs, mainly pelagic limestones like the Italian Scaglia Rossa; and (3) siliceous CORBs, consisting mainly of SiO_2. Although various admixtures occur, e.g., red marls as a mixture of clay and limestone, end members are commonly present, at least as one component of dual cycles, e.g., limestone–marl or chert–shale rhythmites. This ternary classification essentially mimics general classifications of pelagic deep-water sediments in that pelagic clays, biogenous carbonates, or biogenous siliceous sediments are the principal end members, which consist either of biogenous carbonate mainly

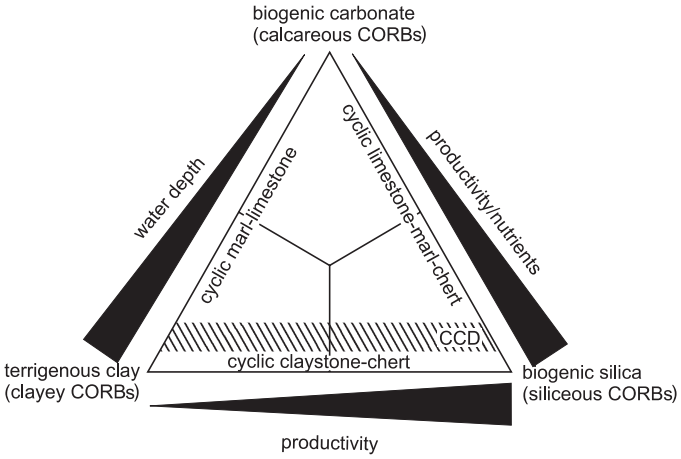

FIG. 11.—Classification diagram of three-component Cretaceous oceanic red beds (CORBs) system and major controlling factors for sedimentation.

from calcareous nannofossils and planktic foraminifera, or siliceous microfossils, mainly radiolaria, or terrigenous clay and silt-size quartz.

Widespread recent analogues for CORB sedimentation are found only for the clayey CORBs type. Recent red pelagic clays are a major facies of the deep sea. They constitute up to 38% of the surface sediments of the oceanic basins and accumulate mainly below the CCD, where biogenic components (carbonate and siliceous plankton tests) are minor due to the presence of low-productivity gyres (Hu et al., 2005). The color of recently sedimented pelagic clays is normally brown; the red color is regarded as a later, diagenetic feature due to postdepositional formation of hematite from iron hydroxides. Essentially, there are three prerequisites for the formation of red pelagic clays: a depositional area below the CCD to dissolve the carbonate plankton fraction, as evident from the dissolution facies of widespread red clays of the PETM event (Paleocene–Eocene Thermal Maximum; e.g., Bralower et al., 2002); overall low plankton productivity such as the low-productivity gyres of the Pacific, hence oligotrophic conditions, to decrease input of siliceous plankton (radiolaria, diatoms, silicoflagellates) to the ocean floor; and low sedimentation rate, to give enough time for (postdepositional) oxidation of organic material in the uppermost centimeters of the sediments, but significant input of terrigenous fine-grained particles such as clays and silt-size quartz, mostly via eolian transport, as proven for the vast red-clay areas of the northwest Pacific, where eolian input from Asian deserts is evident (Pettke et al., 2000; Gleason et al., 2002).

Recent analogues for the other two CORB end members, the carbonate and the siliceous, are extremely rare or virtually absent, as judged by a review of deep-sea-drilling data; most of these oozes display initially gray colors. Brownish nannofossil ooze or chalk, considered as the recent counterpart of red pelagic limestones, forms only under exceptional circumstances. The only widespread occurrence reported from the deep sea is a hematite crust formed by diagenetic oxidation of terrigenous iron during the change from glacial to postglacial sedimentation. In this case, iron dissolved in interstitial water moved upward during compaction and was oxidized when reaching the sediment–water interface and precipitated, forming a centimeters-thick iron-cemented crust (McGeary and Damuth, 1973), resulting in brown-colored nannofossil ooze. Mediation by iron bacteria as interpreted for red limestones (Mamet and Préat, 2006) can be invoked in this special case.

CONCLUSIONS

There are several hypotheses to explain red deep-water sediments called CORBs (Wang et al., 2005; Hu et al., 2006). Prerequisites for Eastern Alpine CORB deposition were low clastic input, low sedimentation rates, and increasing water depth. CORBs show no direct relationship to eustatic sea-level changes or the carbon isotope curve but may be related to a general cooling trend from the Cenomanian–Turonian to the Campanian–Maastrichtian.

A general survey of Late Cretaceous oceanic red beds indicates the Early Turonian to Late Campanian interval as the major phase of CORB deposition, but no significant short-term event can be defined. However, the onset of CORB deposition is interpreted as a major oxygenation event recognized not only in the Tethys but also in the Atlantic as well as the Indian and Pacific oceans (Wang and Hu, 2005). Detailed inventories of this change from OAE 2 to the red highly oxidized CORBs indicate a time span of about 1.1 to 1.5 Myr in the Early to Middle Turonian for red colors to become dominant. Deposition of red beds is interpreted as a result of a stepwise shift towards oligotrophic and more oxic conditions in the oceans in the aftermath of an oceanic anoxic event.

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