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A palynological and sequence-stratigraphic study of Santonian–Maastrichtian strata from the Upper Magdalena Valley basin in central Colombia

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This paper presents a sequence-stratigraphic interpretation from the palynological analysis and lithologic data of two outcrop sections on the NE flank of the Upper Magdalena Valley (UMV) basin primarily comprising the Santonian–Lower Maastrichtian interval. Important stratal horizons are identified in the northeastern part of the UMV basin and ages assigned to them. A cyclic pattern of palynomorph distribution was recognized in both sections and tied to the different stages of the stratigraphic chart. Spikes in abundance of spores accompanied by pollen characterize the lowstand systems tracts and are replaced by the occurrence of euryhaline dinoflagellate cysts (ceratioids and/or gymnodinioids) during the subsequent transgressive phase. Maximum flooding surfaces (MFS) are recognized by a sudden increase in open marine palynomorphs (peridinioids and/or gonyaulacoids) and the scarcity of terrestrial representatives. As sea level starts to fall, the gradual decrease in open marine dinoflagellates along with the occurrence of euryhaline dinoflagellate cysts and terrestrial representatives corresponds to highstand systems tracts. The sequence-stratigraphic interpretation from palynological analysis was correlated to the global sea-level curve allowing the identification of the Santonian–Campanian and Campanian–Maastrichtian boundaries. System tracts from supercycles ZC-3, ZC-4 and TA-1 were recognized from the palynological data.

Keywords: Campanian; dinoflagellate cysts; Maastrichtian; pollen; Santonian; sequence stratigraphy; spores

1. Introduction

Late Cretaceous global sea-level fluctuations generated geological surfaces that constitute important correlation horizons in Cretaceous oil-producing basins from northwest South America. Various authors have discussed the synchronous character of these horizons (e.g. Pocknall et al. 1997; Helenes and Somoza 1999; Guerrero et al. 2000; Vallejo 2002; Jaillard et al. 2005). In Colombia, a number of studies (e.g. Vergara and Rodriguez 1997; Villamil 1998; Guerrero 2002) have provided a sequence-stratigraphic framework for Cretaceous sequences of the Eastern Cordillera, Catatumbo, Llanos Foothills and Upper Magdalena Valley (UMV) basins. The synchronicity of sea-level fluctuations in the UMV basin has been extensively analyzed (e.g. Guerrero and Sarmiento 1996; Villamil 1998) and important boundaries including the Santonian–Campanian and the Campanian–Maastrichtian have been identified from sequence-stratigraphic analysis and correlated with eustatic changes (Guerrero et al. 2000).

Sequence-stratigraphic interpretations are commonly based on stacking patterns and lithological changes, together with marine fossil abundances. However, identifying maximum flooding surfaces and sequence boundaries can be quite difficult in certain settings; for example, different system tracts of the sequence may be represented by monotonous fine-grained deposits. This is potentially the case with the Upper Cretaceous units from the northeastern part of the UMV basin, where the fine-grained lithology and the scarcity of well-preserved calcareous microfossils in certain intervals limit traditional sequence-stratigraphic interpretations. If present, organic-walled microfossils (dinoflagellate cysts, spores and pollen) may constitute an important tool to overcome this problem as the combined lithological/palynological approach can provide a way to refine the sequence-stratigraphic interpretation. Jaramillo and Yepes (1994), Guerrero and Sarmiento (1996) and Yepes (2001) have described palynomorph-rich intervals from Upper Cretaceous UMV strata; however, despite the well-known occurrence of diverse palynomorph assemblages in the area, their application as a tool for sequence-stratigraphic interpretation has rarely been fully explored.

Sequence-stratigraphic interpretations based on palynological analysis have proven to be effective in...
Palynology

2. Geological setting

The UMV is an intermontane basin located in the central part of the Colombian Andes, between the Eastern and Central cordilleras. The Upper Cretaceous units from the northeastern side of the UMV basin were deposited in a passive margin setting on inner to outer shelf environments and are dominated by fine-grained sediments (Dengo and Covey 1993; figure 1).

The lithostratigraphic succession of the UMV basin comprises, from base to top, the lower Lidita Formation, El Cobre Formation, upper Lidita Formation and Buscavidas Formation (Figure 2), following the terminology proposed by Guerrero et al. (2000). In our study area, the lower Lidita Formation is characterized by a succession of siliceous mudstones with inclusions of thin phosphatic laminae, cherts and black shales; the El Cobre Formation is composed of monotonous calcareous black shales; the upper Lidita Formation consists of siliceous mudstones and black cherts; and the Buscavidas Formation is characterized by calcareous gray mudstones interbedded with limestones and calcareous shales.

3. Methods

Two outcrop sections were measured. The Aico Creek section, located at 3° 44' N and 75° 23' W, comprises from base to top the lower Lidita Formation, El Cobre Formation, upper Lidita Formation and Buscavidas Formation (Figure 2). The Buitrera Creek section, located at 4° 30' N and 74° 37' W, is composed of the uppermost part of the El Cobre Formation, the upper Lidita Formation and the Buscavidas Formation (Figure 2). Both sections were previously studied by Jaramillo and Yepes (1994) and Yepes (2001). According to these previous studies, the Aico Creek section comprises sediments of Campanian–Early Maastrichtian age and the Buitrera Creek section includes sediments of Campanian–Early Maastrichtian age.

Ninety palynological samples were analyzed. All samples were treated with hydrochloric and hydrofluoric acids. Following these steps, centrifuging in heavy liquid (ZnBr₂) was used to further separate the organic fraction of the samples (Traverse 1988; Brown 2008). Up to 300 palynomorphs were counted per sample although, when recovery was extremely low, tabulation stopped when the full residue was analyzed. Identification and description of the palynomorphs was carried out using an Olympus BX 41 transmitted light microscope at the Center for Excellence in Palynology (CENEX), Louisiana State University, Baton Rouge, Louisiana. The results were tabulated in Excel spreadsheets and plotted on biostratigraphic distribution charts.

3.1. Sequence-stratigraphic analysis using palynology and lithology

The sequence-stratigraphic interpretations from the Aico Creek and Buitrera Creek sections are based on the Haq et al. (1987) global sea-level curve plotted against the Geologic Time Scale of Gradstein et al. (2004). The chert unit is interpreted to represent deposition in a more basinal paleoenvironment whereas sandstone is interpreted to represent deposition in a more proximal paleoenvironment. Within this context, the upsection lithologic changes were utilized to infer relative sea-level change.

Furthermore, distinct palynological assemblages were identified in order to infer sea-level fluctuations and environments of deposition. The assemblages were grouped by environmental affinities indicative of...
Figure 1. Paleogeographic map illustrating the Late Cretaceous depositional setting of the Upper Magdalena Valley Basin (modified from Dengo and Covey 1993) and the location of the Aico and Buitrera Creek stratigraphic sections. The insert shows the modern geographical location of Colombia.
coastal to open marine depositional conditions and partly supported by previously published studies (e.g. Germeraad et al. 1968; May 1977; Poumot 1989; Gregory and Hart 1992; Schrank 1994; Li and Habib 1996; Holz and Dias 1998; Rull 2000, 2002). Figure 3 illustrates the distribution of the palynological assemblages on a hypothetical onshore–offshore transect and their relation to the sequence-stratigraphic cycle. The composition of the palynological assemblages is presented in Table 1. Several age and environmentally significant palynomorphs are illustrated in Plates 1 and 2. Three broad palynological groups are described below.

3.1.1. Marine group

In this study, both peridinioid and gonyaulacoid dinoflagellate cysts are interpreted as indicators of open marine environments, although their distribution can be constrained by paleoecological preferences other than distance from shoreline. For instance, peridinioid dinoflagellate cysts possess heterotrophic preferences (Jacobson and Anderson 1986; Powell et al. 1990) and higher abundances are often associated with upwelling events or nearshore environments with high terrigenous input (Bujak 1984; Pearce et al. 2003). Conversely, most gonyaulacoid dinoflagellate cysts are autotrophic (Harland 1988; Powell et al. 1990) and are therefore not constrained by nutrient availability, although certain species of gonyaulacoid dinoflagellate cysts (e.g. some species of Spiniferites) have been recorded in great abundance in nearshore settings due to salinity preferences (Davey 1970; Downie et al. 1971; Li and Habib 1996).

3.1.2. Estuarine group

Ceratioid and gymnodinioid dinoflagellate cysts are grouped because of their nearshore paleoenvironmental preference as discussed by May (1977), Wilpshaar and Leerveld (1994) and Leerveld (1995). According to these authors, ceratioid cysts indicate restricted marine or low-salinity environments suggesting nearshore, lagoonal or back-barrier environments. Based on morphological studies, May (1977) concluded that gymnodinioid dinoflagellate cysts are indicative of estuarine environments. He proposed that the unique accordion shape and wall canals of gymnodinioid species are highly effective mechanisms that allow them to tolerate rapid changes in salinity.

3.1.3. Terrestrial group

Pollen and spores dominate this group and indicate terrestrial input. If the parent plant can be
identified, then we are able to make some inferences about the local paleoenvironment prevailing at the time of deposition and the coastal and hinterland vegetation. Consequently, we can also determine if hydrophilic or xerophilic conditions (whether or not a plant can grow and reproduce in conditions with high/low-water availability, respectively) existed. Plants such as ferns that reproduce via spores are considered hydrophilic, as the spores require soil with high-moisture content to produce gametophytes that will generate the next generation of plants. Their predominance in a section can reflect swamp environments. Xerophytic pollen-producing plants do not require moist soil to reproduce and spread, so their occurrence in coastal settings is considered to indicate transport via river input from neighboring dry lands. At times, reconstructing the vegetation can be difficult because many of the Late Cretaceous pollen and spore types have no known living counterpart.

4. Results

4.1. Palynostratigraphy

The stratigraphic distributions of terrestrial, estuarine and marine palynomorphs for both sections are shown
Table 1. List of palynomorphs used to define the palynological groups for sequence-stratigraphic interpretation.

<table>
<thead>
<tr>
<th>Marine</th>
<th>Terrestrial</th>
<th>Nearshore/estuarine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gonyaulacoid</td>
<td>Pollen</td>
<td>Ceratiod</td>
</tr>
<tr>
<td>Aroelligera spp.</td>
<td>Araucariacites spp.</td>
<td>Odontochitina costata</td>
</tr>
<tr>
<td>Circulodinium distinctum</td>
<td>Araucariacites australis</td>
<td>Odontochitina operculata</td>
</tr>
<tr>
<td>Coronifera spp.</td>
<td>Bombacacidites &quot;inciertus&quot;</td>
<td>Odontochitina porifera</td>
</tr>
<tr>
<td>Cyclonephelium spp.</td>
<td>Echimonocolpites &quot;protomargaritae&quot;</td>
<td></td>
</tr>
<tr>
<td>Dipsies sp.</td>
<td>Psilamonocolpites sp.</td>
<td></td>
</tr>
<tr>
<td>Exochaspidiaceae sp.</td>
<td>Psilamonocolpites medius</td>
<td></td>
</tr>
<tr>
<td>Heterochaetidium bifidum</td>
<td>Monocolpellites ssp.</td>
<td></td>
</tr>
<tr>
<td>Hystrichodinium pulchrum</td>
<td>Spiniferites ssp.</td>
<td></td>
</tr>
<tr>
<td>Oligosphaeridium complex</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spiniferites spp.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

From oldest to youngest, Zone 1 is characterized by the co-occurrence of Araucariacites sp. and Scabratriletes sp. Zone 2, the Odontochitina zone, is characterized by the occurrence of Odontochitina costata, O. operculata and O. porifera. Zone 3 is divided into two subzones: the Hamulatisporis zone defined by the occurrence of Hamulatisporis caperatus, Muerrigerisporis ardilensis, Araucariacites australis and Neorastrickia densis; and the overlying Andalusiella zone characterized by the common occurrence of Andalusiella maunhei and A. polymorpha. Finally, Zone 4, the Cerodinium zone, is defined by the first occurrence of Cerodinium diebelii, and the last occurrences of A. australis. Buttina andreevi, Foveotriletes margaritae and Echimonocolpites protofranciscoi occur sparsely within this zone. The zonation helps correlate the two sections in the absence of stratigraphically significant marine microfossils (e.g. foraminifera, nanofossils).

4.2. Distribution of key palynological assemblages

Within the broad palynomorph groups, six distinctive assemblages were recognized: those dominated by ceratiod dinoflagellate cysts, gonyaulacoid dinoflagellate cysts, gymnomonid dinoflagellate cysts, peridinid dinoflagellate cysts, spores and pollen.

Changes in these assemblages are visible in the vertical distribution of species (Figures 4–7). The relative abundances of species in both sections (Figures 10 and 11) reveal some interesting trends. These vertical changes in palynological assemblages are described below.

4.2.1. Aico Creek section

Figure 10 illustrates the vertical distribution of the six assemblages recovered at the Aico Creek section. Palynomorph recovery varies from fair to abundant with some barren intervals occurring throughout the section.

A spike in ceratioid cysts occurs in the lower Lidita Formation at 43.5 m although numbers quickly decline. At 46.4 m, gonyaulacoid cysts dominate with minor abundances of spores and pollen. From 79 to 89 m in the El Cobre Formation, gymnomonid cysts dominate the assemblage with gonyaulacoid cysts, pollen and spores as minor components. The uppermost El Cobre Formation (114.5–127 m) contains a predominantly marine assemblage dominated by gonyaulacoid cysts with decreasing gymnomonid cyst abundances, and with ceratiod cysts and spores common at 125 m. At the base of the Upper Lidita Formation (134 m), gonyaulacoid cysts are recorded followed by the occurrence of gymnomonid cysts, spores and pollen at 143.5 m. The interval from 145 to
Plate 1. Light photomicrographs of key species of marine and terrestrial palynomorphs present in the studied sections. Figure 1. *Buttinia andreevi*, Buitrera Creek 609.8 m, EF X36. Figure 2. *Echimonocolpites protofranciscoi*, Aico Creek 203 m, EF S14. Figure 3. *Cerodinium diebelii*, Aico Creek 229.9 m, EF O44. Figure 4. *Foveotrilites margaritae*, Aico Creek 229.9 m, S36/3. Figure 5. *Spinizonocolpites sutae*, Aico Creek 203 m, EF V27/3. Figure 6. *Oligosphaeridium complex*, Aico Creek 79 m, EF R27/2. Figure 7. *Alisogymnium euclaense*, Aico Creek 229.9 m, EF K9. Figure 8. *Odontochitina operculata*, Aico Creek 125 m, EF E18/4.
Plate 2. Light photomicrographs of species of marine and terrestrial palynomorphs present in the studied sections. Figure 1. *Bacumorphomonocolpites tausae*, Buitrera Creek 619.4 m, EF T42/1. Figure 2. *Bombacacidites inciertus*, Aico Creek 207.7 m, EF P6/4. Figure 3. *Gnetaceapollenites pseudoboltehagenii*, Aico Creek 205 m, EF P25/2. Figure 4. *Dinogymnium undulosum*, Aico Creek 89 m, EF M25. Figure 5. *Alisogymnium glotonicus*, Aico Creek 221.4 m, W39. Figure 6. *Psilamonocolpites medius*, Aico Creek 221.4 m, EF P12/3. Figure 7. *Hamulatisporis caperatus*, Aico Creek 216.7 m, EF H12/3. Figure 8. *Gabonisporis vigourouxi*, Aico Creek 143.5 m, EF Q18/2. Figure 9. *Proxapertites maracaboensis*, Buitrera Creek 609.8 m, EF V38/1.
185 m is barren of palynomorphs. At the base of the Buscavidas Formation (188.5–191.5 m), peridinioid and gonyaulacoid cysts dominate the assemblage. Gymnodinioid cysts, spores and pollen increase in abundance at 200.7 m followed by a spike in spore abundance at 203 m with minor pollen numbers. Terrestrial palynomorphs dominate the assemblage at 205.7 m with gymnodinioid and gonyaulacoid cysts as minor components. From 207.7 to 229.5 m gonyaulacoid, gymnodinioid and peridinioid cyst abundances increase. Pollen and spores dominate the palynological assemblage at the top of the Buscavidas Formation from 275.7 to 276.7 m.

The first occurrence of the important Campanian–Maastrichtian palynological markers, *Echimonoconolpites protofranciscoi* and *Buttinia andreevi* (Muller et al. 1987; Jaramillo and Rueda 2004), are at 200.7 m and 202 m, respectively, in Zone 4 (see Figures 5 and 8). We place the Campanian–Maastrichtian boundary above the first occurrence within the Buscavidas Formation at 240 m in the Aico Creek section (Figure 10). This choice of placement for the Campanian–Maastrichtian boundary is consistent with our sequence-stratigraphic interpretation for the positioning of the 71 Ma sequence boundary (Figure 10, see discussion in Section 5).

Figure 4. Distribution chart of terrestrial palynomorphs from the Aico Creek section.
Figure 5. Distribution chart of marine palynomorphs from the Aico Creek section.
4.2.2. Buitrera Creek section

Figure 11 illustrates the vertical distribution of the six assemblages recovered at the Buitrera Creek section. Palynomorph recovery ranges from fair to abundant throughout, with the exception of barren intervals at the base and middle part of the upper Lidita Formation.

At 19.2 m, at the base of the section in the El Cobre Formation, the palynological assemblage is dominated by terrestrial palynomorphs associated with gymnodinioid cysts. Peaks of peridinioid cysts are observed at 28.8, 56 and 78.4 m and dominate the upper part of the El Cobre Formation. Near the top of the Upper Lidita Formation (198.6 m) and base of the Buscavidas Formation (219.6 m), only peridinioid cysts are recorded. Gonyaulacoid and gymnodinioid cysts re-appear in the section at 238.3 m but peridinioid cysts remain the dominant component up to the sample at 359.5 m. Pollen and spores are minor components of these predominantly marine assemblages. Recovery in the upper part of the Buscavidas Formation is poor with the exception of common spores at 409 m and abundant pollen at 609.8 m. In general, at the Buitrera Creek section, peridinioid cysts dominate the marine assemblages; this is in contrast to their rare presence at the Aico Creek section where gonyaulacoid cysts dominate the dinoflagellate assemblages.

The first observed occurrence of the Campanian–Maastrichtian palynological markers, Echimonomocer- pites protofrancisci and Buttinia andreevi (Muller et al. 1987; Jaramillo and Rueda 2004), is in the uppermost part of the Buscavidas Formation at Buitrera Creek at the top of Zone 4 (i.e. the two samples above 600 m on Figures 7 and 11). No
samples could be obtained between 469.8 m and 609.8 m where the section is not accessible. These species could therefore be present as low as 470 m, i.e. above 469.8 m. On this basis, and on the basis of our sequence-stratigraphic interpretation (see Figure 11 and Section 5 for details), we placed the Campanian–Maastrichtian boundary at 475 m.

5. Sequence-stratigraphic interpretation and discussion

To analyze the distribution of palynomorph assemblages within a sequence-stratigraphic framework, it is assumed that a regular pattern of upsection changes in palynological assemblages correspond to environmental changes associated with sea-level rise and fall (eustacy). Spearman correlation tests and Detrended Correspondence Analysis (DCA) (Hill and Gauch 1980) were performed on the palynomorph percentage data to assess the significance of the observed patterns. DCA is an ordination method used to summarize data variation in a small number of dimensions. The ordination was performed on 5 of the 6 palynological assemblage (i.e. peridinioid cysts, gonyaulacoid cysts, gymnodinioid cysts, pollen and spores) percentage data from both of the studied stratigraphic sections; ceratioid cysts were not included due to their sparse occurrence at Aico Creek and their absence at Buitrera Creek.

Marine affinity palynomorphs (i.e. sum of peridinioid and gonyaulacoid cyst percentages) were compared with estuarine affinity palynomorphs (i.e. sum of gymnodinioid cyst percentages) from Aico Creek and yielded a Spearman’s rank correlation coefficient of –0.39, p-value 0.1075, which indicates a moderate negative correlation between the two groups. Estuarine affinity palynomorphs were then compared with
Figure 8. Palynological range chart of the Aico Creek section. (Terrestrial taxa in black, marine taxa in gray.)
terrestrial affinity palynomorphs (i.e. spores and pollen) from Aico Creek and a Spearman’s rank correlation coefficient of \(-0.58\), \(p\)-value 0.01341, was determined. Comparison between marine affinity palynomorphs and terrestrial affinity palynomorphs from Aico Creek yielded a Spearman’s rank correlation coefficient of \(-0.56\), \(p\)-value 0.009114, indicating moderate negative correlation. An onshore–offshore gradient is apparent on the DCA1 axis for the Aico Creek DCA biplot (Figure 12); pollen plots closely to spores, followed by gymnodinioid cysts, and then gonyaulacoid cysts and peridinioid cysts. A similar pattern for palynological assemblages ordered along a gradient on the DCA1 axis is seen for the Buitrera Creek DCA biplot (Figure 12).

The upsection changes of the palynomorph assemblages described above (Figures 10 and 11) were combined with a conventional lithological interpretation to establish a sequence-stratigraphic framework. In general, the Lowstand System Tract (LST) is characterized by abundance spikes of spores accompanied by pollen whereas the Transgressive Systems Tract (TST) is indicated by the occurrence of estuarine dinoflagellates (ceratioid cysts and/or gymnodinioid cysts). Maximum Flooding Surfaces (MFS) are usually represented by abundant open marine dinoflagellates (gonyaulacoid cysts and/or peridinioid cysts) and the scarcity of terrestrial palynomorphs. A gradual decrease in open marine dinoflagellates, the occurrence of estuarine dinoflagellates and a consistent presence of terrestrial palynomorphs represent the onset of the Highstand Systems Tract (HST).

In terms of sedimentary facies, limestone and chert are considered to represent basinal paleoenvironments whereas mudstone and sandstone are considered to represent more proximal paleoenvironments. Since these basinal and proximal paleoenvironments are lateral facies equivalents, the sequence-stratigraphic interpretation of lithologic data relied heavily on the observed patterns of upsection lithologic changes rather than lithology at any particular depth. The observed upsection lithology change (and/or associated palynomorph-assemblage change) therefore depended upon the paleoenvironment existing at the time prior to the onset of relative sea-level changes.

5.1. Aico Creek section

At the base of the section, up to 43.5 m, the poor recovery of palynomorphs prevented sequence-stratigraphic interpretation as only a few specimens of estuarine dinoflagellates (i.e. gymnodinioid cysts),
peridinioid cysts and spores were found in this part of the section. In this zone, system tracts are interpreted on the basis of lithological changes as well as correlation to the global cycle chart (Haq et al. 1987). At 43.5 m a MFS is placed near the top of the lower Lidita Formation based on the occurrence of a
Figure 11. Stratigraphic distribution chart showing the relative abundance of the six palynological groups (percentage) at the Buitrera Creek section. Also shown are the lithostratigraphy and the sequence-stratigraphic interpretation correlated with the Haq et al. (1987) eustatic curve plotted against the Geologic Time Scale of Gradstein et al. (2004). Percentage values for each assemblage is calculated using the total number of specimens of each assemblage against the sum of specimens of all six palynological assemblages.
Figure 12. DCA biplots of palynological assemblage distribution at the Aico and Buitrera Creek sections.
spike in abundance of ceratioid cysts coincident with an overall lithologic change from limestone in the underlying LST to chert/limestone in the TST, which suggests an overall deepening of water depth at the site. Within the top of the overlying HST, i.e. from 79 to 89 m, the dominance of gymnodinioid cysts coupled with the occurrence of terrestrial palynomorphs is interpreted to correspond to relative sea-level fall at the end of the HST. Sandstone deposition at 99.7 m is interpreted to represent the onset of the Shelf Margin Systems Tract (SMST = lowstand deposition), i.e. a sequence boundary (at 83 Ma) is placed below the sandstone. At 114.5 m, the occurrence of estuarine dinoflagellates coupled with high abundances of gonyaulacoid cysts is associated with the transgressive system tract (TST). A subsequent decrease of gonyaulacoid cysts, together with the occurrence of spores and estuarine dinoflagellates at 125 m, is interpreted to represent the end of the HST, i.e. a sequence boundary (at 80 Ma). The sequence boundary is at the base of the sandstone at 125 m.

Starting at c. 125 m, the upsection vertical change from sandstone to mudstone to limestone is interpreted as representing the progressive deepening from LST to TST within the overlying sequence. The subsequent shift from chert to limestone at 135 m is taken to represent slow relative sea-level fall during the late HST. The sequence boundary (at 79 Ma) is placed above the finer-grained limestone and below the base of the overlying coarser-grained limestone. The overlying LST contains gymnodinioid cysts, pollen and spores which represents the major sea-level fall (associated with the 79 Ma sequence boundary). A sequence boundary (at 77.5 Ma) is placed at c. 155 m at the base of the coarse limestone.

Above the sequence boundary, the lithologic change from limestone to chert is interpreted to represent an overall relative sea-level rise during the LST and TST. The shift from chert to limestone to mudstone is interpreted to represent progressive shoaling during relative sea-level fall associated with the HST. Palynomorphs are absent from the LST, TST and base of the HST; however, marine and estuarine palynomorphs co-occur in the top of the HST. Within the context of the sequence-stratigraphic interpretation, the late HST represents the lowest water depth paleoenvironments for this sequence at the Aico Creek section. The sequence boundary (at 75 Ma) is placed at the base of the coarse limestones. The basal-most LST has an increase in spore and pollen, which is taken to represent the relative sea-level fall associated with the 75 Ma sequence boundary. In the overlying part of the LST and overlying TST; the occurrence of gonyaulacoid and peridinioid cysts is interpreted to represent progressive relative sea-level rise. If correct, the continued presence of spores and pollen represents basinward transport of palynomorphs from terrestrial settings. The inferred decrease of marine and estuarine palynomorphs above 230 m and continued presence of terrestrial palynomorphs are interpreted to represent shoaling in the HST. The sequence boundary (at 71 Ma) is placed at c. 232 m. The overlying sequence and sequence boundary (at 68 Ma) is inferred primarily on the basis of the coarse sandstone beds above the 68 Ma sequence boundary at 252 m, i.e. the base of the sandstone beds. Lowstand deposition is interpreted from the entire interval above the sequence boundary based on the abundances of terrestrial palynomorphs at 275.7 and 276.7 m.

### 5.2. Buitrera Creek section

At the base of the Buitrera Creek section (9.6–28.8 m), the occurrence of gymnodinioid cysts along with spores and pollen are taken to represent the LST. An increase in peridinioid cysts at 56 m indicates the onset of the TST and a spike of peridinioid cysts at 78.4 m at the top of the TST is interpreted as the MFS. A sequence boundary (80 Ma) is placed at 81 m. In the sequence above the 80 Ma sequence boundary, the overlying lithologic change from mudstone to limestone to chert is taken to represent an overall deepening associated with relative sea-level rise.

A sequence boundary corresponding to relative sea-level fall at 79 Ma is inferred to be within the chert sequence. This is consistent with the stratigraphic framework interpreted from the Aico Creek section (Figure 10) although the samples are barren and there are no lithologic changes. The absence of lithologic change may simply mean that water depth remained deep despite a relative sea-level fall. Indeed, the sea-level fall at 79 Ma was relatively minor.

A sequence boundary is placed at the base of the limestone bed at c. 160 m which is interpreted to correspond to an abrupt relative sea-level fall at 77.5 Ma. The increase in peridinioid cysts at 198.6 m is taken to represent the top of the TST, i.e. the MFS. The overlying lithologic change from chert to limestone to mudstone is taken to represent progressive shoaling and relative sea-level fall in the HST. At the top of the HST estuarine and terrestrial palynomorphs become successively abundant, which likewise is consistent with upward shoaling. The sequence boundary (at 75 Ma) is placed at c. 260 m, just below the decrease in marine palynomorphs at 262.2 m. In the overlying LST, the upsection transition from mudstone to limestone is taken to indicate relative sea-level rise. The increased abundance of peridinioid cysts at 294.9 m is taken to correspond to the top of the TST. The increased abundance of pollen/spore at
302.9 m and concomitant decrease in peridinioid
cysts is taken to indicate shoaling and relative sea-
level fall in the HST. The 71 Ma sequence boundary
is placed at c. 400 m based on the abrupt increase in
spores and pollen at 409 m. The sandstone at c.
465 m is considered to be within the LST. The
continued presence of terrestrial and estuarine
palynomorphs together with the absence of peridi-
nioid cysts from the overlying TST and HST is taken
to indicate progressive shoaling. The 68 Ma sequence
boundary is placed at the base of the sandstone at c.
490 m.

Based on (1) the absence of *Echimonocolpites
protofranciscoi* and *Buttinia andreevi* up to the sample
at 469.8 m; (2) their presence at 609.8 m; and (3) the
sequence-stratigraphic interpretation which places the
71 Ma sequence boundary at 400 m and the 68 Ma
sequence boundary at 490 m, we place the Campan-
ian–Maastrichtian boundary at 475 m (Figure 11).
This interpretation also minimizes the difference in
thickness of the Buscavidas Formation between the
Aico and Buitrera Creek sections.

The section just below the unsampled portion of
the Buscavidas Formation is placed within the over-
lying LST. The sandstone above the inaccessible
portion of the Buscavidas Formation is placed within
the LST of the overlying sequence. In other words, the
63 Ma sequence boundary is placed at c. 600 m.

6. Age and correlation

Age dating the Coniacian–Santonian and Santonian–
Campanian boundaries at the Aico Creek section was
accomplished using ammonite and inoceramid data
from previous studies (Etayo-Serna 1994; Villamil
et al. 1998) as well as some key palynological markers
observed in this study and our sequence-stratigraphic
interpretation. On these bases, the Santonian–Campa-
ian boundary is identified at 89 m in Aico Creek
within the middle part of the El Cobre Formation. The
Santonian–Campanian boundary is below the section
at Buitrera Creek.

For the Campanian–Maastrichtian boundary, pa-
lynologic markers such as *Foveotriletes margaritae*,
*Buttinia andreevi* and *Echimonocolpites protofranciscoi*
(Muller et al. 1987; Jaramillo and Rueda 2004) were
identified in both sections and a framework zonation
(Zones 1–4) was established. Poor and erratic recovery
in some parts of both sections and covered intervals
presented a challenge to age assignment based solely
on palynology. The Campanian–Maastrichtian bound-
ary is picked at 240 m in the Aico Creek section within
the Buscavidas Formation. At the Buitrera Creek
section, the Campanian–Maastrichtian boundary is
placed at 475 m within the Buscavidas Formation. In

![Figure 13. Graphic comparison showing correlation
between the Aico Creek and Buitrera Creek sections using
palynological zones, first and last appearance datum,
magnitude flooding surface and sequence boundary as
stratigraphic markers. The table provides the depths of key
stratigraphic events used for the graphic comparison.
The numbers in red are inferred elevations for the top of Zone 1
and Zone 2 at the Buitrera Creek section based on this
comparison.](image)
Correlation between Aico and Buitrera Creek was achieved using the palynostratigraphic Zones 1–4 and the sequence-stratigraphic approach described in the previous section. Figure 13 presents the correlation of the two sections based on the biozones and sequence boundaries.

7. Conclusions
Palynological data recovered from the Aico and Buitrera Creek sections in the UMV has provided useful biostratigraphic and paleoenvironmental information. Four palynological zones are defined that help to differentiate the lithologically monotonous Lower Lidita, El Cobre, Upper Lidita and Buscavidas formations.

Cyclic patterns in palynomorph abundances and lithological changes were used to construct a sequence-stratigraphic framework. In both sections, the absolute abundances of the various palynomorph assemblages enabled recognition of lowstand systems tracts, transgressive systems tracts, maximum flooding surfaces (MFSs) and highstand systems tracts. The sequence-stratigraphic interpretation was based on calibration to the Haq et al. (1987) eustatic sea-level curve for the Santonian–Early Maastrichtian interval. Additionally, previous conventional sequence-stratigraphic interpretations for the same lithostratigraphic units in other parts of the UMV basin (e.g. Guerrero 2002) have been incorporated within our study.

The results of this study support earlier observations by Poumot (1989), Gregory and Hart (1992) and Holz and Dias (1998) who proposed that palynological data is a valuable tool for sequence-stratigraphic interpretation. In diverse geological settings such as the structurally complex UMV, where conventional sequence-stratigraphic tools (i.e. seismic, stacking patterns, lithological changes alone or calcareous microfossil content) cannot be applied, palynological data is essential. Future work on additional outcrop sections is needed to substantiate and build on the framework presented in this paper.

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