

Research Article

# Deep-water Tectono-Stratigraphy at a Plate Boundary Constrained by Large N-Detrital Zircon and Micropaleontological Approaches: Peninsular Ranges Forearc, Baja California, Mexico

Ian A. Kane<sup>1</sup>, David M. Hodgson<sup>2</sup>, Stephen M. Hubbard<sup>3</sup>, Adam D. McArthur<sup>2</sup>, Miquel Poyatos-Moré<sup>4</sup>, Euan L. Soutter<sup>1</sup>, Stephen S. Flint<sup>1</sup>, William Matthews<sup>3</sup>

<sup>1</sup> Department of Earth and Environmental Sciences, University of Manchester, <sup>2</sup> School of Earth and Environment, University of Leeds, <sup>3</sup> Department of Geoscience, University of Calgary, <sup>4</sup> Departament de Geologia, Universitat Autònoma de Barcelona

Keywords: deepwater, sedimentology, detrital zircon, canyon, submarine, stratigraphy, turbidite

<https://doi.org/10.2110/001c.37652>

---

## The Sedimentary Record

---

The distribution of sedimentary systems on Earth's surface is intimately linked to tectonics, therefore, at plate boundaries the stratigraphic archive can unlock the timing and style of tectonism and relative plate motions. Using large-n detrital zircon and micropaleontological analyses, tied to field mapping and data collection, we unravel the timing of strike-slip motion and its influence on the development of a Cretaceous submarine canyon on a long-lived oblique-convergent margin. Structural analysis demonstrates that the canyon bedrock, composed of fluvial rocks (La Bocana Roja Fm., of maximum depositional age (MDA):  $93.6 \pm 1.1$  Ma), underwent both syn- and post-depositional contractional and extensional deformation during the Cenomanian-Turonian in response to dextral strike-slip movement. Relative sea-level rise associated with basin subsidence and hinterland uplift was coincident with incision and fill of a submarine canyon system (Punta Baja Fm., MDA  $87.1 \pm 1.5$  Ma to  $84.9 \pm 2.0$  Ma), which exploited structural lineaments in the bedrock. The canyon was filled by sediment derived from an uplifted magmatic arc during the Coniacian to Santonian, most likely shed from erosional topography associated with plutonic intrusions to the NE. Structural data suggest that oblique dextral strike-slip motion on the Pacific margin controlled the development and location of submarine erosion, and had ended by the earliest Santonian, significantly earlier than previously estimated. Basinward tilting led to uplift, followed by transgression and wave ravinement of the canyon fill, which was then overlain by a shallow-marine to fluvial system. Thus, the canyon was cut, filled, buried, uplifted and rotated basinward, planed off through wave ravinement, and overlapped by shallow-marine to fluvial sediments within an 8 Myr period. Our findings, in part, reconcile contrasting basin evolution models for the Late Mesozoic Pacific margin.

### INTRODUCTION

Submarine canyons are incisional features on continental shelves and act as conduits for large volumes of sediment transferred from continents to oceans (e.g., Fildani, 2017; Shepard & Dill, 1966). The location and spacing of submarine canyons, their geometry and orientation with respect to the regional slope, and their connection to a sediment input, can be strongly affected by tectonics (e.g., Le Dantec et al., 2010; Maier et al., 2018). Shifting shorelines associated with tectonic movements can drive bedrock incision and formation of river valleys and submarine canyons, often strongly controlled by the inherited and/or developing structural grain (e.g., Buffington, 1964). Therefore, the timing of incision and filling of submarine canyons, and their relationship to structural fabric, can inform the timing and style of tectonic activity at plate margins.

The Mesozoic stratigraphy of the Peninsular Ranges forearc basin complex of the Pacific coastal margin of northwestern Baja California and southwestern California

provides a high-resolution record of a long-lived convergent plate boundary (C. Busby et al., 1998). The margin evolved from a highly-extensional intraoceanic arc, through a fringing arc stage, to a compressional continental arc characterized by oblique convergence (C. Busby et al., 1998; Engebretson et al., 1985; Glazner, 1991). From the mid-Cretaceous onwards the shift to a compressional stress regime was marked by reverse faulting and an influx of coarse sediment shed across a narrow shelf into forearc basins associated with batholith emplacement and unroofing (C. Busby et al., 1998; cf. Kimbrough et al., 2001). Although these forearc basins were strongly controlled by strike-slip deformation associated with compression (C. Busby et al., 1998), the timing of stress regimes on the Pacific margin remains poorly constrained (C. Busby et al., 1998; Kimbrough et al., 2001). This uncertainty hinders paleogeographic reconstructions and constraining plate motions relative to the Pacific plate. To address this we examine several unconformity bound sedimentary successions and their structural

relationships, tied to new age constraints from a large-n detrital zircon dataset and micropaleontology.

## STRATIGRAPHY

The Peninsular Ranges stratigraphy can be broadly divided into the 'pre-batholithic' and 'post-batholithic' rocks of the magmatic arc, which lies below but predominantly to the east of the modern coastal margin (Gastil et al., 1975). The pre-batholithic Alisitos Group (140–100 Ma; Allison, 1974; Cathy Busby, 2004) includes a wide variety of volcanic and sedimentary rocks that crop out discontinuously from the Agua Blanca Fault south of Ensenada, to the Baja California National Park of the Central Desert in the South (Cathy Busby, 2004; Fackler-Adams & Busby, 1998; Gastil et al., 1975). The Alisitos Group forms the basement to a thick succession of Upper Cretaceous sedimentary rocks forming the 'post-batholithic' succession.

The post-batholithic succession of the study area (c. 90 Ma and younger; Gastil et al., 1975) was deposited on the eastern side of the west-facing Peninsular Ranges forearc basin complex (Bottjer & Link, 1984; Gastil et al., 1975). These rocks crop out discontinuously along the Pacific coastal margin of northern Baja California and southern California (Beal, 1948; Gastil et al., 1975). The stratigraphy comprises, from base to top: 1) a non-marine interval of fluvial channel-fills, overbank deposits and paleosols (La Bocana Roja Fm.), 2) submarine canyon-fill strata (Punta Baja Fm.), 3) shallow marine deposits transitioning to fluvial red-beds and paleosols (El Gallo Fm.), and 4) a shallow-to deep-marine succession of continental shelf to slope strata (Rosario Fm.) (Fig. 1) (Kilmer, 1963). Unconformable contacts between each of these formational units record basin-ward tilting and associated faulting and folding. Together these are overlain unconformably by a thick package of Paleogene to Neogene sedimentary and lesser volcanic rocks. Sedimentological features of the Punta Baja Fm. canyon-fill, which is the focus of this study, have been described by Boehlke and Abbot (1986) and Morris and Busby (1996).

### La Bocana Roja Formation

La Bocana Roja Formation (Kilmer, 1963) is a c. 675 m thick succession of fluvial sandstones and mudstones (Schile, 1974). The basal contact with the underlying Alisitos Formation is not exposed and initially Kilmer (1963) had suggested that the Bocana Roja might be a stratigraphic equivalent of the lowermost El Gallo Formation; subsequent dating work and the results presented below suggest that the latter is significantly older. This unit forms the bedrock to the Punta Baja Formation canyon.

### The Punta Baja Formation

Kilmer (1963) introduced the general stratigraphy of the Punta Baja Formation but it was Boehlke & Abbot (1986) who made the first detailed study of the Formation. The maximum exposed thickness of the Punta Baja Fm. is c. 120 m thick (Schile, 1974) and is an unconformity-bound stratigraphic interval of bathyal sedimentary rocks, interpreted

to have been deposited within a submarine canyon (Boehlke & Abbott, 1986).

Within the Punta Baja Formation, Kilmer (1963) recorded the ammonite *Metaplacenticeras pacificum*, suggesting that a middle Campanian age (Schile, 1974), however, an Early Campanian age was determined by Boehlke & Abbott (1986) based upon the presence of calcareous nannofossils (*Phanulithus ovalis*, a now outdated synonym of *Calculites ovalis*). 'Giant' specimens of the bivalve *Glycymerita veatchii*, transported within gravity flows, are found in pebbly sandstones of the Punta Baja Formation (Squires, 2010); these are considered to range in age from the late middle Campanian to late Campanian which coincides with the lower half of the *Metaplacenticeras pacificum* ammonite biozone (Squires, 2010).

### The El Gallo Formation

The El Gallo Formation is a ~1300 m thick succession of shallow marine and fluvial deposits (Kilmer, 1963; Renne et al., 1991; Schile, 1974). Kilmer (1963) divides the El Gallo Formation into three informal members: 1) the La Escarpa member, a c. 150 m thick conglomeratic unit representing alluvial fan to braided stream deposits; 2) the El Disecado member, an overlying finer-grained fluvial to tidal member (840–1150 m thick), and 3) the El Castillo member, a laterally discontinuous, poorly-sorted conglomeratic unit that is contained within the El Disecado member, but only preserved toward the east of the present study area (Schile, 1974).

## DATA AND METHODOLOGY

Stratigraphic, sedimentological (including paleocurrents from ripple foresets, clast imbrication and sole structures) and structural data were collected in the field, alongside samples for detrital zircon (Fig. 1, Table 1), micropaleontological, and palynological analysis. Detrital zircons were extracted from samples (N = 8) collected from the La Bocana Roja, Punta Baja, and El Gallo formations; U/Pb ratios and dates of three hundred grains from each sample were obtained using Laser Ablation – Inductively Coupled – Plasma Mass Spectrometry (LA-ICP-MS) following the methodology of Matthews and Guest (2016). Sandstone maximum depositional ages (MDAs) were calculated using the YGC 2 $\sigma$  methodology (Dickinson & Gehrels, 2009), as this has been demonstrated to produce accurate and precise results (Coutts et al., 2019). Where possible, the youngest detrital zircon grains were reablated to test the isotopic homogeneity of the grain(s) used in the calculation of the MDA and to reduce uncertainty (Spencer et al., 2016).

Micropaleontological and palynological samples from the Punta Baja Fm. were analyzed to compare with detrital zircon MDAs. Two samples were collected from the Punta Baja Fm. for palynology analysis to complement existing micropaleontology data (Boehlke & Abbott, 1986). Samples were processed in a standard fashion (Wood et al., 1996). Residues were analyzed for their organic matter content and identification of key dinoflagellate cyst species (Table 2; Supplementary Materials). Species were compared with

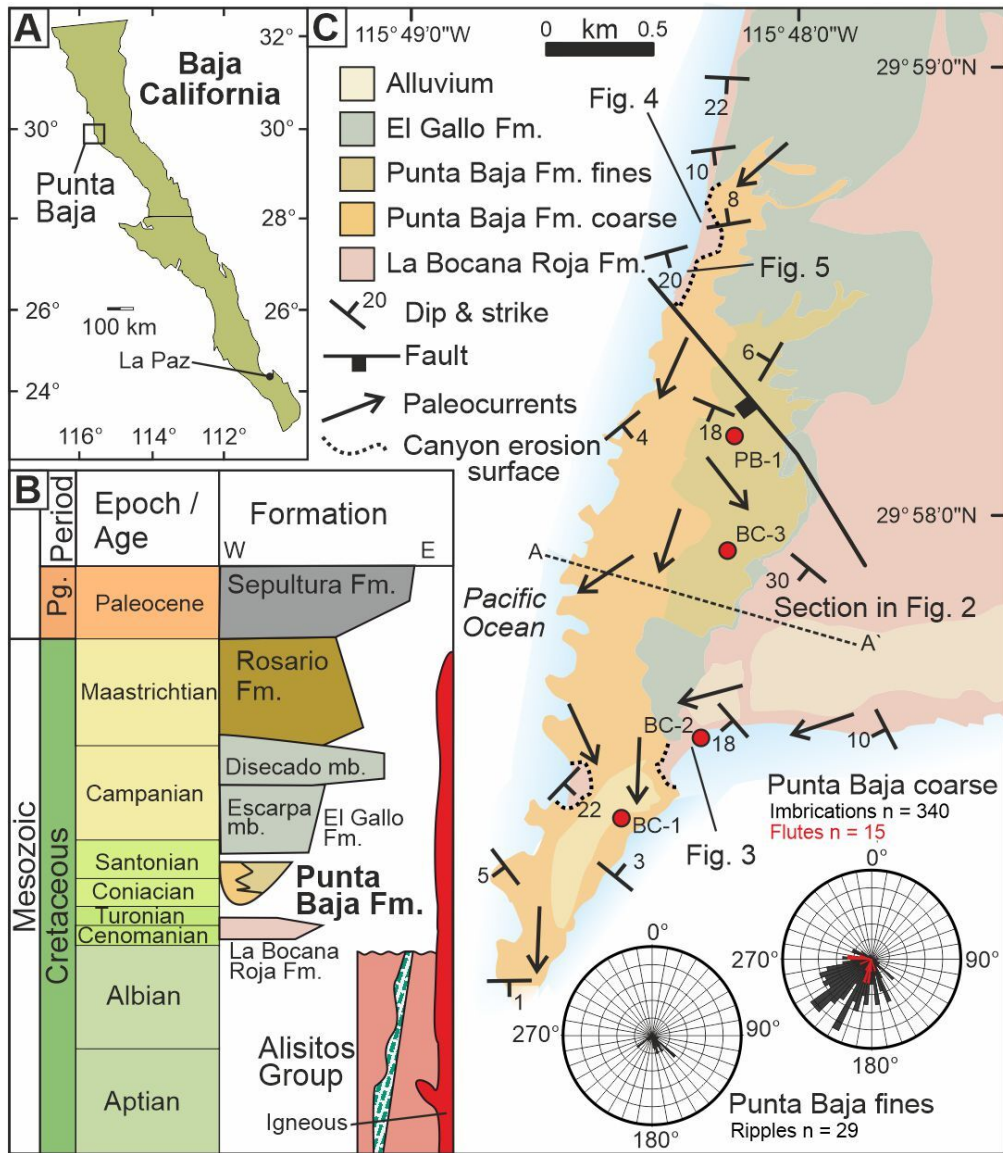


Fig. 1. A) Baja California Peninsula; B) Stratigraphy of the study area modified from Busby et al. (1998), incorporating new age data. Pg: Paleogene; mb: (informal) member. C) Geological mapping from this study. Red dots show selected detrital zircon sample locations; all sample locations are given in Table 1.

Table 1. Detrital zircon sample locations

Sample Name	Stratigraphic unit	Latitude	Longitude
BC-1	Punta Baja Formation	115.80779 W	29.95410 N
BC-2	Bocana Roja Formation	115.80375 W	29.95842 N
BC-3	Punta Baja Formation	115.80242 W	29.964611 N
BC-12	El Gallo Formation	115.40886 W	29.89684 N
BC-13	El Gallo Formation	115.38165 W	29.88224 N
BC-20	El Gallo Formation	115.77956450 W	29.98069183 N
PB-1	Punta Baja Formation	115.802121 W	29.969630 N

published age ranges from the region in order to determine an acme age range.

### STRUCTURAL AND STRATIGRAPHIC FEATURES: OBSERVATIONS

Mapping and stratigraphic correlation indicates that the canyon fill trends NNE-SSW, with paleoflow to the SSW

**Table 2. Dinoflagellate cyst retrieved from the Punta Baja Formation, and their documented age ranges.**

Dinoflagellate cyst	Documented age range (authority)
<i>Alisogymnium cerviculum</i>	Coniacian to Maastrichtian (Helenes, 1984)
<i>Alterbidinium minus</i>	Coniacian to Maastrichtian (Lentin & Williams, 1985)
<i>Apteodinium deflandrei</i>	Cenomanian-Santonian (Lucas-Clark, 1987)
<i>Dinogymnium acuminatum</i>	Cenomanian to Maastrichtian (Helenes, 1984)
<i>Oligosphaeridium complex</i>	Aptian – Maastrichtian (Srivastava, 1995)
<i>Palaeoperidinium pyrophorum</i>	Late Cretaceous to Paleocene (Evitt et al., 1998)
<i>Spiniferites ramosus</i>	Late Cretaceous (Davey & Williams, 1966)
<i>Trichodinium castaneum</i>	Turonian to Campanian (Williams & Bujak, 1985)
<i>Xenascus ceratioides</i>	Coniacian – Maastrichtian (Helenes, 1984)

(Fig. 1 & 2; Boehlke & Abbott, 1986). The canyon's basal erosion surface is exposed along its western margin, where coarse-grained canyon axis facies directly onlap the bedrock. Here, the canyon margin is characterized by localized canyon-base incisions spatially associated with normal faults, superimposed on the major canyon cut (Figs. 2–5). Towards the east, coarse-grained canyon facies transition laterally to finer-grained canyon terrace and internal levee facies, which onlap the bedrock (La Bocana Roja Fm., Boehlke & Abbott, 1986) (Fig. 2). The bedrock is more structurally deformed than younger units (Figs. 2, 3), with a high degree of variability in bedding orientation. Overall, the bedrock forms a broad SW-plunging syncline, with shallow bedding dips predominantly south-southeast on the western side of the canyon fill and towards the southwest at up 18° on the eastern side (Fig. 1). This fold structure is incised and overlapped by the Punta Baja Fm., which dips at 1–8°, with local dip changes in the Punta Baja Fm., related to the underlying bedrock structure (Fig. 1). The overlying, sub-horizontal, El Gallo Fm. displays an angular discordance with the Punta Baja Fm. and beyond the canyon-cut rests unconformably on the La Bocana Roja Fm. A locally discontinuous but aerially extensive cobble lag with well-rounded *Gastrochaenolites* (bored) clasts occurs at the base of the El Gallo Fm.

Several sets of faults affect the bedrock, and to a lesser extent the canyon fill (Figs. 2B, 4). On the western side of the canyon, post-depositional extensional faults dominate within the bedrock and generally strike WNW-ESE, and are downthrown to the south (Fig. 2). A subset of NNE-SSW striking extensional faults in bedrock share the same orientation as syn-depositional faults in the Punta Baja Fm. (Fig. 2). On the eastern side of the canyon, contractional faults dominate, with N-S to NW-SE orientations, overall eastward shortening, and several WNW-ESE and ENE-WSW trending strike-slip faults (Fig. 2B), recognized by offset

strata with minimal vertical displacement but thickness changes, and slickensides, indicating a lateral component of movement. Several fold structures on the eastern side are incised and overlain by low angle bedding within the bedrock. Erosional cuts at the base of the submarine canyon fill, into the bedrock, strike approximately NNE-SSW, dipping towards the SE in the western outcrops, and towards the W-SW in the eastern outcrops, defining a trend that is consistent with the main paleoflow of the canyon (Figs. 1, 2).

## INTERPRETATION

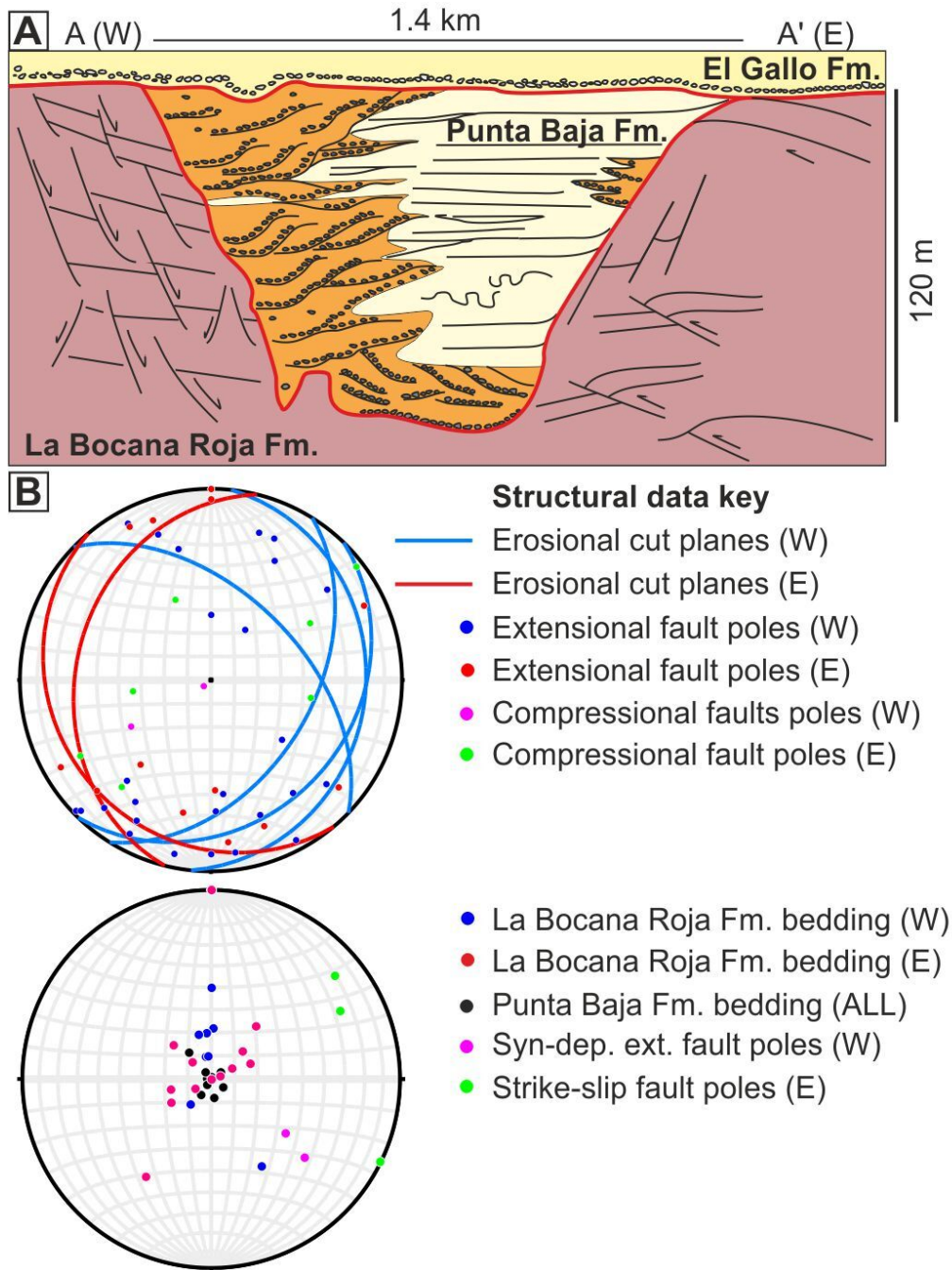
The La Bocana Roja Fm. bedrock underwent extension and contraction associated with strike-slip displacement during and following deposition, which we attribute to releasing and restraining bends on a dextral strike-slip fault zone oriented approximately WNW-ESE (Fig. 2). Canyon orientation follows the axial plane of the SW-plunging syncline developed within the bedrock. Faults superimposed on this syncline may have acted as planes of weakness, and/or formed seabed topography that localized canyon incision. Observations match the regional study of Busby et al. (1998), who suggested that the La Bocana Roja Fm. was folded and dissected by high-angle reverse faults prior to deposition of the Punta Baja Fm. Deformation was interpreted to be associated with normal faults with a dextral slip component that facilitated the high rate of subsidence (600 m/my) required to accommodate the Upper Cretaceous to Palaeogene stratigraphy (C. Busby et al., 1998). Above the submarine canyon fill deposits, the basal surface of the El Gallo Fm. is interpreted to rest on a ravinement surface which is locally overlain by a transgressive lag deposit

## DEPOSITIONAL ARCHITECTURE AND PALEOGEOGRAPHY OF THE CANYON FILL

The canyon-fill is c. 120 m thick, 1.2 km wide and has two broad domains; a coarse-grained channelized domain that onlaps the western margin and represents the paleoflow axis, and a fine grained overbank section to the east (Fig. 2A; Boehlke & Abbott, 1986; W. R. Morris & Busby, 1996). Lenticular and wedge-shaped sandstone bodies, which pass eastward into a thin-bedded turbidite succession, characterize the transition between the two domains and are interpreted to represent overbank channels and scour fills. Rugose basal channel erosion surfaces are overlain by debrites with megaclasts (up to several meters across) and thin-bedded turbidite mudstones and sandstones (Fig. 3). Preferential stacking of channel axes in the western side of the canyon may be a response to dominant extensional faulting and subsidence of bedrock on that side and away from contractional features on the eastern side, or may alternatively reflect an autocyclic control on stacking of component channel-fill (e.g., Hodgson et al., 2011), or an interplay of the two.

## Micropaleontology and palynology

Sample BOC-1 from within the coarse-grained western channel fill was barren of palynomorphs, being dominated by oxidized and degraded wood fragments. Sample PBI-1,



**Fig. 2. Summary cartoon of the Punta Baja Formation canyon fill. B) Equal area stereonet presenting structural data from the canyon (W and E indicate data collected from the western and eastern sides of the canyon, respectively).**

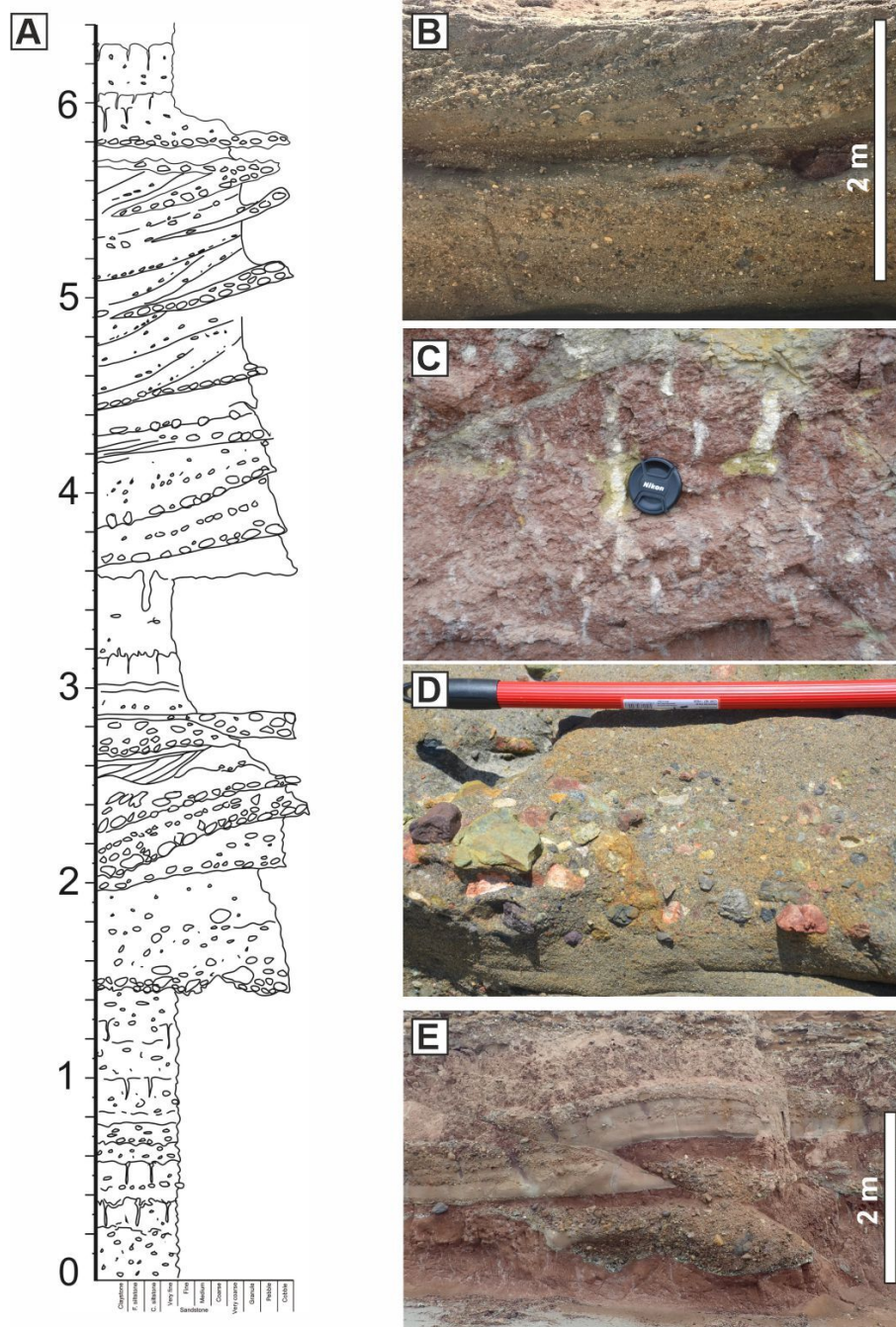
collected from within the fine grained, thin-bedded turbidites of the eastern side demonstrated a wide range of plant fragments, marine detritus and an abundance of paly-nomorphs, including dinoflagellate cysts. The ratio of marine (67.5% n=139) to non-marine (32.5% n=67) paly-nomorphs indicates proximity to a landmass, but is dominantly marine, whilst the ratio of Perinoid (45% n=57) to Gonyaulacoid (55% n=69) dinocysts indicates lower productivity conditions, potentially with a stratified water column, and lacking significant upwelling (Pross & Brinkhuis, 2005).

An abundance of open marine dinoflagellate cysts, e.g., *Spiniferites* sp., supports deposition of the Punta Baja Fm.

canyon sediments in the outer neritic zone, typical of a shelf edge setting (Table 2; Fig. 6). The dominance of gonyaulacoid over perinoid cysts suggests a relatively stratified, lower productivity water column, and the ratio of marine organisms to terrestrial pollen and spores demonstrates proximity to land but an overall marine setting (DR2).

### Depositional Ages

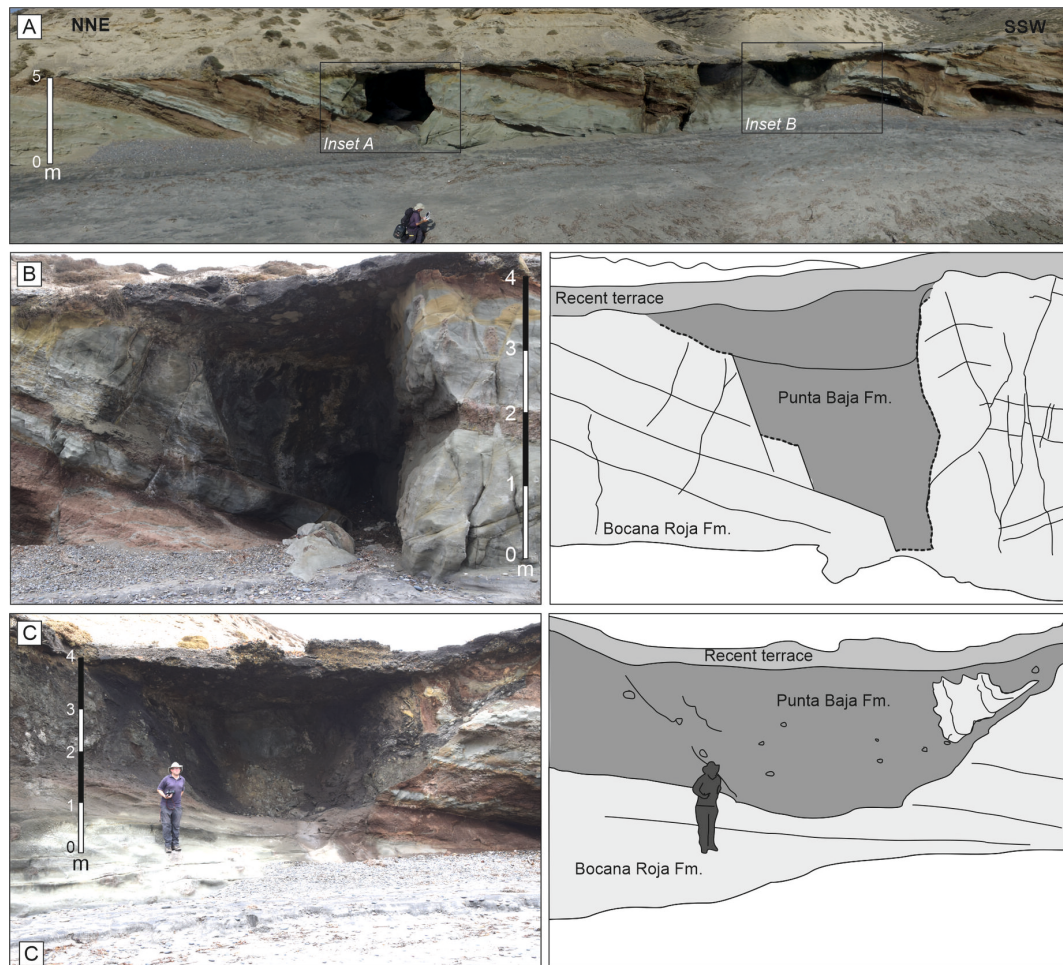
Cumulative and normalized probability density functions for all samples together with MDAs calculated using the YGC 2 $\sigma$  method of Dickinson and Gehrels (2009) are



**Fig. 3. Outcrop characteristics of La Bocana Roja Fm. which forms the canyon bedrock. A) Measured section showing interbedded paleosols and gravelly fluvial channel fill deposits; vertical scale in meters. B) Cross-stratified conglomerate channel fill. C) Rhizololiths in overbank deposits. D) Poorly-sorted immature and diverse clasts within a channel lag deposit. at the base of the Punta Baja Fm. canyon-fill; E) reversed normal fault within the bedrock on the western side of the canyon fill.**

presented for the eight samples analyzed (see methods section; Fig. 8; Table 3). While there is no systematic up-section change in the data presented, the oldest and youngest samples are missing the 150 Ma peak seen in all the Punta Baja samples and the older El Gallo sample, suggesting that rivers were tapping a different source at that time. Samples BC-1 and BC-20 have comparably diverse and slightly more abundant ages >200 Ma than the other samples, also suggesting hinterland drainage changes. The new data yield an MDA for the La Bocana Roja Fm. of  $93.6 \pm 1.1$  Ma (Turonian). Previous work suggested a Campanian age, based largely on

the presence of a theropod dinosaur fossil, *Labocania* (Molnar, 1974). The Punta Baja Fm. MDAs range from  $87.1 \pm 1.5$  Ma in the axis to  $84.9 \pm 2.0$  Ma at the base of the overbank section. Dinoflagellate cysts are abundant in the muddy parts of the canyon-fill, and our analysis (Table 2) suggests a Coniacian to Santonian age, with *Apeteodinium deflandrei* having a last known occurrence in the Santonian; together the two datasets support a probable Coniacian age for the canyon fill. This is considerably older than the Early Campanian age suggested by Boehlke & Abbott (1986) based upon the presence of the calcareous nannofossil *Calculites*



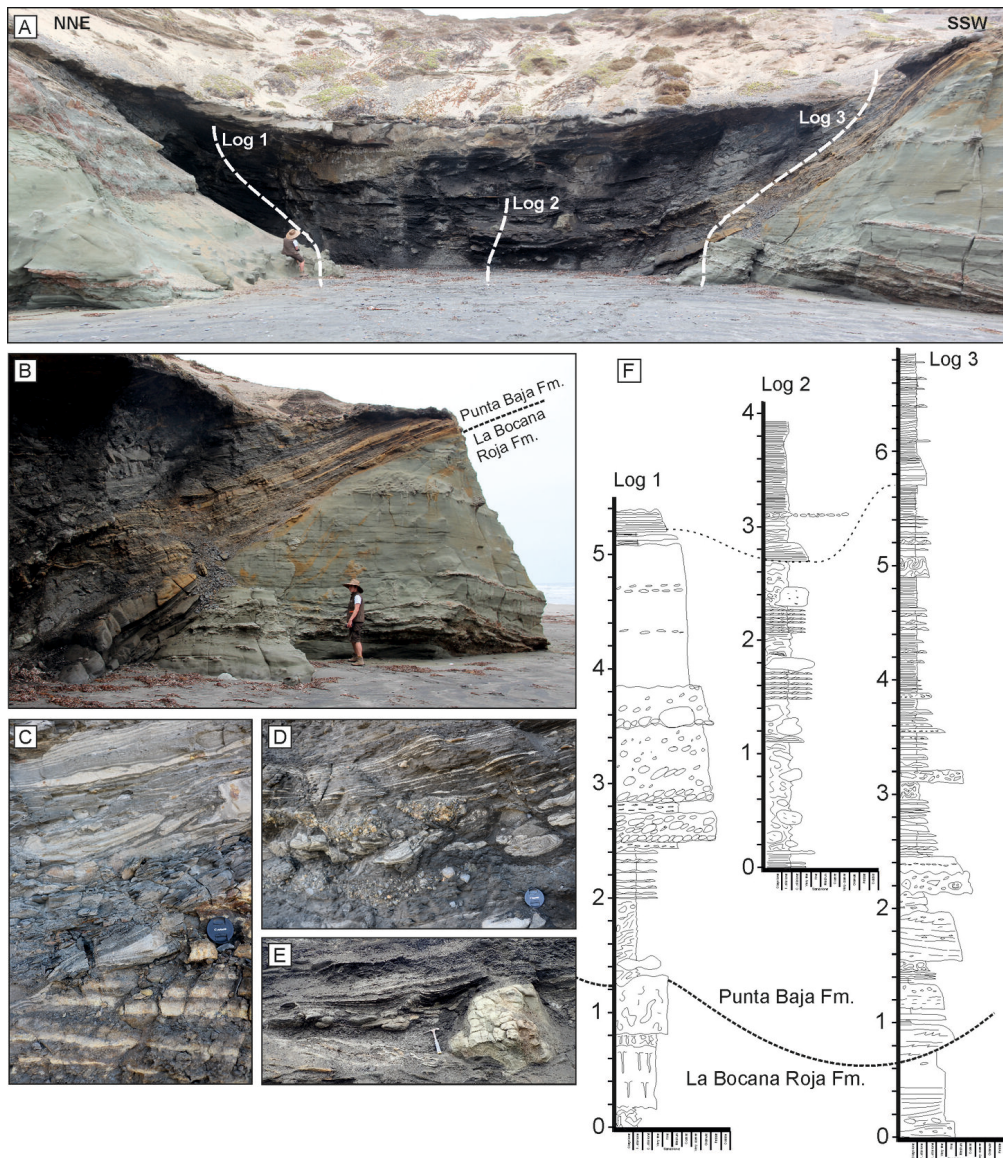
**Fig 4. A) Incisions into the bedrock (La Bocana Roja Fm.) focused on small normal faults on the western side of the canyon fill (See Fig. 3). B) The Punta Baja Fm. fill here is pebbly mudstone with clasts of the bedrock incorporated. C) Large Bocana Roja Fm. clasts incorporated within a Punta Baja Fm. muddy debris**

*ovalis*, which is now known to first appear in the Coniacian (Burnett, 1998), so its presence is not inconsistent with our MDAs. The upper middle Campanian age given by *Glycymerita veatchii* bivalves in the Punta Baja Fm. (Squires, 2010) is based on their general increase in size from the Turonian onwards, so their large size in the Punta Baja Fm. may be related to localized environmental factors.

Immediately above the contact with La Bocana Roja Fm., the El Gallo Fm. yields an MDA of  $86.8 \pm 1.8$  Ma, while MDAs from stratigraphically higher El Gallo Fm. samples yield MDAs of  $72.6 \pm 1.3$  and  $71.9 \pm 1.7$  Ma. Previous  $^{40}\text{Ar}/^{39}\text{Ar}$  analyses of individual sanidine grains from four El Gallo Fm. tuffs yielded Late Campanian ages of  $74.87 \pm 0.05$  Ma to  $73.59 \pm 0.09$  Ma (Renne et al., 1991), while overlying tuffs were dated at  $74.706 \pm 0.028$  Ma (Fastovsky et al., 2020) and  $73 \pm 2$  Ma (W. J. Morris, 1974). The close replication of the previous younger ages supports the robustness of our method, and therefore the older MDA. However, it is possible that older recycled zircons were analyzed. Nonetheless, our data suggest that the El Gallo Fm. may span a considerably longer time period than previously estimated, which given its thickness (1.3 km), and deposition by multiple sedimentary systems in different shallow-marine to terrestrial environments over evolving fault blocks (W. R. Morris & Busby, 1996), is unsurprising.

## DISCUSSION AND CONCLUSION

Uncertainty in the timing of onset and termination of oblique convergence in the Late Cretaceous of the Peninsular Ranges forearc basins has hindered accurate paleogeographic reconstructions, and the constraining of plate motions relative to the Pacific plate (C. Busby et al., 1998; Kimbrough et al., 2001). La Bocana Roja Fm. strata experienced both syn- and post-depositional contractional and extensional deformation during the Cenomanian-Turonian. At this time, a major pulse of coarse grained material was delivered to the forearc; this has been attributed to the intrusion of voluminous tonalite-granodiorite magmas, with associated erosional topography (Kimbrough et al., 2001), or to an accelerated phase of compression with related contractional deformation from 105–95 Ma (C. Busby et al., 1998). Kimbrough et al. (2001) suggest that widespread compressional strain ended at 99 Ma, predating the major intrusive episode. Our field-data support ongoing compression during and after La Bocana Roja deposition, but we revise the age considerably from Campanian to Turonian ( $93.6 \pm 1.1$  Ma); this was largely over by the onset of canyon filling ( $87.1 \pm 1.5$  Ma). Canyon bedrock records oblique contractional deformation with a resulting plunging syncline, and preferential development of extensional faults within



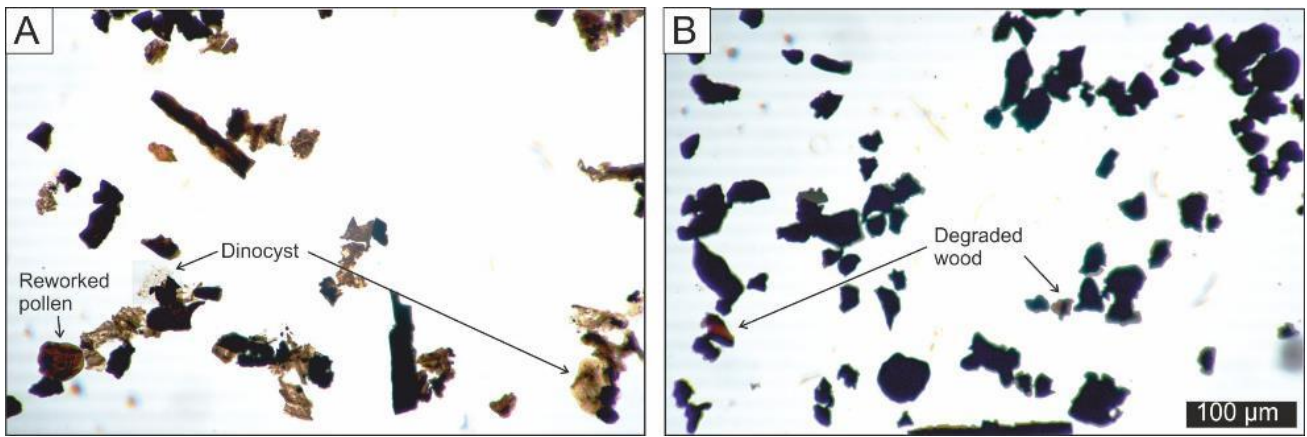
**Fig. 5.** A) Oblique exposure of an incision into the La Bocana Roja bedrock. B) Steep onlap of the canyon wall by thick to thin-bedded turbidites and debrites. C) Erosion surfaces and intra-clasts are evidence of multiple episodes of cutting and filling of the canyon. D) Soft sediment deformation of the fill. E) Large canyon wall clast within the canyon fill (hammer for scale). F. Measured sections through the canyon fill; vertical scale in meters.

its western limb, and contractional topography on the east. We attribute the close association of extensional and contractional domains to releasing and restraining bends on a dextral strike-slip fault zone oriented approximately WNW-ESE that persisted until Late Turonian-Early Coniacian times. These tectonic features appear to have focused sediment gravity flows and canyon incision. Smaller-scale incisions superimposed on the major canyon cut are spatially associated with extensional faults in the bedrock. The canyon was initially a major conduit for sediment bypass to the Pacific Ocean, but the infill became strongly aggradational, suggesting high sediment supply rates and continual development of accommodation through subsidence.

Maximum depositional ages (MDAs) from detrital zircons date the upper part of the fluvial bedrock (La Bocana Roja Fm.) at  $93.6 \pm 1.1$  Ma (Cenomanian-Turonian), the Punta Baja Fm. canyon-fill at  $87.1 \pm 1.5$  Ma to  $84.9 \pm 2.0$  Ma (Coniacian to Santonian), and the overlying El Gallo Fm. at

$86.8 \pm 1.8$  Ma to  $71.9 \pm 1.7$  Ma (Coniacian to Maastrichtian, although the uncertainty overlaps with that of the Punta Baja Fm. suggesting a probable maximum age of Santonian). The timing of the submarine canyon-fill is supported by micropaleontological evidence, which also suggests an uppermost Turonian to Santonian age. Thus, the canyon was cut, filled, buried, uplifted and rotated basinward, planed off through wave ravinement, and onlapped by shallow-marine deposits within an 8 Myr period. The duration of canyon cutting and filling is likely much shorter, but is beneath the resolution of detrital zircon maximum depositional ages (Coutts et al., 2019) and the results demonstrate the relatively short lifespan of major submarine canyons in tectonically active settings (cf. Englert et al., 2018). Plutonic intrusions approx. 100 km to the NE of the study area have been dated at  $97^{+4}_{-1}$  Ma (Ortega-Rivera et al., 1997) and  $96 \pm 4$  Ma (Measures, 1996), slightly predating the La Bocana Roja Fm. sediment flux ( $93.6 \pm 1.1$  Ma), supporting the role of mag-





**Figure 6. Photomicrographs of samples (A) PBI-1 dominated by degraded wood fragments with palynomorphs indicated, and (B) sample BOC-1, which is dominated by oxidized wood. Both at same scale (see B).**

matic emplacement in the generation of erosional topography at this time.

We show that partly syn-depositional oblique contractional deformation of the bedrock influenced canyon incision. However, the canyon fill is not affected by syn-depositional compression suggesting the end of oblique dextral contractional deformation, on this part of the Pacific margin, occurred in the Turonian-Coniacian, significantly later than previously suggested (cf. Kimbrough et al., 2001). Back-dating of the La Bocana Roja bedrock suggests that plutonic intrusions and associated erosional topography to the NE formed likely sediment sources at this time (Kimbrough et al., 2001). Later uplift and basinward tilting of the canyon fill, due to intrabasinal reverse faulting (C. Busby et al., 1998), occurred in mid-Coniacian times, earlier than previously suggested.

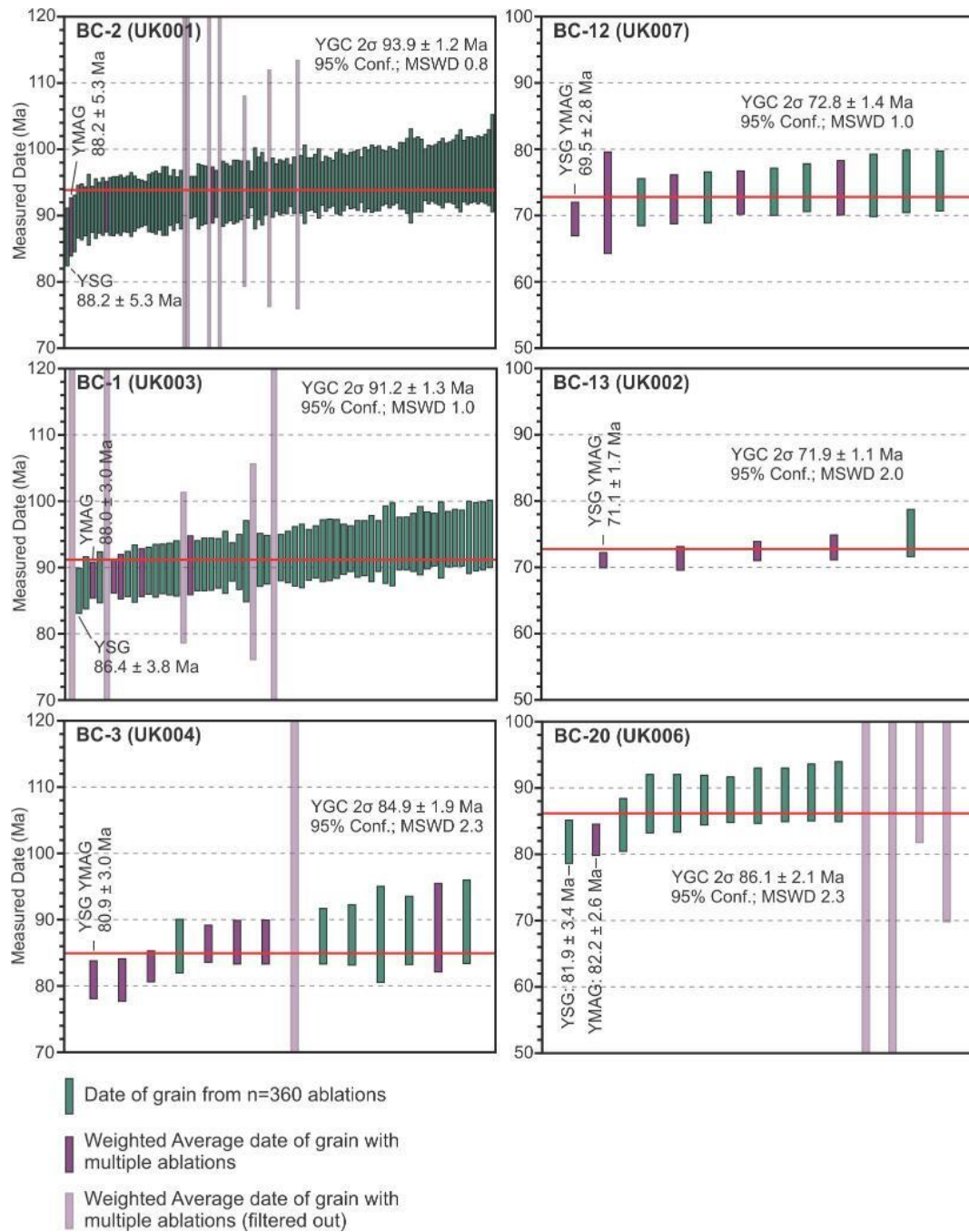
This study provides new insights into the control that antecedent tectonic seabed topography may exert on submarine canyon formation and evolution, and documents the switch from regional extensional to contractional tectonics as recorded in the sedimentary record. Furthermore, the duration of incision and filling of the Punta Baja submarine canyon, and its relationship to structural fabric, has placed new constraints on the timing and style of plate motion relative to the Pacific plate to inform paleogeographic reconstructions.

---

## Acknowledgements

We thank Zane Jobe and an anonymous reviewer for their helpful comments which improved the clarity of the manuscript.

Submitted: June 13, 2022 CDT, Accepted: August 13, 2022 CDT



**Figure 7. Combined results of two rounds of ablation for near-depositional age grains. Green boxes are dates from the n=360 round of ablations; purple boxes are dates from the lower-uncertainty reablation round. Light purple boxes indicate measurements where multiple reablations failed to yield a reproducible uncertainty. Thick red line is the MDA and uncertainty calculated by the YGC 2σ method of Dickinson and Gehrels (2009). MDAs from the YSG and YMAG are indicated above the grain. All uncertainties are reported at 2σ and at 95% confidence. Note the change in vertical scale for sample PC-2.**

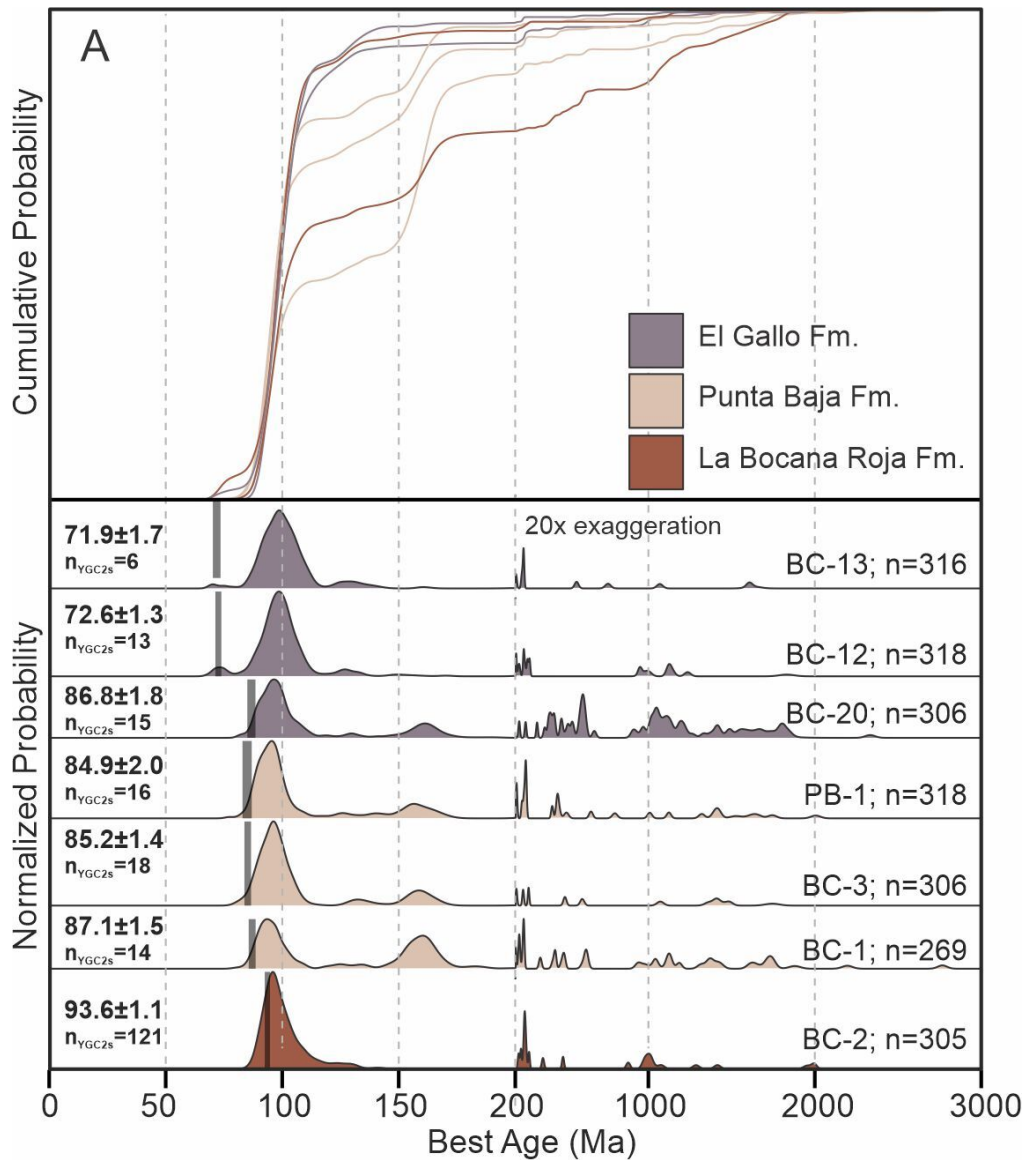
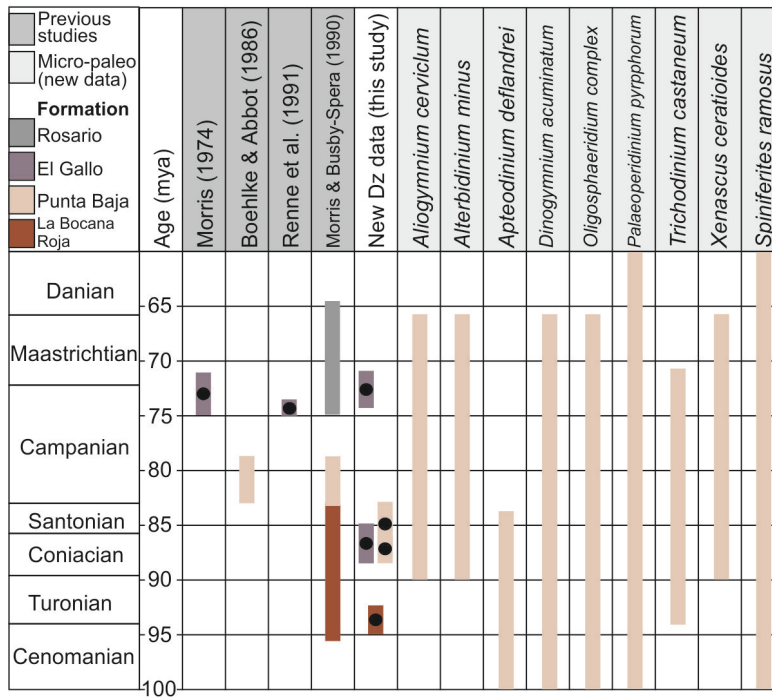


Figure 8) Cumulative and normalized probability density functions for all samples. MDAs were calculated by the YGC  $2\sigma$  method of Dickinson and Gehrels (2009) using only the  $n=360$  round of ablations and are indicated by the vertical grey bar. The width of the bar reflects the  $2\sigma$  uncertainty of the MDA. The number of grains in the MDA is given below the MDA ( $n_{YGC2\sigma}$ ). Curves  $>200$  Ma are 20X vertically exaggerated. Note the change in horizontal scale at 200 Ma.



**Table 3. Age constraints from literature alongside new detrital zircon data and micropaleontological age ranges. Solid black dots in zircon data indicate age, colored bars indicate the uncertainty range.**



This is an open-access article distributed under the terms of the Creative Commons Attribution 4.0 International License (CCBY-4.0). View this license's legal deed at <http://creativecommons.org/licenses/by/4.0> and legal code at <http://creativecommons.org/licenses/by/4.0/legalcode> for more information.

## References

- Allison, E. C. (1974). The type Alisitos Formation (Cretaceous, Aptian–Albian) of Baja California and its bivalve fauna. In R.G. Gastil (Ed.), *Geology of Peninsular California: Guidebook* (pp. 29–59). Pacific Section SEPM.
- Beal, C. H. (1948). Reconnaissance of the geology and oil possibilities of Baja California, Mexico. *Geological Society of America Memoirs*, 31, 1–150. <https://doi.org/10.1130/mem31-p1>
- Boehlke, J. E., & Abbott, P. L. (1986). Punta Baja Formation, a Campanian submarine canyon fill, Baja California, Mexico. In P. L. Abbott (Ed.), *Cretaceous Stratigraphy Western North America* (Vol. 46, pp. 91–102). Pacific Section SEPM.
- Bottjer, D. J., & Link, M. H. (1984). A synthesis of Late Cretaceous southern California and northern Baja California paleogeography. In J. K. Crouch & S. B. Bachman (Eds.), *Tectonics and sedimentation along the California margin: Society of Economic Paleontologists and Mineralogists Pacific Section 38* (pp. 171–188).
- Buffington, E. C. (1964). Structural control and precision bathymetry of La Jolla Submarine Canyon, California. *Marine Geology*, 1(1), 44–58. [https://doi.org/10.1016/025-3227\(64\)90005-2](https://doi.org/10.1016/025-3227(64)90005-2)
- Burnett, J. A. (1998). Upper Cretaceous. In P. R. Brown (Ed.), *Calcareous Nannofossil Biostratigraphy* (pp. 132–199). Chapman & Hall. [https://doi.org/10.1007/978-94-011-4902-0\\_6](https://doi.org/10.1007/978-94-011-4902-0_6)
- Busby, C., Smith, D., Morris, W., & Fackler-Adams, B. (1998). Evolutionary model for convergent margins facing large ocean basins: Mesozoic Baja California, Mexico. *Geology*, 26, 227–230. [https://doi.org/10.1130/0091-7613\(1998\)026%3C0227:EMFCMF%3E2.3.C.O;2](https://doi.org/10.1130/0091-7613(1998)026%3C0227:EMFCMF%3E2.3.C.O;2)
- Busby, Cathy. (2004). Continental growth at convergent margins facing large ocean basins: a case study from Mesozoic Baja California, Mexico. *Tectonophysics*, 392(1–4), 241–277. <https://doi.org/10.1016/j.tecto.2004.04.017>
- Coutts, D. S., Matthews, W. A., & Hubbard, S. M. (2019). Assessment of widely used methods to derive depositional ages from detrital zircon populations. *Geoscience Frontiers*, 10(4), 1421–1435. <https://doi.org/10.1016/j.gsf.2018.11.002>
- Dickinson, W. R., & Gehrels, G. E. (2009). Use of U-Pb ages of detrital zircons to infer maximum depositional ages of strata: a test against Colorado Plateau Mesozoic database. *Earth and Planetary Science Letters*, 288, 115–125. <https://doi.org/10.1130/b26406.1>
- Engelbertson, D. C., Cox, A., & Gordon, R. G. (1985). Relative motions between oceanic and continental plates in the Pacific Basin. *Geological Society of America Special Papers*, 206, 1–60. <https://doi.org/10.1130/spe206-p1>
- Englert, R. G., Hubbard, S. M., Coutts, D. S., & Matthews, W. A. (2018). Tectonically controlled initiation of contemporaneous deep-water channel systems along a Late Cretaceous continental margin, western British Columbia, Canada. *Sedimentology*, 65(7), 2404–2438. <https://doi.org/10.1111/sed.12472>
- Fackler-Adams, B. N., & Busby, C. J. (1998). Structural and stratigraphic evolution of extensional oceanic arcs. *Geology*, 26, 735–738. [https://doi.org/10.1130/0091-7613\(1998\)026](https://doi.org/10.1130/0091-7613(1998)026)
- Fastovsky, D. E., Montellano-Ballesteros, M., Fricke, H. C., Ramezani, J., Tsukui, K., Wilson, G. P., Hall, P., Hernandez-Rivera, R., & Alvarez, G. (2020). Paleoenvironments, taphonomy, and stable isotopic content of the terrestrial, fossil-vertebrate-bearing sequence of the El Discado Member, El Gallo Formation, Upper Cretaceous, Baja California, México. *Geosphere*, 16(4), 991–1011. <https://doi.org/10.1130/ges02207.1>
- Fildani, A. (2017). Submarine canyons: A brief review looking forward. *Geology*, 45(4), 383–384. <https://doi.org/10.1130/focus042017.1>
- Gastil, R. Gordon, Phillips, R. P., & Allison, E. C. (1975). Reconnaissance geology of the state of Baja California. *Geological Society of America Memoirs*, 140, 1–201. <https://doi.org/10.1130/mem140-p1>
- Glazner, A. (1991). Plutonism, oblique subduction, and continental growth: An example from the Mesozoic of California. *Geology*, 19, 784–786.
- Hodgson, D. M., Di Celma, C. N., Brunt, R. L., & Flint, S. S. (2011). Submarine slope degradation and aggradation and the stratigraphic evolution of channel–levee systems. *Journal of the Geological Society*, 168(3), 625–628. <https://doi.org/10.1144/0016-76492010-177>
- Kilmer, F. H. (1963). *Cretaceous and Cenozoic stratigraphy and paleontology, El Rosario area* [Ph.D. thesis]. University of California Berkeley.
- Kimbrough, D. L., Smith, D. P., Mahoney, J. B., Moore, T. E., Grove, M., Gastil, R. G., Otega-Rivera, A., & Fanning, C. M. (2001). Forearc-basin sedimentary response to Late Cretaceous batholith emplacement in the Peninsular Ranges of southern and Baja California. *Geology*, 14, 491–494.
- Le Dantec, N., Hogarth, L. J., Driscoll, N. W., Babcock, J. M., Barnhardt, W. A., & Schwab, W. C. (2010). Tectonic controls on nearshore sediment accumulation and submarine canyon morphology offshore La Jolla, southern California. *Marine Geology*, 268(1–4), 115–128. <https://doi.org/10.1016/j.margeo.2009.10.026>
- Maier, K. L., Johnson, S. Y., & Hart, P. (2018). Controls on submarine canyon head evolution: Monterey Canyon, offshore central California. *Marine Geology*, 404, 24–40. <https://doi.org/10.1016/j.margeo.2018.06.014>

- Matthews, W. A., & Guest, B. (2016). A practical approach for collecting large-n detrital zircon U-Pb data sets by quadrupole LA-ICP-MS. *Geostandards and Geoanalytical Research*, 41(2), 161–180. <https://doi.org/10.1111/ggr.12146>
- Measures, M. A. (1996). *Geology of the Agua Caliente region, southeast Sierra San Pedro Martir, Baja California, Mexico* [M.S. thesis]. San Diego State University.
- Molnar, R. E. (1974). A distinctive theropod dinosaur from the Upper Cretaceous of Baja California (Mexico). *Journal of Paleontology*, 48, 1009–1017.
- Morris, W. J. (1974). Upper Cretaceous 'El Gallo' formation and its vertebrate fauna. In G. Gastil & J. Lillegraven (Eds.), *A Guidebook to the Geology of Peninsular California* (pp. 60–66). AAPG-SEPM-SEG Pacific Section.
- Morris, W. R., & Busby, C. J. (1996). The effects of tectonism on the high-resolution sequence stratigraphic framework of non-marine to deep-marine deposits in the Peninsular Ranges forearc basin complex. In P. L. Abbott & J. D. Cooper (Eds.), *Field Conference Guide, AAPG National Convention, San Diego, California* (pp. 381–408). The Pacific Section American Association of Petroleum Geologists. <https://doi.org/10.32375/1996-gb73.19>
- Ortega-Rivera, A., Farrar, E., Hanes, J. A., Archibald, D. A., Gastil, R. G., Kimbrough, D. L., Zentilli, M., Lopez Martinez, M., Feraud, G., & Ruffet, G. (1997). Chronological constraints on the thermal and tilting history of the Sierra San Pedro Martir pluton, Baja California, Mexico, from U/Pb,  $^{40}\text{Ar}/^{39}\text{Ar}$ , and fission-track geochronology. *Geological Society of America Bulletin*, 109, 728–745.
- Pross, J., & Brinkhuis, H. (2005). Organic-walled dinoflagellate cysts as paleoenvironmental indicators in the Paleogene; a synopsis of concepts. *Paläontologische Zeitschrift*, 79(1), 53–59. <https://doi.org/10.1007/bf03021753>
- Renne, P. R., Fulford, M. M., & Busby-Spera, C. J. (1991). High resolution  $^{40}\text{Ar}/^{39}\text{Ar}$  chronostratigraphy of the Late Cretaceous El Gallo Formation, Baja California del Norte, Mexico. *Geophysical Research Letters*, 18(3), 459–462. <https://doi.org/10.1029/91gl00464>
- Schile, C. A. (1974). *Sedimentology of the El Gallo Formation (Upper Cretaceous)* [M.S. thesis]. San Diego State University.
- Shepard, F. P., & Dill, R. F. (1966). *Submarine Canyons and Other Sea Valleys*. Rand McNally.
- Spencer, C. J., Kirkland, C. L., & Taylor, R. J. M. (2016). Strategies towards statistically robust interpretations of in situ U–Pb zircon geochronology. *Geoscience Frontiers*, 7(4), 581–589. <https://doi.org/10.1016/j.gsf.2015.11.006>
- Squires, R. L. (2010). Northeast Pacific Upper Cretaceous and Paleocene Glycymeridid Bivalves. *Journal of Paleontology*, 84, 895–917. <https://doi.org/10.1016/j.jsf.2015.11.006>
- Wood, G. D., Gabriel, A. M., & Lawson, J. C. (1996). Palynological techniques – processing and microscopy. In J. Jansonius & D. C. MacGregor (Eds.), *Palynology: principles and applications* (pp. 29–50). American Association of Stratigraphic Palynologists Foundation.

## Supplementary Materials

### Supplementary Data

Download: <https://thesedimentaryrecord.scholasticahq.com/article/37652-deep-water-tectono-stratigraphy-at-a-plate-boundary-constrained-by-large-n-detrital-zircon-and-micropaleontological-approaches-peninsular-ranges-fore/attachment/97936.xlsx>

---