Research Article

Calcareous nannofossil biostratigraphic study of forearc basin sediments: Lower to Upper Cretaceous Budden Canyon Formation (Great Valley Group), northern California, USA

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Abstract The results of a calcareous nannofossil biostratigraphic investigation of the North Fork Cottonwood Creek section of the Budden Canyon Formation (BCF; Hauterivian–Turonian) in northern California are summarized using the Boreal – cosmopolitan Boreal Nannofossil Biostratigraphy (BC) – Upper Cretaceous Nannofossil Biostratigraphy (UC) nannofossil zonal schemes of Bown et al. and Burnett et al. Sixteen intervals, ranging from the BC15 to UC8 zones, were established in the section. Combined biostratigraphic and magnetostratigraphic studies suggest a Hauterivian to mid-Turonian age for the studied sequence. The Hauterivian–Barremian, Barremian–Aptian, Aptian–Albian, Albian–Cenomanian, and Cenomanian–Turonian stage boundaries were delineated near the top of the Ogo Member, below the Huling Sandstone Member, within the upper Chickabally Member, in the upper portion of the Bald Hills Member and within the Gas Point Member, respectively. Unconformities probably exist at the base of the Huling Sandstone Member and the upper part of the upper Chickabally Member. The nannofossil assemblage in the North Fork Cottonwood Creek suggests that the study area was under the influence of cold-water conditions during the Barremian to Lower Aptian interval, shifting to tropical/warm-water conditions during the Albian to Turonian interval as a result of the mid-Cretaceous global warming. Although oceanic anoxic events have not yet been reported in the BCF, preliminary total organic carbon, along with nannofossil data, suggest the presence of the global Cenomanian–Turonian boundary oceanic anoxic event 2.

Key words: biostratigraphy, Budden Canyon Formation (BCF), calcareous nannofossils, California, Cretaceous, Great Valley Group (GVG), oceanic anoxic event 2 (OAE2).

INTRODUCTION

The Great Valley Group (GVG, e.g. Surpless et al. 2006), formerly known as the Great Valley Sequence, is a thick (~15 km) sedimentary sequence that formed in a forearc basin along the western border of the Sacramento Valley in northern California, between the Sierra Nevada volcano–plutonic arc and the Franciscan subduction complex, which presently underlies the Coast Ranges of California (Ingersoll 1979; Suchecki 1984; Fig. 1). The formations of the GVG are divided into two regional sequences by the Elder...
The study area is in the region north of the fault known as the Cottonwood district and exhibits fine-grained, deep-water marine sediments (i.e. mudstones and siltstones) of Cretaceous age associated with turbiditic sandstones and conglomerates that are interpreted as submarine fan complexes and tectonic-related components. The Cottonwood district encompasses the drainage basin of all the forks of Cottonwood Creek. The present study is along the North Fork Cottonwood Creek, the northernmost main stream of the district.

Biostratigraphic studies of the Cottonwood district document its geological age to range from the Hauterivian to Turonian based on mollusks, foraminifers, radiolarians, and calcareous nannofossils. Among microfossils, calcareous nannofossils are very useful for correlation between the GVG and the stratotype sections in the European regions, and in dating of each lithological unit. This is best illustrated in the study of Bralower et al. (1990) in the McCarty Creek section (northern part of GVG), wherein the NK2–NK8 biozones of Bralower et al. (1989), established based on European land sections and western North Atlantic Deep Sea Drilling Project (DSDP) sites, were recognized.

Exposures of the GVG north of the Elder Creek Fault belong to the Budden Canyon Formation (BCF), which is the most continuous and fossiliferous Barremian–Turonian sequence in the northwestern part of the Sacramento Valley, northern California (Murphy 1956; Murphy et al. 1964; Dailey 1973; Murphy & Rodda 1996). The present study discusses the results of the combined calcareous nannofossil biostratigraphy and magnetostratigraphic study of the North Fork Cottonwood Creek section of the BCF, which spans the Hauterivian to Middle Turonian. In addition, the positions of several Cretaceous stage boundaries in the BCF and the possible existence of oceanic anoxic events (OAEs) in the eastern

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Pacific region will also be discussed. The studied section is divided into sixteen intervals using the Boreal – cosmopolitan BC – UC zonal schemes of Bown et al. (1998) for the Lower Cretaceous and Burnett et al. (1998) for the Upper Cretaceous, respectively.

**GEOLOGICAL BACKGROUND**

**LITHOSTRATIGRAPHY**

Murphy et al. (1964) revised the lithostratigraphic nomenclature of previously defined formational units into member status, which were subsequently incorporated within a single formation, called the Budden Canyon Formation (BCF). The revised formation consists of seven members: Rector Conglomerate, Ogo, Roaring River, Chickabally, Huling Sandstone, Bald Hills, and Gas Point Members, in ascending order (Figs 2, 3). Dailey (1973) proposed an additional member unit, the Aiken Member, which is basically equivalent to the upper Chickabally Member (Murphy et al. 1964; Peterson 1967). In the present study, the lithostratigraphic nomenclature of Murphy et al. (1964, 1969) was followed. Only the upper six members of the BCF were studied in the North Fork Cottonwood Creek section (Fig. 3), each of which is briefly described below.

The Ogo Member, the oldest lithological unit sampled for calcareous nannofossils, attains a thickness of about 200 m in the studied section. The member consists of massive siltstones and mudstones, which are frequently associated with fine-grained laminated sandstones. The approximately 150-m interval between the uppermost
Fig. 3  Stratigraphic levels of the samples used in the North Fork Cottonwood Creek section. Numbers on the left side of the column refer to sample numbers. Sections along the creek, as shown in Figure 2, are represented by the roman numerals on the right side of the column.
conglomerate in the Ogo Member and the lowermost mudstone of the Chickabally Member is considered in this study as the Roaring River Member. The member consists of laminated sandstones and conglomerates, with siltstone or mudstone interbeds. In the North Fork Cottonwood Creek section, the Chickabally Member is separated into the lower and upper Chickabally Members by the Huling Sandstone Member, a 50-m-thick unit of thinly bedded sandstones and conglomerate. The lower Chickabally Member is about 300 m thick and is composed mostly of mudstones, with alternating beds of mudstones and sandstones near the base of the Huling Sandstone. The upper Chickabally Member, on the other hand, consists of mudstones and intercalations of thinly to thickly bedded sandstones. Based on the dominant lithology, the upper Chickabally Member is separated further into the mudstone-dominated unit (ms-unit) and the alternating sandstone unit (ss-unit; Fig. 3). The ms-unit comprises the lower 410 m of the upper Chickabally Member, and includes a tuff bed approximately 250 m above the Huling Sandstone Member and alternating beds of sandstone and mudstone units near the top. The ss-unit, on the other hand, includes the upper 270 m of the member and, as the name suggests, consists of thin to thick beds of sandstones intercalated with mudstones. A prominent massive sandy mudstone bed occurs at the base of the ss-unit. Overlying the Chickabally Member is the generally coarse-grained Bald Hills Member, consisting predominantly of mudstones and intercalated sandstones, conglomerates and pebbly mudstones. The Bald Hills Member attains a thickness of 160 m in the studied section. The youngest and uppermost unit of the Budden Canyon Formation is the Gas Point Member, which has a thickness of about 730 m in the North Fork Cottonwood Creek section. The Gas Point Member consists of siltstones and mudstones, with sandstone intercalations becoming more common in the upper part of the section.

**BIOSTRATIGRAPHY**

Many biostratigraphic studies have been conducted in the BCF using ammonites, radiolarians, foraminifers, and, to a lesser extent, calcareous nanofossils. Murphy (1956) studied the ammonites in the Lower Cretaceous sequence and established nine zones, from the Barremian Simbirskites (Hollisites) aquila zone to the Alban Mortoniceras hulenanum zone (Fig. 4). Despite some revisions on the age assignments of Murphy's ammonite zones by subsequent studies (i.e. Popenoe *et al.* 1960; Murphy 1969, 1975; Murphy *et al.* 1969; Dailey 1973), the zones remain as useful subdivisions of the record on the western coast of North America, along with the other fossil guides proposed and compiled by Popenoe *et al.* (1960). More recent ammonite studies in the GVG include descriptions of new taxa (Rodda & Murphy 1992; Murphy *et al.* 1995; Amédro & Robaszynski 2005) and discussions on the position of the Alban–Cenomanian boundary in northern California (Murphy & Rodda 1996; Amédro & Robaszynski 2005).

Marianos and Zingula (1966) reported the occurrence of selected planktonic foraminifers from the Hauterivian to Turonian interval, and briefly discussed the geological age assignment of the BCF in the Dry Creek section (Fig. 4). Dailey (1973), on the other hand, established four faunizones (Faunizones I–IV) based on benthic foraminiferal assemblages. These faunizones were used to subdivide the Hauterivian to Cenomanian interval of the BCF in the Ono Quadrangle. Pessagno (1976, 1977) established 12 radiolarian zones in the GVG, ranging from the Berriasian *Obesacapsula rotunda* zone to the Maastrichtian *Orbiculiforma renillaeformis* zone (Fig. 4). These radiolarian zones were correlated to ammonite and planktonic foraminiferal zones and are closely tied to the European stages.

Calcareous nanofossil studies in the GVG are limited to the studies of Worsley (1979) and Bralower (1990; Fig. 4). These studies focused on the Lower Cretaceous sections along McCarty, Dry, Stony, and Grindstone Creeks in Tehama and Glenn Counties, which are all located south of the Cottonwood district. Despite the limited number of samples (9 samples), Worsley (1979) demonstrated that calcareous nanofossil biostratigraphy is effective in dating of sediments in this area. Bralower (1990), on the other hand, further illustrated Worsley's initial work and, in addition, showed the possibility of correlating the calcareous nanofossil zones of the Late Berriasian to Alban interval between the GVG and the standard sections in Europe.

**MAGNETOSTRATIGRAPHY**

The magnetostratigraphy of the North Fork Cottonwood Creek section was investigated at the Center for Advanced Marine Core Research at Kochi University, Japan. At least four reversed
magnetic polarity intervals were determined from the Ogo to the upper Chickabally Members. Correlation of these reversed polarity intervals with the Geomagnetic Polarity Time Scale (GPTS) of Ogg and Smith (2004), and combined calcareous nannofossil and ammonite biostratigraphy, are discussed in Magnetostratigraphic Interpretation.

MATERIALS AND METHODS

SAMPLE PROCESSING, MICROSCOPY, AND COUNTING PROCEDURES

A total of 135 samples were collected from the North Fork Cottonwood Creek, encompassing the Ogo, Roaring River, lower and upper Chickabally, Bald Hills, and Gas Point Members of the Budden Canyon Formation (Fig. 3). No samples were taken within the Huling Sandstone Member, although samples were collected near its lower and upper boundaries.

To analyze the calcareous nannofossil assemblage and establish the calcareous nannofossil biostratigraphy of the section, smear slides were prepared from the samples using standard preparation techniques, and examined under a light microscope using both cross-polarized light (XPL) and phase contrast (PC) methods at 1000 to 1600× magnification. More than 500 fields of view (FOV) were investigated per sample. With the exception of some fossiliferous intervals, most of the samples have low nannofloral densities (<100 specimens per 500 FOV), probably as a result of dilution of siliciclastic materials. Additional FOV were checked to verify rare occurrences of biostratigraphic marker species. Calcareous nannofossil
relative abundance categories were adapted and slightly modified from Bralower (1990), Bown et al. (1998), and Burnett et al. (1998), and are given as follows: (i) common (C), 1 specimen per 1–2 FOV; (ii) few (F), 1 specimen per >2–50 FOV; (iii) very few (VF), 1 specimen per >50–100 FOV; and (iv) rare (R), 1 specimen per >100 FOV.

CALCAREOUS NANNOFOSSIL ZONATION SCHEMES

Several calcareous nannofossil zonation schemes have already been proposed in the Cretaceous, with the zonation schemes of Sissingh (1977; CC zones) and Roth (1978; NC zones) being the most widely used (Fig. 5). The CC zonation scheme was based on data from a geographically wide area, including European and North African sections. The NC zonation scheme, on the other hand, was established in the low-latitude region of the Northwestern Atlantic Ocean (DSDP Leg 44). Despite this, the CC and NC zonation schemes are basically similar in definition and characterization. The most recent zonation scheme proposed for the Cretaceous is the composite zonal scheme of Bown et al. (1998; BC zones) for the Lower Cretaceous and Burnett et al. (1998; UC zones) for the Upper Cretaceous (Fig. 5). The BC zones were defined in the North Sea Basin. While many of the zonal markers used there are also applicable in low to intermediate latitudes, several taxon range zones are diachronous. This results in differences in the zonal characterization between the BC and CC/NC zones, especially prior to the Albian. The UC zones, on the other hand, are derived...
from the CC and NC zones. The UC zonation scheme, however, was established based on recent advances in evolutionary understanding and biogeographic distribution of calcareous nannofossils in high- and intermediate-latitudes, and uses more widely distributed marker taxa compared with the CC/NC zones (Burnett et al. 1998).

Many zonal markers in the Albian–Turonian interval are similar between the BC/UC and CC/NC zones. This is in contrast to the Barremian–Aptian interval, wherein several zonal markers used for the BC zonation scheme are different from the markers used in the CC/NC scheme. This implies that provincialism/endemism occurred during the early Cretaceous, making correlation between the Boreal and tropical/Tethyan regions difficult. During the mid-Cretaceous, global correlation through calcareous nannofossils was achieved. This was attributed to the presence of a low sea-surface temperature gradient between the low- and high-latitude regions and the consequent expansion in the range of tropical/subtropical species to middle- and high-latitude regions (Burnett et al. 1998).

RESULTS

CALCAREOUS NANNOFOSSIL ABUNDANCE AND PRESERVATION

Calcareous nannofossil abundance values are variable and the specimens observed in the samples generally exhibit poor to moderate preservation. Species richness (i.e. total number of species) also appear to be very low compared with other Lower to Upper Cretaceous sections, although Mutterlose et al. (2003) noted similar species richness values (1–40 species/sample) in the Vohrum section in northwest Germany. All these observations are probably the consequence of the relatively high amount of siliciclastic input in the study area (dilution effect). The low species richness may also be attributed to dissolution (or poor preservation of nannofossils), although the presence of moderate- to well-preserved ‘fragile’ forms like Biscutum spp., and Discorhabdus ignotus suggests otherwise.

Calcareous nannofossil abundance and species diversity values display fluctuations in the North Fork Cottonwood Creek section. In general, however, higher nannofossil abundance and species diversity characterize the Albian–Turonian interval compared to the Barremian–Aptian interval (Fig. 6). Calcareous nannofossils in the BCF include some Boreal-diagnostic taxa, but mainly consist of Tethyan species, allowing recognition of Tethyan bioevents and correlation to Tethyan (low-latitude CC/NC) zonation schemes. This is particularly evident for the Albian and younger units in the studied section. Commonly occurring species in the assemblage include long-ranging taxa such as Watznaueria barnesiae, Biscutum constans, Biscutum ellipticum, and D. ignotus. A list of the 129 nannofossil species and subspecies observed in the North Fork Cottonwood Creek section is provided in Table S1 (Supporting Information). Two new calcareous nannofossil species were described by Fernando and Okada (2007) in the North Fork Cottonwood Creek section of the Budden Canyon Formation: Diloma californica and Prediscosphaera quasispinosa. Optical micrographs of selected nannofossil taxa, on the other hand, are illustrated in Figures 7 and 8.

CALCAREOUS NANNOFOSSIL BIOSTRATIGRAPHY

Nine major and 21 supplementary nannofossil bioevents were recognized in the North Fork Cottonwood Creek section (Fig. 9). During the early Cretaceous, however, several species that are considered important markers of the CC/NC zones in other areas are either missing or have been recorded at different levels in the studied section (diachroneity). In this interval, the bioevents used in the recognition of the BC zones of Bown et al. (1998) become invaluable. In cases where zonal markers are not observed, supplementary nannofossil events were used instead. Based on the BC and UC nannofossil zonation schemes, the North Fork Cottonwood Creek section can be divided into 16 intervals, ranging from the BC15 and older zones to the UC8 zone (Figs 5,9). The recognized zones suggest that the geological age assignment of the section is Hauterivian – Middle Turonian, which is in agreement with previously published ammonite and foraminiferal data. The zones are discussed in detail below.

BC15 and older zones (undifferentiated Hauterivian and Barremian)

The lowermost zone recognized in the present study includes the Ogo, Roaring River, and the lowermost part of the lower Chickabally Member, represented by the interval from the lowest sample (OGO-46) to the first significant (probably local) nannofossil event in the section, which is the first nannoconid abundance peak (US-719). This
bioevent occurs above the lowermost occurrence of *Rhagodiscus gallagheri* (US-717). Calcareous nannofossils are rare to few in abundance and are poorly preserved, consisting mostly of long ranging taxa such as *Biscutum* spp. (*B. constans*, *B. ellipticum*), *D. ignotus*, and *W. barnesiae*. Nannofossil markers indicative of Hauterivian and Barremian ages were not observed within the interval. Thus, the lower boundary of the undifferentiated zone is not recognized.

![Calcareous nannofossil abundance and species richness in the North Fork Cottonwood Creek section. The interval with the highest total organic carbon (TOC) values is represented by the area shaded gray, while the interval containing the main δ¹³C isotope excursion is represented by the vertical arrow (T. Tomosugi [TOC] and T. Yamanaka [δ¹³C], unpubl. data, 2006).](image-url)

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Ammonites collected within the interval include *Crioceratites* sp. (Rodda & Murphy 1987) and *Shasticrioceras* sp. *S. patricki*. The former ranges from the Late Valanginian through the Barremian, but are mostly recorded within the Hauterivian (Popenoe et al. 1960), while the latter ranges from the Middle Barremian to the Early Aptian (Murphy 1975). Based on combined ammonite and calcareous nannofossil biostratigraphy, the interval is probably Hauterivian to Late Barremian in age, and could correspond to the BC15 and older zones. The undifferentiated zone is correlated to the NC5 and CC5 – lower CC6 zones.

**BC16–BC17 undifferentiated zone (Late Barremian)**

The undifferentiated zone is the interval between the first nannoconid abundance peak and the first occurrence (FO) of *Flabellites oblongus* (US-013), and includes most of the lower Chickabally Member. Similar to the previous interval, calcareous nannofossils are rare to few and are poorly preserved. The calcareous nannofossil assemblage of this interval, however, is characterized by the continuous occurrence and slightly higher abundance of nannoconids compared to the previous zone (Fig. 9). Commonly occurring taxa within the zone, aside from *Nannoconus* spp., include *B. constans*, *D. ignotus*, *Rhagodiscus asper*, *Rotelapillus crenulatus*, *W. barnesiae*, and *Watznaueria fossacincta*.

The FO of *F. oblongus* was used in the present study to approximate the Barremian–Aptian (B–A) boundary (see discussion in Stage Boundaries in Budden Canyon Formation). Below this bioevent, the second nannoconid abundance peak

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**Fig. 9** Calcareous nannofossil biostratigraphic zonation and distribution of calcareous nannofossil zonal markers and selected taxa in the North Fork Cottonwood Creek section. The *Nannoconus* spp. abundance graph shows the number of *Nannoconus* specimens counted in approximately 500 fields of view (FOV) (smear slide data). Figure 3 shows lithology and sample numbers.
was observed (Fig. 9). Another nannofossil event recognized within the zone is the uppermost occurrence of *Micrantholithus* spp. (*M. census*, *M. obtusus*; US-011). The last occurrence (LO) of *Micrantholithus* spp. is generally recorded at higher levels, within the BC21 nannofossil zone (Bown et al. 1998; NC7 zone of Roth 1978). Barremian-indicative nannofossil taxa such as *Nannoconus inornatus* and *Tegumentum octiformis* were also observed within the lower part of the zone. The BC16–BC17 undifferentiated zone, which is equivalent to the upper NC5 and CC6 zones, is considered Late Barremian in age.

**BC18 zone (Early to Late Aptian)**

The BC18 zone of Bown et al. (1998) is originally defined as the interval zone from the FO of *R. gallagheri* to the FO of *Farhania varolii* (Fig. 5). In the studied section, however, typical specimens and forms similar to *R. gallagheri* were observed in the uppermost part of the Roaring River Member. In the present study, the BC18 zone is considered as the interval between the FOs of *F. oblongus* and *F. varolii* (US-040), both of which occur immediately below and above the Huling Sandstone Member, respectively (Fig. 9). The FO of *F. oblongus* is considered as a supplementary datum within the BC18 zone in Boreal regions and is located above the FO of *R. gallagheri* (Bown et al. 1998).

The zone includes, by default, the Huling Sandstone Member, where no samples were collected for nannofossil analysis. The base of the Huling Sandstone Member has been recognized in earlier studies to be an erosional surface (Peterson 1967; Murphy 1975). The immediate occurrence of *F. varolii* (an Early Aptian bioevent) above the Huling Sandstone Member (Late Aptian based on ammonites) suggests possible erosion of earlier deposited sediments, probably ranging from the uppermost Barremian to Lower Aptian, in the study area. This possibility is further supported by the observation of the Late Aptian ammonites *Eotetragonites wintunius* and *Parahoplites* spp. near the base of the Huling Sandstone Member. The BC18 zone corresponds to the NC6A and CC7a subzones, and is considered Early to Late Aptian.

**BC19–BC20 undifferentiated zone (Late Aptian)**

The zone includes the lowermost upper Chickabally Member, and is the interval between the FO of *F. varolii* and the *Hayesites irregularis*–*Radiolithus orbiculatus*-containing sample (US-037; Fig. 9). *Hayesites irregularis* is used as a B–A boundary marker in low latitude regions (e.g. Thierstein 1976), and is placed within the BC18 zone. The occurrence of *H. irregularis* at the top of the composite zone therefore suggests that the local range of the taxon in the North Fork Cottonwood Creek section is less than its true range. A similar observation in the GVG has been illustrated in Channell et al. (1995), wherein *Rucinolithus* (=*Hayesites*) *irregularis* was not observed above the B–A boundary. *Radiolithus orbiculatus*, on the other hand, is a secondary nannofossil event near the boundary of the BC20 and BC21 nannofossil zones. The undifferentiated zone is correlated to the NC6B–NC7A and CC7a–CC7b zones, and is considered Late Aptian in age.

**BC21 zone (Late Aptian)**

The zone includes the middle part of the mudstone unit (ms-unit) of the upper Chickabally Member, and is the interval between the *H. irregularis*–*R. orbiculatus*-containing sample and the LO of *F. varolii* (US-033; Fig. 9). Calcareous nannofossils are few to common and are poorly to moderately preserved. High nannofossil abundance characterizes the lower and upper parts of the zone (Fig. 6). Common species within the zone include *Biscutum* spp., *D. ignotus*, *F. varolii*, *R. asper*, *Watznaueria* spp., and *Zeugrhabdotus* spp. The FO of *Rhagodiscus achlyostaurion* is an important supplementary event recognized in the upper part of the zone (same level as the LO of *F. varolii*). This bioevent is used to separate the NC7B and 7C subzones of Bralower et al. (1995), and is present within the upper part of the CC7b subzone of Perch-Nielsen (1985). The BC21 zone therefore is correlated to the NC7A–NC7B and CC7b subzones, and is considered as Late Aptian in age.

**BC22 zone (latest Aptian to earliest Albian)**

The zone is the interval from the LO of *F. varolii* to the FO of *Prediscosphaera columnata* (US-020), within the upper Chickabally Member (Fig. 9). This zone is correlated to the NC7C and uppermost CC7b subzones, which are both assigned to the uppermost Aptian. Since the Aptian–Albian (A–A) boundary is delineated just below the FO of *P. columnata* in the Tethyan and Boreal regions (e.g. Bown et al. 1998; Gradstein et al. 2004), the age of this zone is considered in this study to be
from the latest Aptian to the earliest Albian. Mutterlose et al. (2003) in their study of the Vohrum section in northwest Germany, however, find the use of *Prediscosphaera* unsuitable as a marker for defining the A–A boundary since the FO of *P. columnata* is rare in the sections they investigated (see discussion on stage boundaries).

**BC23–BC24 undifferentiated zone (Early to Middle Albian)**

The zone is the interval from the FO of *P. columnata* to the FO of *Azopodorhabdus albianus* (US-041), within the upper part of the *ms*-unit and the lower part of the *ss*-unit of the upper Chickabally Member (Fig. 9). Calcareous nanofossils are rare to few in abundance and mostly composed of *D. ignotus* and species of *Biscutum* and *Watznaueria*. Other bioevents within the zone are the FOs of *Hayesites albiensis* and *Tranolithus orionatus*. The FO of *H. albiensis* defines the boundary between the NC8A and 8B subzones of Bralower et al. (1995). In the studied section, the FO of *H. albiensis* was recorded in sample US-016, below a sandstone bed and near the boundary between the *ms* and *ss* units of the upper Chickabally Member (Figs 3,9). The FO of *T. orionatus*, on the other hand, is used to define the boundary between the BC23 and BC24 zones and between the NC8B–8C and CC8a–8b subzones (Fig. 5). The FO of *T. orionatus*, in addition, appears close to the Early–Middle Albian boundary (Bown et al. 1998; Gradstein et al. 2004). In the North Fork Cottonwood Creek section, however, this datum has been recorded together with the FO of *A. albianus*, above a prominent massive sandy mudstone bed at the base of the *ss*-unit (Figs 3,9). The BC23–BC24 undifferentiated zone corresponds to the NC8 zone and CC8a–8b subzones, and is considered Early–Middle Albian in age.

**BC25–BC26 undifferentiated zone (Middle to Late Albian)**

The zone is the interval from the FO of *A. albianus* to the FO of *Eiffellithus turriseiffelii* (US-046), within the *ss*-unit of the upper Chickabally Member (Fig. 9). Species diversity and nanofossil abundance are high in this zone (Fig. 6). Commonly occurring species are *D. ignotus*, *F. oblongus*, *Repagulum parvidentatum*, *Sericobiscutum gaultensis*, and species of *Biscutum*, *Corollithion*, *Prediscosphaera*, *Rhagodiscus*, *Watznaueria*, and *Zeugrhabdotus*. The uppermost occurrence of the local range of *H. albiensis* was observed within the zone (US-019a). The LO of *H. albiensis* is placed at higher stratigraphic levels in standard sections, at the base of the BC27b–UC0b subzone, within the NC10A subzone of Bralower et al. (1995) and at the boundary between the CC9a and 9b subzones of Perch-Nielsen (1985; Fig. 5). The undifferentiated zone is considered in this study as Middle–Late Albian in age and corresponds to the NC9 zone and the upper part of the CC8b subzone.

**BC27–UC0 zone (Late Albian to Early Cenomanian)**

This zone is the interval from the FO of *E. turriseiffelii* to the FO of *Corollithion kennedyi* (US-058; Fig. 9), and includes samples from the upper Chickabally Member, Bald Hills Member, and the lowermost part of the Gas Point Member. Commonly occurring species are *D. ignotus*, *T. orionatus*, and species of *Biscutum*, *Watznaueria*, and *Zeugrhabdotus*. The zone is correlated to the NC10A and CC9a–9b subzones, and is considered Late Albian to Early Cenomanian in age.

**UC1a–UC1d undifferentiated zone (Early Cenomanian)**

This zone is the interval from the FO of *C. kennedyi* to the FO of *Prediscosphaera cretacea* (US-074), and occurs in the lower part of the Gas Point Member (Fig. 9). The undifferentiated zone is slightly modified from the UC1a–UC1d subzones of Burnett et al. (1998). The FO of *P. cretacea*, which is used as the upper boundary of the zone in the present study, is an event recognized within the UC1d subzone in South England. Calcareous nanofossils are rare to few, and are mostly composed of *D. ignotus*, *Retecapsa crenulata*, *T. orionatus*, and species of *Biscutum*, *Corollithion*, *Eiffellithus*, *Helicolithus*, *Prediscosphaera*, *Rhagodiscus*, *Staurolithites*, *Watznaueria*, and *Zeugrhabdotus*. Based on the FO of *C. kennedyi*, this interval can be correlated to the NC10B and CC9c subzones. The correlation of the upper boundary with the standard Tethyan zonation schemes, however, is difficult, since the FO of *P. cretacea* has not been used in the NC/CC zonation schemes. The age of the undifferentiated zone is considered in this study as Early Cenomanian.

**UC1d–UC3d undifferentiated zone (Early to Late Cenomanian)**

This zone is the interval from the FO of *P. cretacea* to the LO of *C. kennedyi* (US-063), within the lower part of the Gas Point Member (Fig. 9).
The LO of *C. kennedyi* is used as a boundary marker for the UC3d and 3e subzones. Calcareous nannofossils are generally abundant and are well preserved in this interval (Fig. 6). Commonly occurring species are the same as in the previous zone.

The stratigraphic position of the LO of *C. kennedyi* is uncertain in the NC and CC zonation schemes. Correlation between the UC zones and the NC/CC zones, however, can be achieved through the use of the FO of *Lithraphidites acutus* and the LO of *Gartnerago nanum*, neither of which were observed in the studied section. The FO of *L. acutus* is widely used as the zonal boundary between the UC2–UC3, CC9–CC10, and NC10–NC11 zones (Fig. 5). In the UC zonation scheme, the FO of *L. acutus* is placed above the FO of *P. cretacea*, while the LO of *G. nanum*, which defines the UC3c and 3d boundary, is located below the LO of *C. kennedyi*. The LO of *G. nanum* is placed within the upper CC10 zone by Perch-Nielsen (1979). The UC1d–UC3d undifferentiated zone therefore probably corresponds to the interval ranging from the upper part of the CC9c subzone to the lower part of the CC10a subzone. Although the LO of *G. nanum* is not considered a bioevent in the NC zonation scheme, hence the difficulty in the correlation between the UC and NC zones, the undifferentiated zone is probably correlated to the interval from the upper part of the NC10 zone to the lower part of the NC11 zone. The age of the undifferentiated zone is considered in this study as Early–Late Cenomanian.

**UC5c–UC6a undifferentiated zone (Early Turonian)**

This zone is the interval from the FO of *E. octopetalus* to the FO of *E. moratus* (US-088), within the Gas Point Member (Fig. 9). Calcareous nannofossil abundance and diversity values are low and specimens are poorly preserved (Fig. 6). Commonly occurring taxa include *B. constans*, *D. ignotus*, and *Zeugrhabdotus* spp. The zone is considered Early Turonian in age.

**UC6b zone (Early Turonian)**

This interval ranges from the FO of *E. moratus* to the FO of *Quadrum gartneri* (US-091), and occurs within the Gas Point Member (Fig. 9). Compared to the previous zones, calcareous nannofossils are abundant and the preservation is good (Fig. 6). Commonly occurring taxa include *T. orionatus* and species of *Biscutum*, *Calculites*, *Corollithion*, *Eprolithus*, *Prediscosphaera*, *Retecapsa*, *Rhagodiscus*, *Staurolithites*, *Watznaueria*, and *Zeugrhabdotus*. Three bioevents are recognized within the interval: (i) FO of *Helicolithus turonicus* (US-089); (ii) FO of *R. achlyostaurion* (US-089); and (iii) FO of *R. asper* (US-090; Fig. 9). The sequence in which these events were recognized in the studied section is similar to the North Sea zonal scheme of Mortimer (1987). All bioevents occur prior to the FO of *Q. gartneri*.

Using the FO of *Q. gartneri*, the UC6b zone can be correlated to the CC10b subzone. The LO of *R. asper* is used as an upper boundary marker of the IC52 zone of Bralower et al. (1995). The IC52 zone is correlated to the upper part of the NC12 zone (=*Effellithus eximius* subzone of Bralower et al. 1995). In the studied section, the LO of *R. asper* is located just below the FO of *Q. gartneri*. The UC6b zone therefore can be correlated to the NC12 zone.

The age of the zone is considered in this study as Early Turonian. It is important to note,
however, that in earlier studies, the FO of *Q. gartneri* is frequently used as a post Cenomanian–Turonian (C–T) boundary marker (e.g. Tsikos et al. 2004; Kolonic et al. 2005; see discussion on stage boundaries).

**UC7 zone (Early to Middle Turonian)**

The lower and upper boundaries of the zone are defined by the FO of *Q. gartneri* and the FO of *E. eximius* (US-092; Fig. 9). The calcareous nannofossil assemblage is similar to the previous zone. The short duration of the UC7 zone could be due to the presence of condensed parts within the interval in the North Fork Cottonwood Creek section. The lower and upper boundary markers are both recognized in Tethyan and Boreal regions (Fig. 5; Roth 1978; Perch-Nielsen 1979, 1985; Luciani & Cobianchi 1999). The zone corresponds to the CC11 and NC13–NC14 zones, and is considered Early–Middle Turonian in age.

**UC8 zone (Middle Turonian)**

The zone is the interval from the FO of *E. eximius* to the uppermost sample (US-200) of the Gas Point Member in the investigated section (Figs 3, 9). Calcareous nannofossils are few to common, comprised mainly of *T. orionatus*, *D. ignotus*, and species of *Effelliithus*, *Eproolithus*, *Prediscosphaera*, *Watznaueria*, and *Zeugrabdota*. The observation of the lowermost and uppermost occurrences of *Kampptnerius magnificus* (US-097) and *E. octopetalus* (US-098), respectively, within the interval suggests correspondence to the UC8 zone of Burnett et al. (1998). The former taxon occurs within the UC8a subzone, while the latter occurs within the UC8b subzone in northern Europe (Burnett et al. 1998). Because of the poor preservation and rare to few occurrences of nannofossils in the interval, however, the interval can not be subdivided into subzones. Nevertheless, using these supplementary bioevents, the interval can be correlated to the CC12 and NC14 zones, and is considered Middle Turonian in age.

**DISCUSSION**

**CORRELATION WITH AMMONITE ZONES AND GEOLOGICAL AGE OF BUDDEN CANYON FORMATION IN THE NORTH FORK COTTONWOOD CREEK SECTION**

In the North Fork Cottonwood Creek section, several age-indicative ammonite taxa were collected from the Ogo to upper Chickabally Members. The biostratigraphic ranges of these ammonites, along with previously established ammonite zones in the study area, are generally in good agreement with the established nannofossil zonation in the studied section. This suggests that the North Fork Cottonwood Creek section of the BCF, like the Dry Creek section in Tehama County, may also provide information on zonal correlation between macro- and microfossils in the North Pacific region.

In the lowermost nannofossil zone established in the present study, ammonites belonging to the genera *Crioceratites* (Rodda & Murphy 1987) and *Shasticrioceras* (*S. patricki*) were collected, suggesting Hauterivian–Early Barremian and Early to Late Barremian ages for the Ogo and Roaring River Members, respectively. The ages are similar to those proposed by Murphy et al. (1969). The Ogo and lower Chickabally Members, on the other hand, correspond to the *Simbirsrites* (*Hollisites*) *aguila* and *Shasticrioceras poniente* zones, which are both considered Barremian in age, although the *S. poniente* zone could also partially include the Lower Aptian samples below the Huling Sandstone Member (Murphy 1969, 1975).

The nannofossil-derived Late Barremian to Early Aptian age of the lower Chickabally Member is further supported by the reported presence of the Late Barremian ammonites *Heinzia*, *Heteroceras*, and *Lytoceras phestus* and the Late Barremian–Early Aptian ammonites *Toxoceratoideas* spp. near the top of the lower Chickabally Member (approximately the top of the BC16–BC17 undifferentiated zone; Murphy 1956, 1975).

The assignment of the Huling Sandstone Member to the BC18 nannofossil zone (Early–Late Aptian) is supported by the observation of the Late Aptian ammonites *Eotetragonites wintunius* and *Parahoplites* spp. near the base of the member. Murphy (1956), in addition, reported the ammonites *Tropeum parcostatum*, *Phylloceras onoense*, and *E. wintunius*, which are all suggestive of the Aptian *E. wintunius* zone, within the Huling Sandstone Member. Following the suggestion of Murphy (1975), the Huling Sandstone Member is considered in the present study as Late Aptian in age.

The Late Aptian to Late Albian age (BC21 to BC26 zones) of the upper Chickabally Member based on calcareous nannofossils is also consistent with the Aptian to Albian age suggested by ammonites. According to Murphy (1956) and Murphy
et al. (1969), the ammonite zones Acanthohoplites gardneri to Mortoniceras hulenanum zones occur within the upper Chickabally Member. Within the BC21 nannofossil zone, A. gardneri and A. reesidei were collected. Both ammonite taxa are considered as Middle to Late Aptian in age (Popenoe et al. 1960; Murphy et al. 1969; Dailey 1973). In the BC23–BC24 undifferentiated zone, the Early Albian ammonite Leconteites lecontei and the Middle Albian Douvilleiceras mammillatatum were collected near the base and in the middle part of the interval, respectively. Murphy (1956), in addition, observed D. cf. D. mammillatum in the lowermost Albian L. lecontei zone within the upper Chickabally Member. Within the Middle to Upper Albian BC25–BC26 undifferentiated zone, the ammonite taxa Oxytriplioceras packardi (Middle Albian) and Mortoniceras rostratum (Upper Albian) were collected.

The Bald Hills and Gas Point Members, based on calcareous nannofossils, are considered Late Albian–Early Cenomanian and Early Cenomanian–Middle Turonian in age, respectively.

MAGNETOSTRATIGRAPHIC INTERPRETATION

Four reversed magnetic polarity zones were observed from the Ogo Member to the upper Chickabally Member interval (Fig. 10). The lowest three are found below the Huling Sandstone Member at the following levels, in ascending order: (i) lowermost Ogo Member; (ii) Ogo Member and Roaring River Member boundary interval; and (iii) Roaring River Member and lower Chickabally Member boundary interval. The reversed polarity interval recognized above the Huling Sandstone Member, on the other hand, occurs within the lower part of the upper Chickabally Member (Fig. 10). The interval containing the three reversed polarity zones below the Huling Sandstone Member is Hauterivian to Barremian in age. Comparison of the sample distribution maps of Rodda and Murphy (1987) and the present study suggests that Crioceratites sp. was collected within the lowest reversed polarity zone in the Ogo Member. Using this information, the reversed polarity zone within the Ogo Member can be considered as M5r. Consequently, the upper two reversed polarity zones within the Lower and Upper Barremian can be correlated to the M3r and M1r polarity zones, respectively (Fig. 10).

The reversed polarity zone recognized within the lower part of the upper Chickabally Member, on the other hand, occurs above the FOs of H. irregularis and R. orbiculatus, within the BC21 zone (Figs 9,10). In terms of planktonic foraminiferal biostratigraphy, the polarity zone occurs within the G. algerianus zone, suggesting a Late Aptian age. The reversed polarity zone therefore could be correlated to the M-1r zone of the standard GPTS (Gradstein et al. 2004). It should be noted that although the B–A boundary has been delineated and approximated below the Huling Sandstone Member, the M0r polarity zone appears to be missing in the North Fork Cottonwood Creek section. The possibility that the reversed polarity zone above the Huling Sandstone is correlated to the M0r polarity zone, however, is very low, since based on ammonite and nannofossil biostratigraphy (discussed in the previous section) as well as earlier studies in the area, it appears that the uppermost Barremian to Lower Aptian interval is not represented in the stratigraphic record. This could be due to the possible erosion of the uppermost Barremian to Lower Aptian sediments during the deposition of the Huling Sandstone Member (see Hauterivian-Barremian and Barremian-Aptian boundaries and Possible Hiatus Levels).

STAGE BOUNDARIES IN BUDDEN CANYON FORMATION

Hauterivian–Barremian and Barremian–Aptian boundaries

In standard integrated time scales (i.e. Channell et al. 1995; Gradstein et al. 1995; 2004; Erba 1996), the Hauterivian–Barremian (H–B) and Barremian–Aptian (B–A) boundaries are placed at the uppermost M5 polarity zone and at the base of the M0r polarity zone, respectively (Fig. 5). Based on the combined nannofossil and ammonite biosтратigraphy and magnetostratigraphy, the H–B boundary was delineated in the uppermost part of the Ogo Member. The Lower–Upper Barremian boundary, on the other hand, was delineated in the lowermost part of the Roaring River Member; at the top of the M3r polarity zone (Figs 9,10).

In conjunction with magnetostratigraphy, a number of nannofossil events have also been used as B–A boundary markers: H. irregularis (Thierstein 1976), Chiastozygus litterarius (Mutterlose 1991), and R. gallagheri (Bown et al. 1998). Bralower et al. (1994) defined the base of the NC6 nannofossil zone (i.e. the B–A boundary) using the FO of H. irregularis. In the same paper, the FO of F. oblongus, which we are using in the present study to approximate the B–A boundary, is located below the FO of H. irregularis. This succession is similar
to that of the Tethyan nannofossil zonation scheme of Bown et al. (1998). In the paper of Bralower et al. (1995), the FO of *F. oblongus* was used as the base of the NC5E zone, which is within the Upper Barremian.

As mentioned earlier in the paper, the base of the BC18 zone of Bown et al. (1998), that is the B-A boundary, is defined by the FO of *R. gallagheri*. In the North Fork Cottonwood Creek section, however, typical specimens and forms similar to *R. gallagheri* were observed in the uppermost part of the Roaring River Member, which is considered in this study as Early to Late Barremian in age. In addition, the FO of *H. irregularis* was observed above the Huling Sandstone Member, which is Late Aptian in age based on previous and more recent ammonite biostratigraphic studies. The FO of *H. irregularis* was also observed between the range of *F. varolii*, which is a Lower–Upper Aptian marker in the Boreal scheme of Bown et al. (1998). The immediate occurrence of *F. varolii* above the Huling Sandstone Member suggests that the FO of *F. varolii* in the North Fork Cottonwood Creek section may not represent the true range of the taxon. This difference in the stratigraphic occurrence of the taxon in the North Fork Cottonwood Creek section and in other sections can be due to a number of factors such as poor preservation and difference in the paleogeographic positions of the study areas.

The FO of *H. irregularis* is often used as a B–A boundary marker in low latitude regions. However, it is not reported in high latitude sites (e.g. DSDP Sites 511 and 763, Bralower et al. 1994). Channell et al. (1995) illustrated (Fig. 8) the absence of *H. irregularis* above the FO of *C. litterarius* in the Great Valley Group, although Bralower et al. (1994) observed *H. irregularis* in two DSDP Sites in the Central Pacific (DSDP Sites 167 and 463). Bralower et al. (1994) observed that the FOs of *H. irregularis* and *F. oblongus* coincide at the same level in DSDP Site 167. With these observations and problems concerning *H. irregularis* and *R. gallagheri*, the use of the FO of *F. oblongus* to approximate the B–A boundary in the North Fork Cottonwood Creek section is more or less justified. In the Boreal scheme of Bown et al. (1998), the FO of *F. oblongus* is a supplementary datum within the BC18 zone (Early Aptian), above the FO of *R. gallagheri* (Fig. 5). The FO of *F. oblongus* is slightly older than the FO of *H. irregularis* and is younger than the FO of *C. litterarius* in northwestern Europe (Erba 1996). The occurrence of the Early Aptian genus *Toxoceratoides* near the top of the lower Chicka-
bally Member further supports the placement of the B–A boundary in the section.

**Aptian–Albian boundary**

The Aptian–Albian (A–A) boundary in the studied section was delineated using the FO of *P. columnata* near the uppermost part of the ms-unit of the upper Chickabally Member (Fig. 9). The FO of *P. columnata* is considered a marker for the A–A boundary (Fig. 5) and has already been recognized in the Vocontian Basin, southern France (e.g., Bréhéret et al. 1986; Hart et al. 1996; Kennedy et al. 2000). In northwestern Germany, however, the FO of *P. columnata* appears within the lowermost Albian ammonite zone (*L. tardefurcata* zone; Mutterlose 1992; Bown et al. 1998), implying difficulty in using the taxon as a marker for the A–A boundary, which was discussed by Mutterlose et al. (2003). The problem arises mainly from the varying taxonomic concepts of the species belonging to the genus by different workers. It is already widely known that early species of *Prediscospheara* appeared during the Early Aptian are represented by the elliptical *P. spinosa*, followed by the more circular forms above the A–A boundary, which are represented by *P. columnata* (Perch-Nielsen 1979; Mutterlose 1996 in Mutterlose et al. 2003). According to Bown (in Kennedy et al. 2000), the transition from elliptical to circular forms appears to be gradual, thus the difficulty in using the FO of *P. columnata* as a reliable marker for the A–A boundary. In the North Fork Cottonwood Creek section, the identified specimens of *P. columnata* are more or less circular in morphology as opposed to the other species of *Prediscospheara* encountered in the samples (e.g., *P. cretacea*, *P. quasispinosa*, and *P. spinosa*; Fig. 8).

In terms of ammonite biostratigraphy, the A–A boundary is delineated using the FOs of *Leymeriella tardefurcata* and the genus *Dowvilleiceras*, or by the LO of *Hypacanthoplites jacobi* (Bréhéret et al. 1986; Hart et al. 1996). In the study area, *Dowvilleiceras* was observed near the lower part of the ss-unit of the upper Chickabally Member, within the Early Albian *Leconteites lecontei* Zone (Murphy 1956). The A–A boundary as determined by nannofossil biostratigraphy therefore appears to be stratigraphically lower than the boundary determined by previous ammonite studies. A more recent ammonite study by Amédro and Robaszynski (2005) in the North Fork Cottonwood Creek, on the other hand, delineated the A–A boundary approximately 80 m below the nannofossil-derived A–A boundary.

Following previous studies on ammonites (e.g., Murphy 1975), the Early–Late Aptian boundary is placed near the base of the Huling Sandstone Member (Fig. 9). Delineation of the Early–Middle–Late Albian boundaries using calcareous nannofossils, on the other hand, is problematic as several marker taxa were not observed in the section. The FO of *A. albianus* was used to approximate the Middle–Late Albian boundary (Figs 5, 9; Bralower *et al.* 1995; Bown et al. 1998; Gradstein et al. 2004). Amédro and Robaszynski (2005) used the base of the *Oxytropidoceras Pachardi zone* as the Early–Middle Albian boundary and the base of the *Dowvilleiceras cristatum zone* as the Middle–Late Albian boundary. The former corresponds to the lower part of section IV of the present study and is more or less consistent with the delineated Early–Middle Albian boundary using calcareous nannofossils (Figs 3, 9). The base of the *D. cristatum zone*, unfortunately, was not recognized in the North Fork Cottonwood Creek section (Amédro & Robaszynski 2005).

**Albian–Cenomanian boundary**

Using the FOs of *E. turriseiffelii* and *C. kennedyi*, the Albian–Cenomanian (A–C) boundary was delineated within the Bald Hills Member, consistent with results from the nearby Dry Creek section and subsequently collected Albian ammonites of the genera *Mortoniceras* and *Lechites* in the lower beds of the Bald Hills Member (Murphy & Rodda 1996). The FO of *C. kennedyi* is widely used in both the Tethyan and Boreal zonal schemes, and has been used as a post boundary marker nannofossil taxon (Fig. 5; Perch-Nielsen 1979, 1985; Tröger & Kennedy 1996; Burnett *et al.* 1998). The sedimentation of the Bald Hills Member in the North Fork Cottonwood Creek is believed to have begun earlier than at Dry Creek (Amédro & Robaszynski 2005). This explains the observation of Murphy and Rodda (1996) in the Dry Creek section that the A–C boundary is constrained to a thin interval encompassing the base of the Bald Hills Member. This boundary was delineated using the LOs of the typical Albian genera *Mortoniceras* and *Stoliczkaia* and the entry of mantelliceratine juveniles (probably *Graysonites*) and *Mariella*.

**Cenomanian–Turonian boundary**

A number of calcareous nannofossil markers have been suggested to delineate the Cenomanian–
Turonian (C–T) boundary. These include the LOs of *L. acutus*, *A. albianus*, and *H. chiastia* and the FO of *Q. gartneri* (Fig. 5). These events have been recognized in Europe (England, Spain, southeastern France, Italy), North America, Jordan, and Africa (e.g. Bralower 1988; Jarvis et al. 1988; Lamolda et al. 1997; Luciani & Cobianchi 1999; Paul et al. 1999; Schulze et al. 2004; Fernando et al. 2010). The FO of *Q. gartneri* is considered important to the delineation of the C–T boundary. This event occurs within the *W. devonense* zone and above the carbon isotope excursion in Pueblo (Colorado). In the study of Bralower (1988), a nanofossil zonation scheme tied up with ammonite and foraminiferal zonations was established for the Western Interior Basin. This was supplemented by an informal scheme by Bralower and Bergen (1998) for the Cenomanian–Santonian interval. In these zonation schemes, the C–T boundary is delineated using the LO of *H. chiastia (=Microstaurus chiastus)* which also defines the boundary between the *Microstaurus chiastus* subzone (Late Cenomanian) and the *Eiffellithus eximius* subzone (Early Turonian). These two subzones comprise the *Rhagodiscus asper (=Parhabdolithus asper)* zone, which straddles the C–T boundary. The succession of bioevents across the C–T boundary was also determined in the Western Interior Basin. Above the LO of *H. chiastia*, the events include (from oldest to youngest): LO *R. asper*, LO *Cretarhabdus lori*ei, FO *E. octopetalus*, FO *Eprolithus eptapetalus*, and LO *E. octopetalus* (Bralower & Bergen 1998). Below the LO of *H. chiastia*, on the other hand, the bioevents (from oldest to youngest) are as follows: FO *Q. gartneri*, FO *Gartnerago segmentatum*, FO *Microhabdus decoratus*, LO *Gartnerago nanum*, LO *C. kennedyi*, FO *Corollithus exiguus*, LO *A. albianus*, LO *L. acutum*, and FO *E. eximius* (Bralower 1988). Not all of these bioevents are recognized in the North Fork Cottonwood Creek section. Moreover, in terms of the stratigraphic succession of bioevents between the two areas, several discrepancies can be observed. These include the earlier disappearance of *H. chiastia* and *A. albianus* (occurring below the LO of *C. kennedyi*), later appearance of *Q. gartneri*, G. *segmentatum*, and *E. eximius* (above the FO of *E. eptapetalus*) and later disappearance of *R. asper* (above the FO of *E. eptapetalus*). The early disappearance of *H. chiastia* in the North Fork Cottonwood Creek section is also the reason for delineating the C–T boundary near the FO of *E. octopetalus* (see discussion in the previous section). The differences observed between the Western Interior Basin and the North Fork Cottonwood Creek section can be attributed to differences in the paleogeographic position and depositional environment (i.e. epeiric sea vs forearc basin) that could have influenced the distribution, abundance, and preservation of calcareous nanofossils in the two areas during the Cenomanian–Turonian interval.

POSSIBLE HIATUS LEVELS

The occurrence of a widespread Early Cretaceous unconformity has already been documented in
northern California and Oregon Provinces (Peterson 1967). This unconformity corresponds to the lithological boundary between the lower Chickabally Member and the Huling Sandstone Member. The base of the Huling Sandstone consists of poorly sorted, relatively massive sandstones with minor amount of conglomerates (Murphy et al. 1964, 1969). The onset of the deposition of the sandstone member coincided with a sealevel drop during the earliest Aptian (Peterson 1967; Dailey 1973; Hardenbol et al. 1998; Gradstein et al. 2004), and was probably preceded by the erosion of a major portion of the Lower Aptian, resulting in the very short Lower Aptian interval in the section. This erosion could be the reason for the non-recognition of the M0r reversed polarity zone in the studied section (Fig. 10).

A possible hiatus could also be present within the Lower Albian interval, between the BC23–24 and BC25–26 undifferentiated zones. This possible hiatus is suggested by the co-occurrence of the two marker taxa T. orionatus and A. albianus above a prominent massive sandy mudstone bed at the base of the ss-unit in the upper Chickabally Member (Figs 3,9). The presence of this unconformity, however, is not supported by recent ammonite studies and previously conducted geological mapping in the study area (e.g. Amédro & Robaszynski 2005).

NANNOFOSSIL BIOPROVINCE IMPLICATIONS AND POSSIBLE OCEANIC ANOXIC EVENT

The development of the sedimentary basin along the coast of California coincided with an eastward transgression, triggered by the mid-Cretaceous global warming (Ojakangas 1968). The resulting expansion of the tropical to subtropical climate induced intense chemical weathering, resulting in the deposition of abundant clay materials in the basin (Ojakangas 1968). Sedimentation rates in the BCF are estimated in the present study to range from 15 to 54 mm/kyr during the Lower Cretaceous and 12 to 220 mm/kyr during the Upper Cretaceous. These values are comparable to the values estimated by Ojakangas (1968), which were 107 and 137 mm/kyr in the Lower and Upper Cretaceous, respectively.

The mid-Cretaceous global warming also affected the faunal and floral bioprovinces in the North Pacific region. Although the paleolatitude of northern California has been estimated to be located at about 40–50° latitude (e.g. Barron et al. 1981; Smith et al. 1994), the ammonite and nannofoossil assemblages contain many Tethyan features. The ammonites in the BCF consist mainly of widespread Pacific fauna, associated with some indigenous species in California and several typical Tethyan-diagnostic taxa, suggesting a temperate to Boreal bioprovince (Murphy 1956, 1969; Murphy & Rodda 1996). Calcareous nannofossils in the BCF, on the other hand, include some Boreal-diagnostic taxa, but mainly consist of Tethyan species, allowing recognition of Tethyan bioevents and correlation to Tethyan (low-latitude) zonation schemes possible. This is particularly evident for the Albian and younger units in the studied section. Global correlation of nannofossil zones between the Tethyan and Boreal realms, however, becomes difficult during the Barremian to Lower Aptian interval due to pronounced biogeographic separation of taxa and species diachronity (Bown et al. 1998; Street & Bown 2000). In the study area, this is evident in the presence of typical Boreal calcareous nannofossils such as N. inornatus and F. varolii in the lower part of the studied section, within the Barremian to Early Aptian interval (Figs 7,9). Both taxa have been reported in the North Sea and other Boreal sections, but not in Tethyan regions (Bown et al. 1998), suggesting that the nannofossil bioprovince in the BCF had been under the influence of cooler temperate to cold water conditions during the interval.

In the North Fork Cottonwood Creek section, nannoconids occur within the Late Barremian lower Chickabally Member (Fig. 9). Species belonging to the group include N. inconspicuus, N. inornatus, N. minutus, N. cf. N. steinmannii, and N. truitti truitti, although most of the nannoconids observed in the samples are narrow-canalled ‘discs’ 6–9.5 µm (average 7.6 µm) in diameter (Fig. 8). As mentioned earlier, two nannoconid abundance peaks were observed in the Upper Barremian. The first peak occurs within the M1r polarity zone, while the second occurs near the top of the lower Chickabally Member, below the Huling Sandstone Member and the FO of F. oblongus. The decline of nannoconids after the second peak in the studied section therefore could be related to the uppermost Barremian decline in nannoconid abundance prior to the ‘nannoconid crisis’ in the Early Aptian (Erba 1994, 2004; Erba et al. 2004; Erba & Tremolada 2004).

Compared with the Cretaceous sections in Europe, which are mostly composed of marl–limestone facies, the BCF is composed of monotonous gray to dark gray terrigenous mudstones and
sandstones. For this reason, lithological recognition of black shales on outcrop scale is difficult, and the presence of OAEs, not surprisingly, has not yet been reported in the BCF. Preliminary results, however, show distinct excursions in the total organic carbon (TOC) data between the UC3e–UC5c to UC5c–UC6a zones, across the C–T boundary (T. Tomosugi, unpubl. data, 2006; Fig. 6). This excursion in TOC, along with the drastic decline in nannofossil abundance across the C/T boundary, is believed to be correlated to the OAE2.

CONCLUSIONS

The work is summarized as follows.

1. The present study provides a mid-Cretaceous standard calcareous nannofossil biostratigraphy in the North Pacific region. Using the Boreal BC zonation scheme of Bown et al. (1998) for the Lower Cretaceous and the cosmopolitan UC zonation scheme of Burnett et al. (1998) for the Upper Cretaceous, 16 nannofossil zones were recognized in the North Fork Cottonwood Creek section of the BCF in Shasta County, northern California. The zones correspond to the BC15 and older zones to the UC8 zone, suggesting an age of Hauterivian to Middle Turonian, which is basically in good agreement with the ammonite biochronology of Murphy (1956, 1969).

2. The age of the members of the BCF in the present study using combined biostratigraphic and magnetostratigraphic data confirms the results of previous studies done in the area: (i) Ogo–Hauterivian to Lower Barremian; (ii) Roaring River–Upper Barremian; (iii) lower Chickabally–Upper Barremian to lowermost Aptian; (iv) Huling Sandstone–Upper Aptian; (v) upper Chickabally–Upper Aptian to Upper Albian; (vi) Bald Hills–Upper Albian to Lower Cenomanian; and (vii) Gas Point–Lower Cenomanian to Middle Turonian.

3. Stage boundaries were likewise established in the North Fork Cottonwood Creek section. The H–B and Lower–Upper Barremian boundaries were placed in the uppermost M5 and M3r polarity zones, near the upper part of the Ogo Member and the lowermost portion of the Roaring River Member, respectively. The B–A boundary, on the other hand, was placed at the topmost portion of the lower Chickabally Member. The A–A, A–C, and C–T boundaries were delineated within the upper Chickabally Member, at the top of the Bald Hills Member and within the Gas Point Member.

4. An unconformity is documented in the studied section, represented by the base of the Huling Sandstone Member. This could have resulted in the erosion of a portion of the Lower Aptian, and probably the interval containing the M0r reversed polarity zone, and thus its non-recognition in the studied section. A second unconformity is postulated at the base of the 8s-unit of the upper Chickabally Member (Lower Albian), between the BC23–24 and BC25–26 undifferentiated zones.

5. The nannofossil assemblage in the North Fork Cottonwood Creek suggests that the study area was under the influence of cold water conditions during the Barremian to Lower Aptian interval. During the Albian to Turonian interval, however, the assemblage is dominated by Tethyan taxa, probably resulting from the mid-Cretaceous global warming.

6. The presence of OAEs has not yet been reported in northern California. Preliminary TOC and δ13C isotope data, however, show that the global C–T boundary OAE2 can be present in the studied section.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Table S1 Calcareous nannofossil distribution in the North Fork Cottonwood Creek section. Bibliographic references can be found in Perch-Nielsen (1985) and Bown (1998, 2005). Two new calcareous nannofossil species were described by Fernando and Okada (2007) in the North Fork Cottonwood Creek section of the Budden Canyon Formation: Diloma californica and Prediscosphaera quasispinosa.

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