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Integration of macrofossil biostratigraphy and magnetostratigraphy for the Pacific Coast Upper Cretaceous (Campanian– Maastrichtian) of North America and implications for correlation with the Western Interior and Tethys

Peter D. Ward^{1,†}, James W. Haggart^{2,†}, Ross Mitchell^{3,†}, Joseph L. Kirschvink^{4,†}, and Thomas Tobin¹

¹Department of Earth and Space Sciences, The University of Washington, Seattle, Washington 98195, USA ²Geological Survey of Canada, 625 Robson Street, Vancouver, British Columbia V6B 5J3, Canada ³Geology and Geophysics Department, Yale University, P.O. Box 208109, New Haven, Connecticut 06520-8109, USA ⁴Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California 91125, USA

ABSTRACT

New biostratigraphic data obtained from measured stratigraphic sections of Santonian through Maastrichtian age located along the west coast of North America necessitate changes to the currently accepted chronostratigraphic framework for this region of the North Pacific biotic province. We recognize and/or define 12 molluscan zones over this interval of the Upper Cretaceous and propose revisions to the currently accepted integration of ammonite zones with global Upper Cretaceous magnetochrons. Our findings demonstrate that there was significantly more faunal interchange between the North American Pacific Coast and both the Western Interior and Gulf Coast regions of North America during the Late Cretaceous than has previously been recognized, and because of this, novel and direct biostratigraphic correlations can be made. These new faunal correlations are augmented with the magnetostratigraphic record from Pacific Coast localities to arrive at better interregional correlation for the Upper Cretaceous globally. The new integration of the global polarity time scale with the local, west coast ammonite zonation now allows better correlation between sections both within the North Pacific province (but geographically far from our study areas) as well as to sections outside of the province itself. However, we note here that previous correlations between biostratigraphy and the top and bottom of magnetochron 33r in west coast

North American sections appear to have been in error due to unrecognized, modern-day normal-field overprint of originally reversed polarity in Upper Cretaceous sections. We reinterpret the position of this chron based on this new information.

INTRODUCTION

The Late Cretaceous world, during the Cenomanian through Maastrichtian ages, was geographically composed of a large Pacific Ocean, a still-opening Atlantic Ocean, and a relict but still important Tethyan region. Various marine biogeographic provinces have been defined for this time interval (Matsumoto, 1959a; Jeletzky, 1971; Klinger and Kennedy, 2001), based on faunal and floral differences in both microand macrofossil assemblages. The existence of what has appeared to be separate and distinct faunas within these regions during this interval has, in no small way, negatively impacted the definition of a worldwide late Mesozoic chronostratigraphy. The supposedly high degree of faunal endemism among the most important biostratigraphic markers (ammonites and planktonic foraminifera) has required other correlation tools to be brought to bear on the problem (Sugarman et al., 1995; Hardenbol et al., 1998), including radiometric dating, magnetostratigraphy, sea-level analysis, and various methods of chemostratigraphy. In some regions, such as the Western Interior and Gulf Coast regions of the United States and the Tethyan and Boreal shelf regions of Europe, integration of fossil biostratigraphy with these other methods has resulted in highly refined time scales. Unfortunately, such high resolution is not yet available for many other regions of the Cretaceous Earth,

in particular, the Pacific Coast of North America, which is part of the vast North Pacific biotic province, extending from western North America around the circum–North Pacific through East Asia (Jeletzky, 1971; Kauffman, 1973).

It has long been accepted that, of the North American Pacific Coast Upper Cretaceous ammonite taxa, only a few species are also found in contemporaneous Western Interior, Gulf Coast, or Tethyan regions (Jeletzky, 1971), and that those taxa that do co-occur are typically nondiagnostic, long-ranging species (Matsumoto, 1959a). Among the few exceptions are Nostoceras hornbyense, found in Angola (Howarth, 1965), and, more recently, the identification of the Pacific Coast zonal indices Neodesmoceras catarinae and Pachydiscus hornbyense (diagnostic of the Upper Campanian on the west coast) in the Upper Campanian of the Western Interior (Kennedy and Cobban, 1999). In this latter paper, it was also mentioned that there were ammonites characteristic of the Gulf Coast and Western Interior that had not previously been found along the Pacific Coast as well, and we expand upon this observation in the following section.

To better refine the current chronostratigraphy of the North American west coast Upper Cretaceous, we conducted new macrofossil collection efforts from both classic and new localities up and down the coast (Fig. 1), and then compared these fossils and their ranges to both the currently understood ranges as well as to selected index fossils diagnostic of the Western Interior and Gulf Coast regions. Our results show that the west coast ammonite faunas share more chronostratigraphically diagnostic species with the Western Interior, the Gulf Coast, and the Tethyan parts of Europe than previously

[†]E-mails: argo@u.washington.edu; jhaggart@ nrcan.gc.ca; ross.mitchell@yale.edu; kirschvink@ caltech.edu

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Figure 1. Map showing locations of stratigraphic sections of Upper Cretaceous strata along the Pacific Coast of North America discussed in this study. Sections derive from three major basins, schematically outlined and labeled. Numbered locations refer to localities discussed in text.

recognized, and that current biostratigraphic zonal correlations of the west coast to the magnetostratigraphic reversal record must be amended in light of this new information.

Previous Work on North Pacific Biostratigraphy and Magnetostratigraphy

The biostratigraphic framework for Campanian-Maastrichtian shelf strata of the Pacific Coast, based on macrofossils, was put on a modern footing through the work of Matsumoto (1959a, 1959b, 1960). Significant revisions and modifications to the framework were subsequently made by Jeletzky (1970), Almgren (1973), Sliter (1973, 1979), Ward (1978a, 1978b), Ward and Haggart (1981), Haggart (1984, 1991a, 1991b), Haggart and Ward (1984, 1989), Saul (1988), Elder and Saul (1996), Squires and Saul (2001), and Haggart et al. (2005, 2009). A summary of the presently accepted succession of standard biostratigraphic zones for the Santonian-Maastrichtian part of the west coast Upper Cretaceous is presented in Table 1. However, as noted in the Introduction, there has been little success at high-resolution correlation of the various micro- and macrofossil zones to other provinces. Thus, other chronostratigraphic tools have been brought to bear, and for the west coast Upper Cretaceous, this has mainly been through correlation of biostratigraphic zones to the global polarity time scale (GPTS; Fig. 2).

The chron pattern recognized for the Campanian through Maastrichtian is composed of both shorter and longer reversals, and it has aspects making it especially useful for global correlation. As shown in Figure 2, the currently accepted GPTS for Late Cretaceous time has, in its lower portion, the "Cretaceous Long Normal," a 36 m.y. period of time lacking magnetic reversals that ranges from near the end of the Lower Cretaceous to near the base of the Campanian stage. The first reversed polarity interval after the Cretaceous Long Normal (designated C33r) is itself of relatively long duration (estimated at 4 m.y. by Cande and Kent, 1992) compared to the average longevity of most reversals of the preceding Jurassic and Lower Cretaceous, which average less than a million years in length

TABLE 1. CURRENTLY ACCEPTED "STANDARD ZONES" FOR UPPERMOST CRETACEOUS STRATA, NORTHEAST PACIFIC REGION

Stage	Zonal name	Other diagnostic ammonites			
Upper Maastrichtian					
Lower Maastrichtian	Pachydiscus catarinae	Baculites Iomaensis			
Upper Campanian	Nostoceras hornbyense Metaplacenticeras cf. pacificum subzone	Baculites occidentalis Baculites rex			
Lower Campanian	Hoplitoplacenticeras vancouverense Baculites chicoensis	Baculites inornatus, Canadoceras newberryanum Submortoniceras chicoense, Canadoceras newberryanum			
Santonian	Sphenoceramus schmidti Eubostrychoceras elongatum	Canadoceras yokoyamai Glyptoxoceras subcompressum			
Note: From Jeletzky (1970), Ward (1978a), Haggart et al. (2009), and Matsumoto (1959b; for the Maastrichtian).					

(based on data from the International Committee on Stratigraphy [ICS] Geological Time Scale, 2006). C33r is followed by an even longer interval of normal polarity, C33n. Shorter magnetochron durations are not observed until near the end of the Campanian. Because it appears



Figure 2. Current global polarity time scale (GPTS; absolute ages after Gradstein et al., 2004).

after the Cretaceous Long Normal, and because it is itself succeeded by a relatively long normal interval, the C33r magnetochron is more readily, and unambiguously, identified than succeeding intervals of reversed polarity, and it is thus potentially of high value as a correlation tool.

The application of magnetostratigraphy as a correlation tool in the Upper Cretaceous of the North Pacific biotic province was first undertaken by Ward et al. (1983), who used it for interregional correlation of Pacific Coast strata, identifying C33r at several localities in northern California. This was followed shortly thereafter by work by Fry et al. (1985) and Bannon et al. (1989), who both recognized this same magnetochron in southern California, and by Verosub et al. (1989), who undertook an expanded study of the magnetostratigraphy of the Sacramento Valley of California. Importantly, Bannon et al. (1989) also first identified C32r, of late Campanian age, in southern California, while Filmer and Kirschvink (1989), who conducted magnetic sampling from the Punta San Jose section of the Rosario Formation in Baja California, recovered normal polarity at one of their sites, the thick section at Punta San Jose, as well as reversed directions from Punta Banda in Baja California. Ward et al. (1997) subsequently identified reversed magnetochrons in Campanian rocks of the Nanaimo Group on Hornby Island and Texada Island, British Columbia, correlating them to C32r and C33r, respectively. Most recently, Enkin et al. (2001) added new information about the magnetostratigraphic record from various localities in the Nanaimo Group, and Haggart et al. (2009) then extended this work to Queen Charlotte Islands, British Columbia.

Since first identified by pioneering work on the pelagic limestones of the Scaglia Rossa in Italy (Lowrie and Alvarez, 1977), C33r has been depicted on virtually every correlation chart and GPTS as reversed polarity over its entire length, as in Figure 2. However, examination of the primary data sampled over this interval at several localities-especially those with rapid sediment accumulation rates-suggests the presence of a short interval of normal polarity within C33r. In the Pierre Shale of the North American Western Interior, high-quality paleomagnetic data, with the prospect of radiometric control, depict normal polarity not far beneath the definitive, reproducible C33r-C33n reversal (Mitchell et al., 2006). This normal polarity subchron within C33r has also been seen in paleomagnetic data from the English Chalk (Montgomery et al., 1998) and deep-sea sediments. The subchron is also permitted by a "similar zone of [paleomagnetic directional] disturbance" and sampling gap in both the classic Gubbio and Moria sections in Italy (Lowrie and Alvarez, 1977; Alvarez and

Lowrie, 1978), and is consistent with the C33r.a "tiny wiggles" noted in marine magnetic records of this age (Bouligand et al., 2006). At the present time, we are unable to assess the validity of this possibility, but we note that the strata preserved along west coast North America may provide a rigorous test of its existence, with further magnetostratigraphic sampling in several of the sections discussed later herein.

MATERIALS AND METHODS

Stratigraphic analysis was undertaken at eight different localities along the Pacific Coast of North America (Fig. 1), where each locality included one or more measured stratigraphic sections. Some of these localities, such as Big Chico Creek in northern California and Sucia Island in Washington State, are classic localities that have a long history of collection and study. Others, such as Punta San Jose and San Antonio del Mar, both in Baja California, have not previously been reported in detail in the scientific literature.

Four types of data are described in this paper: (1) measured stratigraphic sections; (2) biostratigraphic range data (first appearance datums [FADs] and last appearance datums [LADs]) of key ammonite species; (3) the previously published magnetic polarity record (normal, reversed, or mixed signal) of the various measured sections; and (4) ⁸⁷Sr/⁸⁶Sr data previously reported in graduate theses from the University of Washington for four of the sections referred to in this paper, but not previously published. The ranges of Santonian–Maastrichtian ammonites presented here have been compiled through new collection and/or analysis of museum collections.

All biostratigraphic zones referred to in this paper will be given their full name on first usage, and then for brevity will be referred to by the species name only, following Jeletzky (1970). We have organized the data presented here in temporal order, starting with oldest first. We also follow Western Interior usage in recognizing Lower, Middle, and Upper Campanian subdivisions.

RESULTS

Guinda and Forbes Formations, Western Sacramento Valley, California (Santonian– Middle Campanian) (Fig. 1, Locality 1)

The ammonite-rich sections found in the Rumsey Hills, along the western flank of the Sacramento Valley of California, have provided the longest continuous section that has been sampled for both biostratigraphy and magnetostratigraphy for the interval from the Santonian through the Lower Campanian. Within the

Rumsey Hills, a series of parallel, east-westtrending creeks, extending from north to south over a 15 km interval, expose Upper Cretaceous strata overlain by younger sedimentary rocks and alluvial deposits.

The lithology and molluscan biostratigraphy of the Sand and Salt Creek sections of the Rumsey Hills were described by Ward and Haggart (1981), Ward et al. (1983), and Haggart and Ward (1984), and no new collections have been described in the literature since. Four biostratigraphic zones were recognized along these creeks, in ascending stratigraphic order: (1) a lowermost Eubostrychoceras elongatum zone (Elongatum zone) with E. elongatum and Glyptoxoceras subcompressum as dominant taxa; (2) the Sphenoceramus schmidti zone (Schmidti zone), with the zonal index as well as the abundant pachydiscid ammonite Canadoceras yokoyamai; (3) the Submortoniceras chicoense zone (Chicoense zone), with Baculites chicoensis showing the same stratigraphic range and equally diagnostic, as first recognized by Ward (1978a, 1978b); and (4) the Hoplitoplacenticeras vancouverense zone (Vancouverense zone), with one fragmentary but probable specimen of the index species recovered, along with other associated diagnostic elements for the zone, including Baculites inornatus, Canadoceras newberryanum (also found in the subjacent Chicoensis zone), and Desmophyllites diphylloides.

The stratigraphic sections of the Rumsey Hills are of critical importance in west coast Upper Cretaceous biostratigraphy because they represent the only area where these four successive molluscan biostratigraphic zones are found in continuous marine sections without intervening nonmarine units or apparent disconformities. The stratigraphic ranges of key ammonites in these sections are shown in Figure 3.

Magnetostratigraphic sampling was conducted along several creeks in the Rumsey Hills (Ward et al., 1983; Verosub et al., 1989). At Sand and Petroleum Creeks, all samples from the Guinda Formation, as well as the Dobbins Shale member of the Forbes Formation, showed exclusively normal polarity in the two lowermost zones (Elongatum and superjacent Schmidti zones), and dominantly, but not exclusively, reversed polarity in the upper two zones (Chicoense and Vancouverense zones; Ward et al., 1983; Verosub et al., 1989). Because all beds below the Chicoense zone were found to be of normal polarity, this lowermost magnetochron was interpreted by both Ward et al. (1983) and Verosub et al. (1989) to represent the top of the Cretaceous Long Normal, C34n, and the overlying reversely magnetized beds containing the ammonites Baculites chicoensis



Figure 3. Composite measured stratigraphic section for Rumsey Hills (from Sand, Salt, and Petroleum Creeks), northern California, showing paleomagnetic record from Verosub et al. (1989), plotted against ammonite ranges. Data are after Ward et al. (1983), Haggart and Ward (1984), and Verosub et al. (1989), as well as a possible reinterpretation based on the new paleomagnetic analysis.

Rumsey Hills: Great Valley sequence

and Canadoceras newberryanum were thus correlated with C33r. Beds above this interval containing abundant Baculites inornatus and fewer Canadoceras newberryanum were found to be of mixed polarity (Ward et al., 1983; Verosub et al., 1989). Most importantly, a single specimen of Hoplitoplacenticeras vancouverense, the zonal index of the Vancouverense zone, was found in beds showing reversed polarity and containing B. inornatus and C. newberryanum (Ward and Haggart, 1981; Ward et al., 1983). The highest beds of the Forbes Formation, sampled only on Salt Creek, were of normal polarity but unfortunately contained no macrofossils. However, microfossils from high in these sections were consistent with an age no younger than late Campanian (Almgren, 1973).

A caveat with the earlier paleomagnetic work reported by Ward et al. (1983) and Verosub et al. (1989) is that only alternating field (AF) demagnetization was used for magnetic cleaning, which was fairly standard procedure at that time. Since then, it has been demonstrated numerous times that weathering-induced magnetic components of normal polarity carried by antiferromagnetic minerals like goethite and hematite can often have far higher resistance to AF cleaning than the original components, typically preserved by ferromagnetic minerals like magnetite. For shallowly dipping strata, this makes it difficult to distinguish a primary normal-polarity direction from a recent overprint. (Reversed directions are usually a reliable indication of the primary polarity.) Thermal cleaning to moderate temperatures in a controlled atmosphere, however, is often able to remove these overprints preferentially, allowing underlying reversed polarity components to be identified. As a spot check of our earlier work, we conducted a pilot sampling program of the Sand Creek section reported by Ward et al. (1983) and Verosub et al. (1989), using a hybrid AF-thermal demagnetization scheme. This pilot test showed that strata interpreted to have normal polarity in the previous studies are, in fact, reversed. This has been confirmed by multiple samples. Because of this, the long-accepted level for the base of chron 33r in west coast North America strata must be reinterpreted. Our new work indicates that the base of 33r is below the oldest fossiliferous strata on Sand Creek, found within the Sphenoceramus schmidti zone, and that the top of C33r extends well above the previous interpretation as well, which was that 33r was entirely contained within the Baculites chicoensis zone. Both the base and top of this magnetochron are now extended.

Because of the mixed polarities discovered, and because the fossils indicated an early Campanian age at youngest, the upper parts of these sections were not correlated to the global polarity time scale (GPTS) by Ward et al. (1983) and Verosub et al. (1989), due to what appeared to be a major conflict between magnetostratigraphy and biostratigraphy. However, with subsequent paleontological work in biostratigraphically correlative strata on Sucia Island, Washington (see following), the existing magnetostratigraphic record from the Forbes Formation cropping out along the western flank of the Sacramento Valley (Ward et al., 1983; Verosub et al., 1989) is herein reinterpreted as shown in Figure 3, with all of the strata on Sand Creek now interpreted to lie within chron 33r. Chron 33r extends from below the Baculites chicoensis zone into, and perhaps through the Hoplitoplacenticeras vancouverense zone.

Chico Formation, Eastern Sacramento Valley, California, Upper Santonian– Lower Campanian (Fig. 1, Locality 2)

The biostratigraphy of the Upper Cretaceous along Big Chico Creek, northeastern Sacramento Valley, has long been documented, with its ammonite fauna (Matsumoto, 1959b; Ward et al., 1983; Haggart, 1984) and nonammonite molluscan fauna (Saul, 1988; Elder and Saul, 1996; Squires and Saul, 2001) the subject of a number of published studies. The stratigraphic section along the creek contains the underlying mid-Santonian Baculites capensis zone, disconformably overlain by Lower Campanian Chicoense zone. The presence in these younger strata of the ammonite genus Submortoniceras indicates that the beds must correspond closely in age with the base of the Campanian Stage in Europe and the American Gulf Coast (Young, 1963; Hancock and Gale, 1996). Ranges of key fossils are shown in Figure 4.

Magnetostratigraphy for the Big Chico Creek section was reported on by Ward et al. (1983) and, later, Verosub et al. (1989), both of which showed that all samples from the Capensis zone (Santonian) along the creek were found to be of normal polarity. Because these strata are older in age than any sampled in the Rumsey Hills, they add evidence that the Capensis zone is within the Cretaceous Long Normal interval.

On Big Chico Creek, the lowest beds of the disconformably superjacent Chicoense zone were also found to be of normal polarity by Ward et al. (1983) and Verosub et al. (1989), but ~20 m above this contact, all samples were found to be of reversed polarity. Samples from the highest part of the Big Chico Creek section were again found to be of normal polarity. Based on these results, both the base and the top of C33r were interpreted to be entirely within the Chicoensis zone, as exposed along Big Chico Creek (Ward

et al., 1983; Verosub et al., 1989). This was considered problematic, however, as the assignment of one ammonite zone for the entire duration of C33r (estimated to be ~4 m.y. long) in California suggested that, at least for this range zone, evolution and survivorship of not only the zonal index, but other co-occurring species as well, were far longer than typical in other areas of the globe. This problem is resolved, however, if the same pervasive normal overprint affected these strata, as it did the geographically close sections along the west side of the Sacramento Valley reported in the previous section.

At the present time, neither the base nor the top of 33r can be established with any confidence on the east side creeks of the Sacramento Valley, and a reevaluation through new sampling is warranted. The best that can be said is that the highest fossils found within the chron (in the Rumsey Hills sections) are specimens of *Baculites inornatus* and *Canadoceras newberryanum*, the former first appearing in the Vancouverense zone, and both of these occurring in the lower half of the Campanian stage elsewhere in the Indo-Pacific realm (Matsumoto, 1960), and thus globally consistent with being in chron 33r.

Cedar District Formation, Sucia Island, Washington State, Lower–Middle (?) Campanian (Fig. 1, Locality 3)

The stratigraphic section exposed along southeast Sucia Island, Washington State (Fig. 5), is famous for its abundant and wellpreserved Late Cretaceous molluscan fauna, recovered from shallow-marine shelf strata assigned to the Cedar District Formation of the Nanaimo Group. The section of Cedar District Formation at Sucia Island includes a conglomerate with distinctive white quartz pebbles in its middle part, both underlain and overlain by fossiliferous siltstone. Nowhere is either the base or top of the Cedar District Formation observable on Sucia Island, as the highest exposure of the formation is cut by a major fault zone (Ward, 1978a).

The Sucia Island ammonite fauna has long been considered to be uniform throughout, with diagnostic elements of the Vancouverense zone, including *Hoplitoplacenticeras vancou*verense, Baculites inornatus, Desmophyllites diphylloides, Canadoceras newberryanum, and Pseudoxybeloceras lineatum, along with long-ranging specimens of Neophylloceras, Epigoniceras, and Gaudryceras, found both above and below the middle conglomeratic unit (Fig. 5).

Ward (1978b) described baculitid ammonites from the Sucia Island section that were then referred to as *Baculites occidentalis*, based on





Figure 4. Measured stratigraphic section for Big Chico Creek, northern California, showing our new interpretation of magnetic polarity for this section. 0 m reflects base of measured section for paleomagnetic study; additional strata crop out beneath this level. As in the Rumsey Hills, it is probable that all of this section within the zone of *B. chicoensis* is reversed rather than containing intervals of normal polarity.

prominent flank ribbing. However, further study of large populations of *Baculites inornatus* from both Sucia Island and Rosario Formation deposits at Punta San Jose, Baja California (see following), has shown that variants of this species show flank ribbing resembling that seen on the Sucia Island *B. occidentalis* specimens (Backus, 1998). The baculitids from Sucia Island previously assigned to *B. occidentalis* are thus now assigned to *B. inornatus*.

Two specimens of *Baculites subanceps* were also recovered from high in the Big Sucia Island section, marking the first time this taxon has been recovered from this locality.

Based on the presence of *Hoplitoplacenticeras vancouverense, Canadoceras newberry-anum*, and *B. inornatus*, we correlate the entire fossiliferous Sucia Island section to the lower Forbes Formation on Sand and Salt Creeks (Ward and Haggart, 1981), and thus, as we have done there, with the upper part of C33r. To date, no magnetostratigraphic data have been published for this locality, but we are presently initiating analysis of cores collected from Big Sucia Island. Preliminary results from eight sample localities from above the conglomerate on Big Sucia Island all show reversed polarity, consistent with the fossil content of Sucia Island being within chron 33r.

Strontium isotope analysis was also undertaken on two ammonites with pristine aragonite shell material from geographically nearby and closely correlative Little Sucia Island (Zweible, 1999). The two ⁸⁷Sr/⁸⁶Sr data points (Fig. 6) are very closely similar in value, with an average of 0.707475 (Backus, 1998). These data, while obviously few in number, are useful in that they confirm the correlation of the Sucia Island section and the Vancouverense zone in the sense of Ward (1978a) with the *Baculites* sp. (smooth) and *Baculites* sp. (weak flank ribs) zones from the U.S. Western Interior, based on similarity to strontium results from that region (McArthur et al., 1994).

Cedar District Formation, Denman Island, British Columbia, Middle Campanian (Fig. 1, Locality 4)

The fossil succession along the west coast of Denman Island provides a modest record of invertebrates, including ammonites (Fig. 7). North of the ferry terminal on the west side of the island, near the middle of the section of the Cedar District Formation, numerous, wellpreserved specimens of *Metaplacenticeras* cf. *pacificum* and *Baculites rex*, of late Campanian age (Matsumoto, 1959b; Jeletzky, 1970) and assignable to the cf. Pacificum zone, have been collected (Ward, 1978a). Elsewhere in

Sucia Island: Nanaimo Group



Figure 5. Measured stratigraphic section for Sucia Island, Washington State, showing ranges of important index fossils collected from the Cedar District Formation. Recent magnetostratigraphic work indicates that the entire section is of reversed polarity.

this part of the section, specimens of Baculites subanceps (previously identified as B. anceps pacificus; Ward, 1978b) have been found as well, while the lowest strata on the west side of the island contain numerous, well-preserved specimens of Pachydiscus suciaensis (collections of Vancouver Island Paleontology Museum, Qualicum Beach, British Columbia). This important locality shows that the range of B. subanceps is, in the Nanaimo Group, similar to the ranges of Metaplacenticeras cf. pacificum and B. rex, a relationship previously recognized in sections in the Great Valley sequence of California (Elder and Saul, 1993), and recognized by us for the first time at Punta San Jose, Baja California. It also shows that P. suciaensis ranges lower in the Nanaimo Group than previously thought, down into the ranges of B. rex and M. cf. pacificum.

Only limited sampling of these strata for magnetostratigraphy has been attempted to date (Enkin et al., 2001). All samples were taken low in the section, within the range of M. cf. pacificum and B. rex, and all were of normal polarity, although data are of low quality, and even polarity is barely apparent (Enkin et al., 2001). These results are nonetheless important because they show that the upper parts of the Cedar District Formation, including beds with M. cf. pacificum, are of normal polarity, and also that the Cedar District section is correlative with the top of the section at Punta San Jose, Baja California, as both share the presence of B. rex. These relationships imply that the top of 33r is either near the top of the Vancouverense zone or near the base of the cf. Pacificum zone.

Rosario Formation, Punta San Jose, Baja California, Middle Campanian (Fig. 1, Locality 5)

The monotonous succession of the Rosario Formation exposed along the coastline near Punta San Jose, Baja California, consists of siltstone with channel-fill conglomerates near its top and contains numerous ammonites. The section has never been figured previously, although numerous publications have mentioned various ammonites recovered from it. Previous work in this region was undertaken by Kilmer (1966), Gastil et al. (1975), and Filmer and Kirschvink (1989). This latter publication was the first to note the presence of *B. inornatus* in the Punta San Jose section; subsequently, Backus (1998) studied the extent of morphological variation in that species, using populations collected from the section.

The fossil record at this section is composed of few ammonites, but all are important as biostratigraphic markers (Fig. 8). *Baculites*

A	A GPTS		rs	B WESTERN INTERIOR	C Sr	D	WEST COAST LOC/ZONE
	_	AN	C29n C29r	Jeletzkytes nebrascensis			?
Age (Ma)	_	UPPER MAASTRICHTI#	C30n C30r C31n	Hoploscaphites nicolleti			
	ł	s.	C31r	Hoploscaphites birkelundae			
0-		AAA		Baculites clinolobatus			
		Ľ		Baculites grandis	.707757		San Antonio del
				Baculites baculus			Mar (Neubergicus
			(32n	Baculites eliasi	.707728		Zone)
			C3211	Baculites Jenseni			20110)
	_		C32r	Baculites reesidei			Can Antonia dal
		VIAN	C32r	Baculites cuneatus	.707688		
		AMPAN		Baculites compressus	.707679		Zone)
	_	PER C/		Didymoceras cheyennense			,
<u>ب</u>		UP		Exiteloceras jenneyi			
				Didymoceras stevensoni			Durate Conclusion
			Coon	Didymoceras nebrascense	.707612		Punta San Jose
	7		Cooli	Baculites scotti	.707584		(Nebrascense Zone)
				Baculites gregoryensis	707577		
		N		Baculites perplexus (late)			
		ANI/		Baculites gilberti	.707588		
	_	MP/		Baculites perplexus (early)			
		CA		Baculites sp. (smooth)			
	_	OLE		Baculites asperiformis			
		IDIV		Baculites maclearni			
0		~		Baculites obtusus	.707574		
8	ļ			Baculites sp. (weak flank ribs)			
	_	AN		Baculites sp. (smooth)	.707512		
		PANI	C33r	Scaphites hippocrepis III			Sucia Island
	_	AMI		Scaphites hippocrepis II			(Vancouverense
	_	LOWER (Scaphites hippocrepis I	.707466		Zone)
	f	z		Scaphites leei III			
85	_	NTONIA	C34n	Desmoscaphites bassleri			
		SAľ					

Figure 6. Strontium values for molluscan shell aragonite from west coast Campanian and Maastrichtian fossil localities, plotted against Western Interior faunal zones and the Sr curve of McArthur et al. (2000). Shading bars show sample value ranges and error. Localities are: Sucia Island, Washington State (Cedar District Formation of Nanaimo Group, *Hoplitoplacenticeras vancouverense* zone); Punta San Jose, Baja California (Rosario Formation, *Didymoceras nebrascense* zone); SADM lower—lower section at San Antonio del Mar, Baja California (Rosario Formation, *Nostoceras hornbyense* zone); and SADM upper—upper section at San Antonio del Mar (Rosario Formation, *Pachydiscus neubergicus* zone). GPTS—global polarity time scale.

inornatus ranges throughout the ~80 m of section beneath the conglomerate unit underlying the lighthouse. A second baculitid species, *B. rex*, co-occurs with *B. inornatus* in the 30 m of section beneath the conglomerate, where it also co-occurs with numerous specimens of the Western Interior zonal index species *Didymoceras nebrascense* (see Figs. 11G and 11H; identification verified by W.A. Cobban, 2008, personal commun.). However, both *B. rex* and *D. nebrascense* are found above the conglomerate, whereas *B. inornatus* is not.

There is also a single specimen of *Baculites subanceps* from the locality, found beneath the range of *B. rex* but within the range of *B. inornatus*. This discovery helps link this section to Sucia Island.

The ammonites are indicative of two or perhaps three biostratigraphic zones. The presence of *Baculites inornatus* is characteristic of the Vancouverense zone, while *B. rex* is found commonly in the overlying cf. Pacificum zone in the Nanaimo Group. This is the first time that these ammonites have been found in a single section, and the first evidence that they overlap high in the range of *B. inornatus*. It is also the first time that *D. nebrascense* has been identified from the Pacific Coast Cretaceous, and it is evidence that there was more mixing of fauna between the North American west coast and Western Interior provinces than has been previously acknowledged.

The magnetostratigraphic record from the section was described by Filmer and Kirschvink (1989), and normal polarity characterizes the entire section. Our findings thus show that while the FAD of *Baculites inornatus* is found in chron 33r, the upper part of the taxon's range, as well as its last occurrence datum (LAD), are firmly within chron C33n. Our results also indicate that the entire ranges of *D. nebrascense*, as well as that of *B. rex*, on the Pacific Coast are both within zones of normal polarity that we identify as C33n (Fig. 8).

In addition to biostratigraphy and magnetostratigraphy, pristine aragonite from fossils from the Punta San Jose section has also been analyzed for strontium isotopes (Backus, 1998). The mean result from six different fossils (each with a % standard error ranging from 0.0006 to 0.0007) from the upper half of the section is 0.707649, with a standard deviation of ± 0.000045 (Fig. 6). This value is equivalent to the base of the middle-upper Campanian transition in the Western Interior (McArthur et al., 1994), and it is approximately equivalent to the level of the Didymoceras nebrascense zone (one of the ammonites utilized in this study). These values are useful in that they demonstrate not only the younger age of this section compared to Sucia Island, with its



Denman Island, Nanaimo Group

Figure 7. Measured stratigraphic section for west coast of Denman Island, British Columbia, showing ranges of important index fossils collected from the Cedar District Formation and our interpretation of magnetostratigraphy.

Baculites inornatus, but also that the Punta San Jose section is older than Western Interior strata with *B. compressus* and *B. cuneatus* (McArthur et al., 1994). These values are also consistent with the normal polarity recovered over the entire thickness of this section.

Northumberland, Geoffrey, Spray, and Gabriola Formations, Hornby Island, British Columbia, Upper Campanian– Maastrichtian (?) (Fig. 1, Locality 6)

Fossils have been collected from the lower parts of the Hornby Island section for more than a century, mainly from mudstone exposed along the northwestern coastline. Diagnostic invertebrate fossils are known from strata now referred to as the Northumberland Formation (Katnick and Mustard, 2001, 2003), but efforts to subdivide the succession through biostratigraphy have proven challenging. Jeletzky (1970) reported that the key index ammonites *Baculites occidentalis, Pachydiscus suciaensis*, and *Nostoceras* *hornbyense* all range through the entire thickness of fossiliferous beds on Hornby Island, while Muller and Jeletzky (1970) proposed dividing the fossiliferous strata into subzones.

We resampled the ~200-m-thick fossiliferous succession of the Northumberland Formation on Hornby Island and recognize a threefold subdivision of strata, based on the ranges of distinctive ammonites and inoceramid bivalves (Fig. 9). From the base of the section on the southwest side of the island (just north of the ferry terminal) northward to near Phipps Point, an Upper Campanian fauna of Gaudryceras denmanense and Pachydiscus suciaensis is found, co-occurring with rare specimens of Nostoceras hornbyense. In the upper parts of this succession, there is a distinctive unit of shale with numerous large inoceramids (I. Platyceramus cf. Inoceramus. cycloides) as well as large but poorly preserved and unidentifiable pachydiscid ammonites. Within this unit, the stratigraphically lowest identifiable specimens of B. occidentalis have been recovered, and all are small in size.

From this level upward, B. occidentalis specimens become more common and larger in size, while the large inoceramids are replaced by smaller species, as yet unidentified. The upper part of the range of both the baculitids and the inoceramids overlaps with that of Nostoceras hornbyense in the lower part of that taxon's range. Higher in the Hornby Island section, however, N. hornbyense becomes rare; it has not yet been collected from the highest fossiliferous strata of the Northumberland Formation on Hornby Island where B. occidentalis can still be found. Thus, N. hornbyense clearly predates the first occurrence of B. occidentalis, which then ranges to higher stratigraphic levels than N. hornbyense. As we will show below, this same pattern is present at San Antonia del Mar, in Baja California.

Ward et al. (1997) first demonstrated the presence of magnetic polarity reversals from what is now interpreted as Northumberland strata on Hornby Island. Enkin et al. (2001) extended the magnetic stratigraphy record on the island by recognizing intervals of both normal and reversed polarity in strata of the Geoffrey, Spray, and Gabriola Formations on the island, and correlating them to C31r; the highest strata on Hornby Island, assigned to the Gabriola Formation, showed both normal and reversed polarity, and were thus correlated with C30n (Enkin et al., 2001).

Raub et al. (1998) also reported on the results of magnetostratigraphic sampling from the base of the Northumberland Formation to the highest strata on Hornby Island. This work, unfortunately only an extended abstract (but with figures showing section and results), correlated the reversed intervals from the Northumberland Formation with C33r. This is clearly in error (Fig. 9). We continue to concur with Ward et al. (1997) and Enkin et al. (2001) in the correlation of the lowest reversal on Hornby Island with global magnetochron C32r, since the strata from which the reversed samples come have yielded undoubted late, rather than early, Campanian ammonites, thus eliminating the possibility that the reversed interval within the Northumberland Formation could be C33r. Because the ammonites appear older than species typically spanning the Campanian-Maastrichtian boundary elsewhere, correlation with C32r also appears justified. The magnetic record from the Northumberland Formation on Hornby Island is now well known, and it shows a pair of stratigraphically narrow reversals in a sequence of otherwise normal polarity within the formation (Fig. 9).

Our own interpretation of the Raub et al. (1998) data is shown in Figure 9, compared with that of Enkin et al. (2001). In both cases,

Figure 8. Measured stratigraphic section for Punta San Jose, Baja California, showing paleomagnetic record (from Filmer and Kirschvink, 1989) plotted against new data about ammonite ranges reported here. All paleomagnetic samples were of normal polarity. Because *Baculites inornatus* occurs throughout this section, it indicates that the species occurs in strata of both reversed (33r; Rumsey Hills) and normal (C33n; Punta San Jose) polarity.



the dearth of identifiable fossils from any strata above the Northumberland Formation makes any correlation above C32r problematic.

Rosario Formation, San Antonio del Mar, Baja California, Upper Campanian– Paleocene (Fig. 1, Locality 7)

A thick succession of conglomerate, sandstone, siltstone, and shale assigned to the Rosario Formation is located along the coastline near San Antonio del Mar, Baja California, and it is of great importance in demonstrating Upper Campanian as well as Maastrichtian faunal zones for the Pacific Coast (Fig. 10). Strata in the upper part of the section contain fossils younger than any in the Nanaimo Group, thus providing needed information about the still poorly known uppermost Campanian and Maastrichtian of the Pacific Coast region.

The succession at San Antonio del Mar is exposed in two separate stratigraphic sections along beach cliffs, separated by ~1 km of alluvial cover. The section representing the stratigraphically lower part of the formation (Fig. 10A) is to the north and rests unconformably on volcanic basement. The second section (Fig. 10B) consists of younger strata (based on diagnostic fossils) and does not overlap the first; this section is covered by alluvium at both its base and top.

Ammonites are found sporadically through the two sections but, where present, can be abundant. The stratigraphically lowest strata contain specimens of Nostoceras hornbyense and Solenoceras sp. These strata are overlain by a thicker succession of siltstone with a more diverse ammonite fauna, including numerous B. occidentalis and lesser numbers of Anapachydiscus peninsularis and Pachydiscus suciaensis. This is the first record of N. hornbyense in Baja California, and the specimens are both abundant and well preserved. Our discovery of N. hornbyense in the San Antonio del Mar succession allows direct correlation with the Hornby Island section of the Nanaimo Group of British Columbia, and the stratigraphic position of this species superjacent to and only partially overlapping the range of *B. occidentalis* confirms the ranges of these same two taxa on Hornby Island.

Overlying the zone with *N. hornbyense*, there is a thick sequence with specimens of *P. suciaensis*, as well as the continued presence of *B. occidentalis*. As on Hornby Island, the *B. occidentalis* specimens at this locality show a progressive size increase going up-section and remain the most abundant faunal element through their entire range. The highest *B. occidentalis* specimens are very large in size and appear identical to *B. cuneatus* from the U.S. Western Interior.

The upper section at San Antonio del Mar (Fig. 10B) contains few ammonites, but those collected to date have great importance for biostratigraphy. We identified the globally distributed, lower Maastrichtian marker *Pachydiscus neubergicus* from this locality (Fig. 11J), along with fragments of *Glyptoxoceras* sp. and small, unidentifiable fragments of *Baculites*. This is the first report of *P. neubergicus* from the Pacific Coast. As we discuss in the next section, we also collected this taxon from the next locality described in this paper, Santa Catarina Landing.

The highest part of the section at San Antonio del Mar contains a mass occurrence of the gastropod *Turritella* sp., belonging to a Paleocene species (LouElla Saul, 1997, personal commun.).

In addition to the previously cited work, limited numbers of strontium analyses from both the lower and upper section have been completed (Zweible, 1999). The lowest sample, from beds with *N. hornbyense* and *B. occidentalis*, was 0.707685 \pm 0.00002, while a second sample taken 140 m higher in the section, with *B. occidentalis* but above the range of *N. hornbyense*, was 0.707693 \pm 0.000020 (Fig. 6). In the Western Interior, both of these values are found in the *B. cuneatus* zone (McArthur et al.,

Geological Society of America Bulletin,





Figure 9. Measured stratigraphic section at Hornby Island, British Columbia, Canada, with ammonite ranges and our interpretation of prior magnetostratigraphy. Only the lowermost formation, the Northumberland Formation, contains diagnostic fossils. Correlation with magnetic chrons above this fossiliferous formation remains problematical.

1994), the zone that we correlate with the San Antonio del Mar strata, based on fossil content. For the higher San Antonio del Mar section, yielding *P. neubergicus*, a global Maastrichtian marker found in beds at the transition of Lower to Upper Maastrichtian, a value of 0.707788 ± 0.00002 was recovered from ammonite aragonite, while a value of 0.707800 ± 0.00002 was obtained from a planktonic foraminiferan. These values characterize the *Baculites clinolobatus* to *Hoploscaphites nicolleti* zones of the U.S. Western Interior, the former of which is the highest zone of the lower Maastrichtian, and the latter of which occurs in the upper, but not highest, Maastrichtian (McArthur et al., 1994).

Rosario Formation, Santa Catarina Landing, Baja California, Upper Campanian–Maastrichtian (Fig. 1, Locality 8)

The area around Santa Catarina Landing in Baja California has long been known as one of the most prolific regions for the collection of Upper Cretaceous ammonites and other mollusks in all of the southern part of the North Pacific biotic province. It may also contain the longest continuous record of fossiliferous mid-Campanian through Maastrichtian strata of any locality in the province. Older collections from Santa Catarina Landing housed at the Los Angeles County Museum, as well as more recent collections made from correlative sections at Carlsbad, California, and also housed at the Los Angeles County Museum, indicate the presence of Upper Campanian assemblages that are unknown from the Nanaimo Group of British Columbia, and that are rarely found elsewhere along the Pacific Coast of North America. Thus, documenting the ammonite succession of this locality is of fundamental importance for understanding both the stratal succession of index ammonites within the North Pacific biotic province, as well as for correlation of these faunas with those of other regions.

Unfortunately, the detailed stratigraphic and taxonomic work necessary to accomplish this task has never been undertaken. There is no single stratigraphic section preserved; rather, the outcrops are restricted to numerous small gullies containing typically flat-lying strata that are distributed over several square kilometers. Museum collections indicate that many of these gullies, where specimens were collected prior to either global positioning system (GPS) or even good maps of the area, contain short-ranging ammonites but quite often have no zonal transitions.

We were able to study this locality in the field only briefly. Our most important find was the discovery of multiple specimens of *P. neubergicus*





Figure 10. Measured stratigraphic sections at San Antonio del Mar, Baja California, with new ammonite range data. (A) Stratigraphically lower section. (B) Stratigraphically higher section, showing the first record of the Tethyan index fossil *Pachydiscus neubergicus*, of undoubted Maastrichtian age.

(see Fig. 111), the marker for the lower Maastrichtian and conspecific with the specimens found in the upper section at San Antonio del Mar, described already. Other age-diagnostic species found in collections of the Natural History Museum of Los Angeles County include the Gulf Coast–Tethyan species Nostoceras draconis, Nostoceras hyatti, Nostoceras helicinum, and Nostoceras approximans (see Fig. 11) and small trigonal baculitids identified as Baculites lomaensis. These taxa provide an important correlation tie-point with the Gulf Coast and U.S. Western Interior, as well as to the Hyatti zone, the highest Campanian biostratigraphic zone of the North American Gulf Coast and Tethyan parts of Europe.

Inland from the coastal Santa Catarina Landing outcrops, and presumably stratigraphically higher, Natural History Museum of Los Angeles County (LACMNH) Locality 11952 has yielded specimens of *Eubaculites ootacodensis* (= *E. lyelli*; Kennedy, 1986a, 1986b), indicating a late Maastrichtian age for this fauna (Matsumoto, 1959b, 1960); unfortunately, it is not known precisely how these beds relate stratigraphically to the beds along the coast with *P. neubergicus*.

DISCUSSION

Our new ammonite data indicate that substantial revisions to the currently accepted biostratigraphic framework of west coast North America Santonian through Maastrichtian strata are warranted. The new and presently unpublished paleomagnetic data demonstrate that previous interpretations identifying magnetostratigraphic chron 33r have been compromised by a formerly unrecognized normal overprint of what were originally considered to be reversed polarity strata; these new data thus mandate rejection of the previous placement of both the base and top of Chron 33r in west coast sections. While integration of magnetostratigraphy and macrofossil biostratigraphy within outcropping sections of strata younger than early Campanian provides a better and higher-resolution correlation of Upper Campanian strata within the Pacific Coast basins, a thorough restudy of the Lower Campanian stratigraphy of the region is necessary.

In a more positive contribution, our new interpretations demonstrate that greater faunal similarity exists among the North American west coast, Western Interior, Gulf Coast, and east coast regions than has previously been accepted, with significant paleobiogeographic implications. The abundance of important index taxa common to these different biotic provinces shows that far more faunal interchange took place between the provinces than has heretofore been recognized, at least during the last two ages of the Cretaceous Period. This may reflect the presence of marine connections between the Pacific Coast and Western Interior regions to the south of present-day Baja California, or perhaps at other localities along the Cretaceous Cordilleran belt, although much more work will be necessary to confirm these linkages.

To date, only Elder and Saul (1993) and Squires and Saul (2001) have attempted to integrate macrofossil biostratigraphy with magnetostratigraphy for the entire Santonian through Maastrichtian of the Pacific Coast, and this is the currently accepted zonation for the study interval. Our results require changes to the status quo zonation in two ways. First, our new data on species ranges require modification of the correlation of west coast faunal zones with those of the international stage standards for the Santonian through Maastrichtian. Second, we advocate here that, where possible, planispiral ammonite index fossil species be changed to either Baculites species or heteromorphic species, such as Nostoceras and Didymoceras, because in most cases, these taxa are not only shorter ranging, but more abundant than the planispiral forms. The baculitids and other heteromorphs appear



Figure 11. Biostratigraphically important index ammonites from the west coast of North America that are shared with other faunal provinces. (A–C) *Nostoceras draconis*, Rosario Formation, Santa Catarina Landing, Baja California; (A) University of Washington, Burke Museum (UWBM) No. 93738; (B) UWBM No. 93739; (C) UWBM No. 93740. (D–F) *Nostoceras approximans*; (D) UWBM No. 93741, San Joaquin Valley, California; (E) UWBM No. 93742, Rosario Formation, Santa Catarina Landing, Baja California; (F) UWBM No. 93743, Rosario Formation, Santa Catarina Landing, Baja California: (G–H) *Didymoceras nebrascense*, Rosario Formation, Punta San Jose, Baja California; (G) UWBM No. 93744; (H) UWBM No. 93745. (I–J) *Pachydiscus neubergicus*; (I) UWBM No. 93746, Santa Catarina Landing, Baja California; Go UWBM No. 93746, Santa Catarina Landing, Baja California; Go UWBM No. 93746, Santa Catarina Landing, Baja California; (G) UWBM No. 93746, Santa Catarina Landing, Baja California; (G) UWBM No. 93746, Santa Catarina Landing, Baja California; (G) UWBM No. 93746, Santa Catarina Landing, Baja California; (J) UWBM No. 93747, Rosario Formation, San Antonio del Mar, Punta San Jose, Baja California. (L–N) *Hoplitoplacenticeras vancouverense*, Cedar District Formation (Nanaimo Group), Sucia Island, Washington State; (L) UWBM No. 93749; (M) UWBM No. 93750; (N) UWBM No. 93751. All specimens illustrated at 50% natural size.

on average to be shorter ranging and more widespread (e.g., Kennedy and Cobban [1976] for the U.S. Western Interior), and allow more direct correlation with regions beyond the Pacific Coast. This is a practical change that will help future stratigraphers and geologists.

It is important to note that in our proposed succession of ammonite faunal zones of the eastern North Pacific biotic province (Fig. 12), we have stacked the zones in contiguous order, without indicating any barren interzones. This is certainly misleading for some of the zones. Although we have confidence in the stratigraphic continuity of the Eubostrychoceras elongatum through Metaplacenticeras cf. pacificum zones, there is no definitive evidence relating to stratigraphic continuity of the still higher zones. Consequently, in comparing the North Pacific faunal zones with those from the U.S. Western Interior, it may appear that some discrepancies in zonal durations exist. We believe, however, that this is likely not the case, but rather that it is an artifact of the nature of Cretaceous sediment accumulation along the Pacific Coast, where packages of unfossiliferous turbidites and submarine-fan deposits are commonly found stratigraphically intercalated with highly fossiliferous continental-shelf successions (England and Hiscott, 1992; Mustard, 1994).

Our new results lead us to propose the accompanying biostratigraphic zonation (Table 2). This is very much a work in progress, especially for the uppermost Campanian through Maastrichtian, but we believe that the new zonation more accurately portrays the succession of biochronologically important macrofossil index taxa. For each zone listed, the name, zonal index species, and whether or not this is a change to a current zone are given.

Correlation of Upper Cretaceous Strata within the North Pacific Region

Using biostratigraphy and magnetostratigraphy, we can now confidently integrate ammonite zones with the magnetostratigraphic record of the west coast Campanian–Maastrichtian, and use this combined approach to better correlate the various sections examined in this study. Figure 13 represents our conclusions for correlation between various sections.

While this result gives a more refined correlation than previously available, it is not without uncertainty, the greatest being how the tops and bottoms of stratigraphic sections located within a magnetochron correlate to the absolute age time scale. For example, both the base and top of the section at Punta San Jose are placed within the normal polarity time scale of C33n, but we cannot with any certainty suggest that it





starts at 79 Ma and ends at 74 Ma, compared to an alternative of, for example, 76 Ma to 75 Ma. These finer range assignments may eventually become available by integrating FADs and LADs of other fossil groups such as planktonic foraminifers, gastropods, or calcareous nannofossils, or utilizing strontium data from the various sections. We consider it unlikely, however, that new ammonite data will be useful in further refinement of the correlation.

Secondly, while there is now good coverage and confidence in the correlation of Santonian to mid-Campanian strata of the west coast, correlations of uppermost Campanian and especially Maastrichtian rocks are more problematic because of a paucity of fossiliferous outcrops of this age. For instance, while the Santonian to Upper Campanian is relatively rich in fossils in the Nanaimo Group of British Columbia, by late Campanian time, many of the Pacific Coast depositional basins had begun to fill with turbidites, followed by nonmarine strata. In the Great Valley of California, there are no macrofossils that can be confidently assigned to the highest Upper Campanian (above the range of B. occidentalis), while the San Joaquin Valley was also filled with turbidites, and then was capped by the deeply weathered, Maastrichtianage Moreno Formation, resulting in a very poor record for this time interval. Fortunately, it appears that the fossil-rich Santa Catarina Landing locality in Baja California has the potential to fill some of these gaps.

Correlation of North Pacific Ammonite Zones with Standard Zones of the Western Interior

The recognition that there was greater faunal mixing with other regions than previously assumed allows a new and higher-resolution correlation with the fossiliferous Upper Cretaceous of the North America Western Interior. The nearly continuous record of sediment accumulation during the Late Cretaceous within the Western Interior, with its abundantly fossiliferous shale interbedded with dateable bentonite deposits, has allowed development of very highresolution chronostratigraphic schemes for the region. Our use of magnetostratigraphy allows a higher-resolution correlation between the two provinces than has previously been available (Fig. 14). At the same time, new approaches to taxonomic analysis of the Western Interior zonal index species of the genus Baculites (Ward et al., 2008) have demonstrated that some important index taxa are synonymous with one another and/or with species from the Pacific Coast. For instance, using multivariate analyses on large numbers of Baculites specimens both

	TABLE 2. REVISED B	IOSTRATIGRAPHIC ZON	IATION FOR	CAMPANIAN-MAASTRICHTIAN STRATA, NORTHEAST PACIFIC REGION
Stage	Zone name (taxon name)	Subzone name (taxon name)	Chron	Remarks
Upper(?) Maastrichtian	Ootacodensis (Eubaculites ootacodensis)		30n-29r?	This is a range zone of the index taxon, but the full range within the upper Maastrichtian is still unknown. It appears to be the youngest ammonite present along the Pacific Coast.
Lower Maastrichtian	Neubergicus (Pachydiscus neubergicus)		31r	New. This is a range zone of the index taxon. It has not been identified on the Pacific Coast previously but is widespread elsewhere.
	Hyatti (Nostoceras hyatti)		32n	New. This is a range zone of the index taxon. Nostoceras approximans and Nostoceras draconis are commonly associated with the zonal index.
Upper Campanian	Occidentalis (Baculites occidentalis)		32r32n	New. This is the range zone of <i>Baculites occidentalis</i> . The stratigraphic segregation of the index taxon with the subjacent <i>Nostoceras hornbyense</i> is present on both Hornby Island BC and San Antonio del Mar, Baja California.
	Hornbyense (<i>Nostoceras hornbyense</i>)		33n–32r	This zone has been defined recently by Haggart et al. (2009) and is equivalent to the lower part of the range of Pachydiscus suciaensis. Its base is defined by the FAD of the zonal index, and its top by the FAD of Nostoceras hornbyense.
Middle Communica	Nebrascense (Didymoceras nebrascense)		33n	New. The range of the index taxon defines the zone, and the base and top of the zone correspond to the FAD and LAD of the index taxon, respectively. This is the first time the zonal index has been recognized from the west coast of North America. In spite of its rarity everywhere except Baja California, this taxon allows direct correlation to the <i>D. nebrascense</i> zone of the North American Western Interior.
	cf. Pacificum	Rex (<i>Baculites rex</i>)	33n	New subzone. This subzone is equivalent to the upper part of the cf. Pacificum zone, and its top is defined by the base of the overlying Nebrascense zone.
	(Metaplacenticeras cf. pacificum)	Subanceps (<i>Baculites subanceps</i>)	33n	New subzone. The subzone is defined by the FAD of the zonal index to the FAD of Baculites rex.
	Inornatus (Baculites inornatus)		33n	New. The base of this zone is defined on the LAD of <i>Hoplitoplacenticeras vancouverense</i> , rather than by the FAD of <i>Baculities inormatus</i> . This is necessary because <i>B. inormatus</i> is now known to be long-ranging, but can be useful as a zonal index if the zone is defined for that part of the range found only in chron C33n, rather than any part of the overlying C33r. The top of <i>H. vancouverense</i> , from available data, appears to coincide with the top of 33r.
Lower Campanian	Vancouverense (Hoplitoplacenticeras vancouverense)		33r	Unchanged
	Chicoense Chicoense (Submortoniceras chicoense)		33r	Unchanged. Concurrent with range of Baculites chicoensis.
Upper Santonian	Yokoyamai (Canadoceras yokoyamal)		33r (part)	Name change. We advocate replacement of the existing Schmidti zone (<i>Sphenoceramus schmidt</i>) with <i>Canadoceras yokoyamai</i> because true <i>S. schmidti</i> can be confused with slightly older sphenoceramids of the orientalis-elegans group.
	Elongatum (<i>Fubostrychoceras elondatum</i>)		34n	Unchanged



Figure 13. Correlation of North Pacific localities of this study (from north to south) using integrated biostratigraphic and magnetostratigraphic framework of global polarity time scale (GPTS).

from the Western Interior and Pacific Coast, work by Ward et al. (2008) has shown that substantial revision of the Western Interior zonation is required, based on careful studies of morphometric variation within species of this genus.

Correlation to Antarctica

In recent years, new work on the Upper Cretaceous of Antarctica has shown a surprising (given the geographic distance) similarity of faunas between that region and the Pacific Coast sections studied here, for the Santonian through part of the Campanian. The Santa Marta and Lopez de Bertodano Formations, James Ross Island and Seymour Island, Antarctica, upper Santonian– lower Danian, have one of the most expanded Cretaceous-Tertiary boundary sections in the world. The lowermost zone of the Santa Marta Formation, "association *Baculites* aff. *kirki*," is represented by the common Indo-Pacific taxon *Baculites kirki*, as well as other fauna found commonly in the Upper Cretaceous of the North American west coast and Japan, including *Bacu*- lites bailyi, Eubostrychoceras elongatum, and Polyptychoceras sp., while higher zones contain the west coast elements Baculites subanceps, B. inornatus, a possible B. chicoense, Pachydiscus ootacodensis, and specimens of Hauericeras, Metaplacenticeras, and Hoplitoplacenticeras. By the middle part of the Campanian, however, this fauna is gradually replaced by one composed of endemic members of Kossmaticeradae, including Kossmaticeras (Natalites), Kossmaticeras (Karapadites), Maorites, Grossouvrites, Neograhamites, and Gunnarites.

			GPTS	WESTERN INTERIOR		NORTH PACIFIC
			C29n			
Age (Ma)	_	CHTIAN	C29r C30n	?		?
		MAASTRIC	(30r	leletzkytes nehrascensis		Eubaculites ootacodensis
		PPER	CSIII	Hoploscaphites nicolleti		?
	-	⊃ 	C31r	Hoploscaphites birkelundae		
20		L.MAAS		Baculites clinolobatus Baculites grandis Baculites baculus		Pachydiscus neubergicus
			C32n	Baculites jenseni Baculites reesidei		Nostoceras hyatti
		AN	C32r	Baculites cuneatus		Baculites occidentalis
	_	IPANI	CJZI	Didymoceras cheyennense		
	_	CAN		Exiteloceras jenneyi		Nostoceras hornbyense
		PPEF		Didymoceras stevensoni		
-25				Didymoceras nebrascense		Didymoceras nebrascense
				Baculites scotti		
	-		C33n	Baculites gregoryensis		Baculites rex
				Baculites perplexus (late)		Baculites subanceps
	-	N		Baculites gilberti		່ວ subzone
		ANI		Baculites perplexus (early)		
		AMP,		Baculites sp. (smooth)		
		E C/		Baculites asperiformis		Baculites inornatus
	DLE	JDC		Baculites obtusus		
<u> </u>		MID		Baculites sp. (weak flank ribs)		
	_	AN	-	Baculites sp. (smooth)		vancouverense
		LOWER CAMPANI	C33r	Scaphites hippocrepis III		
	_			Scaphites hippocrepis II		Submortoniceras chicoense/Baculites
	_			Scaphites hippocrepis I		chicoensis
				Scaphites leei III		Canadoceras vokovamai
85			C34n	Desmoscaphites bassleri		
		SAN				Eubostrychoceras elongatum

Figure 14. Correlation of Western Interior ammonite zones with the new zonation for west coast North America proposed here. GPTS—global polarity time scale.

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