Palynostratigraphy and palaeoenvironments of the Eagle Ford Group (Upper Cretaceous) at the Lozier Canyon outcrop reference section, west Texas, USA

Paul Dodsworth*

StrataSolve Ltd, 42 Gaskell Street, Warrington WA4 2UN, UK

This study describes the detailed palynology of the Eagle Ford Group at Lozier Canyon, its principal outcrop reference section in west Texas. Prominent marine phytoplankton assemblages are consistent with a proposed depositional setting for Lozier Canyon on a submarine platform within the Cretaceous Western Interior Seaway (KWIS) of the USA. The Lower Eagle Ford Formation (middle to upper Cenomanian) was deposited under restricted marine conditions with oxygen-deficient, probably anoxic bottom waters, as indicated by the black, organic-rich (ca. 1 to > 6% total organic carbon) shale lithology. The formation comprises two fourth-order stratigraphical sequences, each showing sedimentary evidence of increasing water depth during deposition. Palynomorph assemblages from the sequences are dominated by green algal prasinophyte phycomata in the lower parts and peridinioid dinoflagellate cysts in the upper parts. The productivity of these marine phytoplankton groups may have been stimulated by availability of ammonium (prasinophytes) and nitrite (peridinioids) from upwelling, or vertical expansion of the oxygen-minimum zone. The transition from prasinophyte- to peridinioid-dominated assemblages may reflect elevation of the photic zone to a level less regularly encroached by deeper, ammonium-enriched waters of the denitrification zone. The overlying Upper Eagle Ford Formation (upper Cenomanian to upper Turonian or Coniacian) was deposited under deeper, relatively open marine conditions, as indicated by a decrease in organic carbon content and an increase in carbonate content. This is supported by the presence of diversified dinoflagellate cyst assemblages, including inter-regional (high- to mid-latitude) marker events; in the upper Cenomanian, base and acme Cyclonephelium compactum-membraniphorum, top consistent and frequent Litostrophia siphoniphorum, and top Adhatosphaeridium tutulosum; in the middle to upper Turonian, range bases of Heterosphaeridium difficile and Senonisphaera rotundata. The stratigraphical resolution offered by palynology indicates potential application to wellsite 'geosteering' of commercial shale oil and shale gas wells drilled in the Eagle Ford Group.

Keywords: Eagle Ford Group; Lozier Canyon; Cenomanian—Turonian boundary events; dinoflagellate cysts; prasinophyte phycomata; shale oil; geosteering; Texas

1. Introduction

1.1. Background and objectives

The Cenomanian to Coniacian (Upper Cretaceous) Eagle Ford Group is a mixed siliciclastic/carbonate unconventional hydrocarbon reservoir in south Texas (e.g. Treadgold et al. 2011; Workman 2013). It is characterised by organic-rich carbonate mudstones, limestones and numerous bentonites. It is underlain and overlain by massive limestones, the Buda Formation and the Austin Chalk Formation, respectively. Exploration and development of the Eagle Ford Group began in earnest in 2008, with daily production of shale oil, condensate and dry gas increasingly rapidly between 2009 and 2014 (Railroad Commission of Texas 2015).

The Eagle Ford Group and its component Lower and Upper Eagle Ford Formations were formally defined at the ca. 58-m-thick Lozier Canyon outcrop in Terrell County, west Texas (Figure 1), by Donovan et al. (2012). This British Petroleum (BP) USA Inc.-leased, private-property exposure has become an established reference section for the study of the Eagle Ford Group at the surface. It is located about 1 km south of Lozier Bridge which crosses US Highway 90. The Lower Eagle Ford Formation is also exposed in an 8-m-thick road cutting along Highway 90, west of Comstock, Val Verde County. Comstock West is located about 65 km ESE of Lozier Canyon (Figure 1). West Texas outcrops of the Eagle Ford Group consist of a vertical succession of five distinct facies, labelled A–E, each of which contains a vertical succession of sub-facies (Figure 2). These can be correlated into the subsurface of south Texas (Donovan et al. 2012).

Dinoflagellate cysts and other palynomorphs were first reported from the Eagle Ford Group in northeast Texas by Brown & Pierce (1962). Normapolles pollen...
were recovered from the Eagle Ford Group by Christopher (1982). More recently, Schwab et al. (2011) reported unsieved kerogen samples from the Lower Eagle Ford Formation at Lozier Canyon and Comstock West. Donovan et al. (2012, fig. 9, table 1) published a summary of some of the Lozier Canyon palynological data presented here, i.e. the summed abundance of BP’s Cenomanian marker dinoflagellate cyst taxa (listed in their table 1) and summed pollen and spores counts. No information about the distribution of individual marker dinoflagellate cysts or the relative abundance of other palynomorph groups was given. In January 2012, Shell drilled a relatively expanded, ca. 112-m-thick section of the Eagle Ford Group at Lozier Canyon and Comstock West. Donovan et al. (2012, fig. 9, table 1) published a summary of some of the Lozier Canyon palynological data presented here, i.e. the summed abundance of BP’s Cenomanian marker dinoflagellate cyst taxa (listed in their table 1) and summed pollen and spores counts. No information about the distribution of individual marker dinoflagellate cysts or the relative abundance of other palynomorph groups was given. In January 2012, Shell drilled a relatively expanded, ca. 112-m-thick section of the Eagle Ford Group, the Iona-1 core (Figure 1). Iona-1 is located about 120 km SE of Lozier Canyon, at Sycamore Creek, near Del Rio. Uranium-lead (U-Pb) dates from individual zircons from 10 bentonite layers in Iona-1 provided geochronological constraints for astronomically tuned age models for individual bio-events (Eldrett et al. 2015). The detailed dinoflagellate cyst stratigraphy of Iona-1 has been analysed from 195 samples, from the upper part of the Buda Formation, Eagle Ford Group and lower Austin Chalk Formation (Dodsworth, in Eldrett et al. 2015). However, palaeoenvironmental and sequence stratigraphical interpretations derived from palynology were not discussed.

This paper summarises palynological data for 87 samples collected from the section at Lozier Canyon. Five samples were also analysed from Comstock West. The paper aims to calibrate occurrences of inter-regional dinoflagellate cyst marker taxa and events at Lozier Canyon and to integrate them with other fossil and geochemical data published from the section by Donovan & Staerker (2010), Donovan et al. (2012), Corbett & Watkins (2013, 2014) and Lowery et al. (2014). Comparisons are made with Iona-1, the Global boundary Stratigraphical Section and Point (GSSP or ‘golden spike’) for the base of the Turonian Stage at Rock Canyon, Pueblo, Colorado (Kennedy et al. 2005) and the adjacent Portland-1 core (e.g. Sageman et al. 2006), and with other published dinoflagellate cyst range data from sections farther north in the Cretaceous Western Interior Seaway (KWIS), Europe and Morocco, north Africa (Prauss 2012a, 2012b). Relative abundances of different palynomorphs, grouped according to botanical affinity, from the Lower and
Upper Eagle Ford Formations are discussed here for the first time in terms of palaeoenvironments, sequence stratigraphy and Cenomanian–Turonian boundary (CTB) events. Controversy regarding an upper Turonian or Coniacian age of the Langtry Member at Lozier Canyon (Figure 2) is reviewed with respect to the new palynological data. A further aim was to assess the operational (‘geosteering’) application of palynology to the drilling of long-reach ‘horizontal’ wells in the unconventional Eagle Ford Group reservoirs of south Texas, including the viability of time-constrained analytical techniques at wellsite.

1.2. Geological setting

The Late Cretaceous was characterised by a sustained warm climate resulting in high eustatic sea levels and numerous epicontinental seaways. Several major global perturbations in the carbon cycle occurred, such as oceanic anoxic events (OAE), the most prominent spanning the Cenomanian–Turonian transition, and termed OAE-2 (Schlanger & Jenkins 1976; Schlanger et al. 1987). This interval in particular was characterised by the widespread deposition of organic-rich, fine-grained sediments marked by a globally recognised positive carbon isotope (δ13C) excursion, reflecting the widespread removal of δ12C-enriched organic matter in marine sediments under global anoxic conditions (Jenkyns 2010 and references therein). The Cenomanian–Turonian transition was also an interval of extreme warmth (e.g. Huber et al. 2002; Forster et al. 2007). However, the early stages of OAE-2 are characterised by a short-lived colder interval, termed the ‘Plenus Cold Interval’ by Gale & Christensen (1996).

The Eagle Ford Group was deposited in the southern gateway of the KWIS to the Gulf of Mexico carbonate shelf and the Tethys Ocean (Figure 1). A sea level rise associated with the Lower–Upper Eagle Ford Formation boundary marks the transition from restricted-circulation, Tethys-influenced conditions from the south to more boreal, open marine-influenced conditions from the north (Eldrett et al. 2014). Despite a globally contemporaneous δ13C excursion, sediments from the Upper Eagle Ford Formation and coeval sediments in Colorado, i.e. the Portland-1 core at Pueblo, were mostly oxygenated during OAE-2, as indicated by limited or no enrichment in redox-sensitive elements (Meyers 2007, fig. 4; Eldrett et al. 2014).

Donovan & Staerker (2010) suggested a depositional setting for Lozier Canyon and Comstock West on a submarine platform at a likely distance of 300–500 km from the nearest landmass and water depths of approximately 60 m during commencement of deposition of the Lower Eagle Ford Formation. Iona-1 was located in an intra-shelf basin, the Maverick Basin (Figure 1). Eldrett et al. (2015) estimated that deposition of the Eagle Ford Group took place over approximately 7 million years, between ca. 97 and 90 Ma.

2. Methods

Splits of 87 closely spaced samples from Lozier Canyon, that have previously been analysed for micro- and nannopalaeontology (Figures 3 and 4), were supplied by BP for palynological analysis. Samples were sequentially dissolved in hydrochloric (30% HCl) and hydrofluoric (60% HF) acids. Post-HF oxidative treatment was necessary to liberate palynomorphs from the prominent translucent, fluffy amorphous organic matter (AOM). Subsequent treatment with an alkali solution was necessary to remove post-oxidation waste products. Previous work on Cenomanian–Turonian organic-rich shales has indicated that excessive post-HF treatment led to selective destruction of non-peridinioid dinoflagellate cysts (Dodsworth 1995, 1996, 2004a). Experiments with Eagle Ford Group post-HF residues indicated that ‘optimum oxidation’ was achieved with extended maceration in cold or warm nitric acid. Schulze’s Solution (warmed 70% nitric acid supersaturated with potassium chloride) and/or fuming nitric acid, followed by a single rinse in a detergent that contained a trace of ammonia. This produces relatively uniform assemblages, although scanning over many remaining AOM fragments is necessary to achieve sufficient specimen counts.

Separate kerogen and post-oxidation biostratigraphy slides were prepared. All preparations were sieved at 15 μm. The palynological counting technique used in this study involved making an initial count of 100 specimens to establish broad trends amongst different palynomorph botanical groups (Appendix 1), i.e. peridinoid, areoligeracean, ceratioid, Dinogymnium, gonyaulacacean and associated chorite dinoflagellate cysts, prasinophyte phycocyst, acanthomorph acritarchs, fresh/brackish-water algae, foraminiferal test linings and terrigenous palynomorphs. These data are plotted in alphabetical order in Figures 3–5, using StrataBugs software. Where possible, counting of dinoflagellate cysts was continued until a total of 100 specimens was reached. Any remaining slide material was thoroughly scanned for additional rare palynomorph taxa. Semi-quantitative relative abundance (percentage) categories are described as rare (1 or outside the count), frequent (2–4), common (5–14), abundant (15–49) or super-abundant (50+). Total counts of all strewn angiosperm pollen, gymnosperm pollen and pteridophyte/bryophyte spores were also undertaken and are plotted in Figures 3–5, along with the number of dinoflagellate cyst taxa recorded (‘species
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**Lozier Canyon: Integrated Stratigraphy**

- **57.15m PALY**: *Isabelinidium magnum* [P14] & sparse long-ranging peridinioid dinoflagellate cysts;
  prominent prasinophyte phycomata in sparse-recovery weathered samples; NANN: Top *Lucianohabbus maleformis*
- **54.10m MICRO**: Base cf. *Dicarinella concavata*; NANN: Base *Brachiospora furcata?*
- **46.70m PALY**: Top non-peridinioid dinoflagellate cysts, incl. rare *Heterosphaeridium difficil*; frequent *Florentina* spp. & *Spiniferites* spp.
- **45.42m PALY**: Base prominent prasinophyte phycomata
- **44.81m PALY**: Frequent *Sonorastra rotundata* [P13]; Top common *Subliophora* *pinnarisens*
- **44.04m NANN**: Top *Stevensia ephelosus* [N18], Base *Marthasterites fornicatus* [N17], *Lucianohabbus maleformis* [N16] & *Effulidites eximus* [N13]; PALY: Base *Sonorastra rotundata*, Top abundant non-peridinioid dinoflagellate cysts
- **42.98m NANN**: Top *Eplithus eplipticus*; NANN: Base *Lithastrus sepiarium* [N15] & *Eplithus moratus*
- **39.93m NANN**: Base *Quadrum gaudinii* [N9] & *Eplithus eplipticus* [N16]; PALY: Base *Chataniella* spp. [P9], Base common *Subliophora pinnarisens*
- **39.78m GEOCHEM**: Top carbon isotope anomaly, interpreted as truncated by erosion surface
- **37.80m NANN**: Top *Helaina cheiata* [N7]
- **36.12m PALY**: Top influx relatively abundant terrestrial pollen
- **34.32m PALY**: Base influx relatively abundant terrestrial pollen
- **33.53m PALY**: Top *Adnathostrphaedium tulatulon* [P5]; MICRO: Base prominent *Heterohexa* spp. [F15]
- **32.61m GEOCHEM**: Base carbon isotope anomaly
- **32.31m PALY**: Top abundant non-peridinioid dinoflagellate cysts, influx *Cyclonephelin membranebifurcum* [P14]
- **29.60m PALY**: Top persistent *Lithostraedium siphonophorum* [P6] & *Wurmea* spp. / *Diploufusa* geeriensis; NANN: Top *Coriolithon kennedyi* [N5] & common *Helaina cheiata*
- **28.96m PALY**: Top frequent *Lithostraedium siphonophorum*, Base *Adnathostrphaedium tulatulon*
- **28.62m PALY**: Base consistent *Cyclonephelin compactum* - *membraniferorum* [P4]
- **28.50m MICRO**: Top *Rotalipora* spp. [F12] & *Globigerinelloides bentonensis*; PALY: Base abundant non-peridinioid dinoflagellate cysts
- **26.52m PALY**: Top prominent prasinophyte phycomata
- **25.30m PALY**: Base *Wurmea* spp. / *Diploufusa* geeriensis; NANN: Top *Axopodorhabbus bicornularis*
- **22.10m PALY**: Top common *Bosedina* cf. sp.1 & sp.3 Prauss (2012b) [P2]
- **17.53m PALY**: Base prominent prasinophyte phycomata
- **11.34m PALY**: Top frequent *Aeroligeracean dinoflagellate cysts* (*Cunningia reticulata, Circulodinium distinctum, Tenia hystris*); NANN: Base? *Coriolithon kennedyi* [N7]
- **9.60m PALY**: Top prominent prasinophyte phycomata
- **6.55m PALY**: Top influx *Lithostraedium siphonophorum*. Top (sporadic) *Endoceratium turneri*
- **5.18m PALY**: Base influx *Lithostraedium siphonophorum*
- **1.91m PALY**: Base common *Bosedina* cf. sp.1 & sp.3 Prauss (2012b)
- **1.52m PALY**: Influx common *Gonyaulacacean dinoflagellate cysts*
- **0.01m PALY**: Sparse recovery with frequent *Lithostraedium siphonophorum* [P1]
Palynology

361

richness’), as an indication of their diversity. Palynomorph taxa recovered are listed in Appendix 1; range charts of individual taxa are provided in the Supplemental Data. All slides illustrated in Plate 1 are curated at the Centre for Palynology, University of Sheffield, UK. As most previous published work on Lozier Canyon has used imperial measurements, and sample heights above base of the Eagle Ford Group were supplied in feet, both metric and imperial measurements are given in Figures 3 and 4 and the plate caption, to allow ready comparison with other datasets.

The counting technique used here for estimating percentage abundances follows a standard method widely used on site in the hydrocarbon industry, sometimes referred to as the ‘van Veen method’. It provides a practicable means of analysis that can usually be reproduced under time-constrained conditions during wellsite ‘geosteering’ operations. However, it may not be suitable for rigorous statistical treatment (e.g. see discussion in Traverse 2007). The items selected for plotting in Figures 3–5 were chosen to aid palaeoenvironmental interpretation at Lozier Canyon and Comstock West.

3. Results

The laboratory preparation of material from Lozier Canyon, particularly from the Lower Eagle Ford Formation, has not been as successful as that of material from Iona-1 (Eldrett et al. 2015) and Comstock West. Preservation at Lozier Canyon is often poor and many dinoflagellate cyst specimens are partially obscured by fine films of AOM, hindering confident identification at the species level.

The Lozier Canyon samples yielded predominantly marine phytoplankton assemblages; green algal prasinophyte phycomata (e.g. Tyson 1995) and dinoflagellate cysts. Three intervals are dominated by prasinophytes (Figures 2–4), mainly Leiosphaeridia, Pterospermella and Tasmanites with subordinate Crassosphaera, Leiospsaphaelidium and Pterosphaeridia. Peridinoid taxa are the most abundant dinoflagellate cysts in the majority of assemblages: Palaeohystrichophora infusorioides, Subtilisphaera pontis-mariae, Subtilisphaera spp. and Corculodinium inaffectum sensu Harris & Tocher (2003) have a fairly ubiquitous distribution; Bosedinia cf. sp. 1 & sp. 3 of Prauss (2012b) is common in the Cenomanian section, 1.91 to 22.10 m; poorly preserved peridinoid taxa with probable penitabular grana, questionably assigned to Chichaouadium and Spinidinium, are also common in the Lower Eagle Ford Formation; Subtilisphaera? pirnaensis sensu Davey (1970) is common in the Langtry Member, from 39.93 to 44.81 m.

Gonyaulacacean dinoflagellate cysts are mostly represented by Spiniferites ramosus, Spiniferites twistringiensis, Florentinia spp., Pterodinium cingulatum cingulatum and, in the Cenomanian section from 0.01 to 29.66 m, Litosphaeridium siphoniphorum. Areoligeracean dinoflagellate cysts, mainly Canningia reticulata, Circulodinium colliveri, Circulodinium distinctum and Tenua hystrix, have a fairly ubiquitous occurrence. Specimens of Heterosphaeridium heteracanthum and Cyclonephlia longispinatum are rare to frequent in the Lower Eagle Ford Formation, although preservation often renders distinction between them difficult. Cyclonephlia compacta, Cyclonephlia membraniphorum and taxa transitional between them (Marshall & Batten 1988) are relatively persistent in the Scott Ranch Member. Ceratioid dinoflagellate cysts and Dinogymnium spp. are rare and sporadic at Lozier Canyon. The latter genus is a more consistent component of palynological assemblages at higher stratigraphical levels within the Upper Cretaceous (e.g. Costa & Davey 1992).

Land-derived (terrogenous) pollen and spores are mainly represented by gymnosperm pollen (bisaccate pollen and Classopollis), angiosperm Normapolles (Atlantopollis and Complexiopollis) and tricolpate pollen. Pteridophyte/bryophyte spore occurrences are sporadic. Terrigenous palynomorphs are rare through most of the succession but are common from 25.91 to 32.31 m with an influx of relatively abundant taxa, mainly Normapolles pollen, from 34.32 to 36.12 m (Figure 4).
Figure 3. Palynological data from the Lower Eagle Ford Formation at Lozier Canyon. Relative abundance (%) estimates of palynomorph botanical groups from an initial 100-specimen count, dinoflagellate cyst species richness (i.e., number of taxa recorded) and total counts of all angiosperm pollen, gymnosperm pollen and pteridophyte/bryophyte spores are plotted. Note that in three samples, fewer than 100 specimens were recorded from the entire microscope coverslip (0.01 m, 26 specimens; 2.90 m, 44 specimens; 14.94 m, 69 specimens), and full counts are given for those samples instead of percentages.

Schwab et al. (2011) recovered probable freshwater placoderm desmid-like microalgae, 6–12 microns in size, in unsieved kerogen preparations from the Lower Eagle Ford Formation at Lozier Canyon and Comstock West. Occasional specimens with comparable morphology but larger size were recovered in the sieved post-oxidation preparations of the present study (Plate 1), throughout the Eagle Ford Group at Lozier.
Canyon, 1.91 to 39.62 m. They are frequent at 34.32 m and common at 36.12 m, in the same samples that contain abundant Normapolles pollen, supporting the interpretation of them being freshwater in origin, ‘washed’ into a distal marine palaeoenvironment along with the pollen by continental run-off. Schwab et al. (2011) suggested that there are high concentrations of the colonial fresh/brackish-water green alga *Botryococcus braunii* (e.g. Zippi 1998) in the AOM of their Lower Eagle Ford Formation samples. Specimens of *B. braunii* were only rarely recovered in the sieved preparations in the present study (apart from the sample at

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Figure 4. Palynological data from the Upper Eagle Ford and Austin Chalk formations at Lozier Canyon. Relative abundance (%) estimates of palynomorph botanical groups from an initial 100-specimen count, dinoflagellate cyst species richness (i.e. number of taxa recorded) and total counts of all angiosperm pollen, gymnosperm pollen and pteridophyte/bryophyte spores are plotted.
24.08 m, which yielded common *B. braunii*), and its presence in abundance is not corroborated. The Comstock West samples are rich, apart from the uppermost sample (4634-005). Assemblages are dominated by peridinioid dinoflagellate cysts, mainly *Bosedinia* cf. sp. 1 & sp. 3 and *Ascodinium* cf. *ovatum* (Figure 5).

### 4. Biostratigraphy

The Lozier Canyon section has been studied for foraminifera, calcareous nannofossils, geochemistry (including $\delta^{13}$C isotopes) and macrofossils by Donovan & Staerker (2010) and Donovan et al. (2012). More recent work has been published from the outcrop on calcareous nannofossils (Corbett & Watkins 2013, 2014) and planktonic foraminifera (Lowery et al. 2014). A middle to late Cenomanian age is indicated by these studies for the Lower Eagle Ford Formation. A late Cenomanian to late Turonian, or possibly Coniacian, age is indicated for the Upper Eagle Ford Formation. The widely used informal term ‘uppermost Cenomanian’ is used to describe strata dated as late Cenomanian that occur above the extinction of the Cenomanian keeled planktonic foraminiferal genus *Rotalipora* Brotzen 1942 (28.50 m at Lozier Canyon; Figure 2).

The high-resolution palynological study of the Eagle Ford Group at Lozier Canyon presented here identifies stratigraphical events that can be correlated locally, e.g. Iona-1, regionally within the KWIS, e.g. the Global boundary Stratigraphical Section and Point (GSSP or ‘golden spike’) at Rock Canyon and adjacent Portland-1 core, near Pueblo, Colorado, and inter-regionally, e.g. Europe. In Iona-1, correlative bio-events based on palynology, i.e. dinoflagellate cysts, labelled with a ‘P’, calcareous nannofossils (‘N’) and planktonic foraminifera (‘F’), were calibrated against core depth (Eldrett et al. 2015).

Eldrett et al. (2015) used bentonite dating in conjunction with astronomical (obliquity and eccentricity) modelling of the inter-bedded Eagle Ford Group and adjacent Buda
and Austin Chalk Formations to provide age estimates for each bio-event in Iona-1. Many of the Iona-1 bio-events have been recognised at Lozier Canyon, as indicated in the following sections and in Figure 2.

4.1. Base frequent/common Litosphaeridium siphoniphorum (0.01 m; Iona-1 event P1)

In Iona-1, occurrences of L. siphoniphorum are sporadic and rare in the Buda Formation but the taxon is frequent or common in the overlying Lower Eagle Ford Formation (144.21 to 104.83 m; Eldrett et al. 2015). The frequent/common occurrence of L. siphoniphorum from the base of the Eagle Ford Group in Lozier Canyon is consistent with this, although samples were not analysed from the Buda Formation. The event is also recorded in Portland-1, Colorado (178.10 m, Eldrett et al. 2015). In the Texan sections, it is overlain by an acme of L. siphoniphorum, at 5.18 m at Lozier Canyon, and 143.37 m in Iona-1. In Tarfaya, Morocco, Prauss (2012a) reported a comparable distribution, with base frequent and overlying acme of L. siphoniphorum calibrated to the upper part of the Rotalipora reicheli Foraminiferan Zone which spans the lower–middle Cenomanian substage boundary.

4.2. Top prominent Boseditina cf. sp. 1 & sp. 3 (22.10 m; Iona-1 event P2)

At Lozier Canyon, Boseditina cf. sp. 1 & sp. 3 are common between 1.91 and 22.10 m. In Iona-1, the taxon occurs over a comparable stratigraphical interval but in greater relative abundance (superabundant), from 132.76 to 120.40 m (Eldrett et al. 2015). The influx occurs around a regionally correlated bentonite (the ‘X-bentonite’) in Iona-1. The X-bentonite has not yet been identified at Lozier Canyon. An influx of Boseditina cf. sp. 1 & sp. 3 were also recorded in Portland-1, Colorado. However, the influx is stratigraphically higher (155.45 to 163.03 m) and Iona-1 (103.44 and 104.83 m; Eldrett et al. 2015), possibly reflecting a higher sampling density in these sections. In southern England, top consistent and frequent L. siphoniphorum occurs in Plenus Marls Bed 6 at Lulworth and Eastbourne (Dodsworth 2000; Pearce et al. 2009).

4.3. Top common Cyclonephelium longispinatum (Iona-1 event P3)

The event was recorded at approximately the same stratigraphical level as top prominent Boseditina cf. sp. 1 & sp. 3 in Iona-1 and Portland-1 (Eldrett et al. 2015), but the common occurrence of C. longispinatum was not recorded at Lozier Canyon.

4.4. Base Cyclonephelium compactum-membraniphorum (28.62 m; Iona-1 event P4)

The lowermost consistent occurrence of these dinoflagellate cysts is in a comparable stratigraphical position at Lozier Canyon, Iona-1 (Eldrett et al. 2015), the Pueblo GSSP (Dodsworth 2000), other sites within the KWIS (Harris & Tocher 2003) and southern England, where Dodsworth (2000) and Pearce et al. (2009) recorded the base of C. membraniphorum within the Plenus Marls. Courtinat et al. (1991) recorded it in a comparable stratigraphical position, a short distance below the range tops of Rotalipora cashmani (planktonic foraminiferan) and Litosphaeridium siphoniphorum (dinoflagellate cyst), in Vergons, southern France. However, van Helmmond et al. (2014) reported the event from stratigraphically lower levels within the Cenomanian, at higher palaeolatitudes in New Jersey, USA and Alberta, Canada (see section 5.2 for discussion).

4.5. Top consistent/frequent Litosphaeridium siphoniphorum (29.66 m; Iona-1 event P6)

Top consistent and top frequent L. siphoniphorum occur at the same level in the GSSP section at Pueblo (Bed 73; Courtinat 1993; Dodsworth 2000), where L. siphoniphorum is consistent up to mid-levels of the S. gracile Ammonite Zone. The two events are separated by a short distance at Lozier Canyon (29.66 and 28.96 m) and Iona-1 (103.44 and 104.83 m; Eldrett et al. 2015), possibly reflecting a higher sampling density in these sections. In southern England, top consistent and frequent L. siphoniphorum occurs in Plenus Marls Bed 6 at Lulworth and Eastbourne (Dodsworth 2000; Pearce et al. 2009).

4.6. Top Wuroia spp./Diplofusa gearlensis (29.66 m; acritarch event not ranked in Iona-1)

Elongate, crescent-shaped palynomorphs assigned to these taxa are consistently present over a limited stratigraphical interval in Lozier Canyon, 29.66 to 25.30 m, and Iona-1, 104.18 to 107.82 m (Eldrett et al. 2015). Their range tops are roughly coincident with that of L. siphoniphorum. They provide a supplementary local/regional correlative event.

4.7. Top Adnatosphaeridium? chonetum (Iona-1 event P7)

At the GSSP in Pueblo, A? chonetum is consistently recorded from upper Cenomanian strata (intra-Bed 78
downwards) (Dodsworth 2000). Harris & Tocher (2003) recorded a similar distribution at Bunker Hill, Arizona, Wahweap Wash, Utah, and Bunker Hill, Kansas. In Iona-1, it has a possibly reworked top at 88.77 m, around the Cenomanian–Turonian stage boundary (Eldrett et al. 2015). It has not been recorded from the Upper Eagle Ford Formation at Lozier Canyon.

4.8. Top common Cyclonephelium compactum-membraniphorum (32.31 m; Iona-1 event P10)

There is an isolated influx of common C. compactum-membraniphorum at 32.31 m in Lozier Canyon. The taxa are frequent in the uppermost Cenomanian to lower Turonian in Iona-1 (72.75 to 102.95 m; Eldrett et al. 2015) and at the Pueblo GSSP (Bed 94 to Bed 66), and common in the uppermost Cenomanian at Pueblo (Bed 74 to 84, Dodsworth 2000, fig. 12). In Europe, they have a common uppermost Cenomanian to lower Turonian occurrence in Germany (Marshall & Batten 1988; Prauss 2006), Crimea (Dodsworth 2004a), Poland (Dodsworth 2004b) and France (Foucher 1983; Courtinat et al. 1991). The taxa have not been recorded in coeval Tethyan sections further south, in Spain (Lamolda & Mao 1999; Peyrot et al. 2011, 2012) and Morocco (Prauss 2012a, 2012b). The isolated influx at Lozier Canyon is stratigraphically lower and therefore older than the astronomical age calibration (92.87 Ma; Figure 2) for top frequent C. compactum-membraniphorum in Iona-1.

Plate 1. Palynomorphs from the Eagle Ford Group at Lozier Canyon (LC) and Comstock West (CW) outcrops and Iona-1 core. Specimens were magnified at 400×; the 50-μm scale bar applies to all specimens. The stratigraphical heights of samples above the base of the Eagle Ford Group are given for Lozier Canyon samples, while sample names are given for Comstock West and core depths are given for Iona-1. England Finder coordinates are listed for the specimens illustrated.

Figure 1. Crassosphaira spp., CW, 4634-004, N22/0;
Figure 2. Pterosphaeridia spp., CW, 4634-004, L33/2;
Figure 3. Pterospermella spp., CW, 4634-003, H59/1;
Figure 4. Tasmanites spp., LC, 47.24 m (155 ft), R35/1;
Figure 5. Senonisphaera rotundata Clarke & Verdier 1967, LC, 44.81 m (147 ft), W20/2;
Figure 6. Heterosphaeridium difficile (Manum & Cookson 1964) Ioannides 1986, LC, 42.52 m (139.5 ft), T15/0 (damaged specimen);
Figure 7. Subtilisphaera pontis-mariae (Deflandre 1936) Lentin & Williams 1976, CW, 4634-004, H33/2;
Figure 8. Cyclonephelium compactum-membraniphorum complex of Marshall & Batten (1988), LC, 32.31 m (106 ft), L41/0;
Figure 9. Isabelidinium magnum (Davey 1970) Stover & Evitt 1978, Iona-1, 7.91 m, W36/4;
Figure 10. Lithosphaeridium siphoniphorum (Cookson & Eisenack 1958) Davey & Williams 1966, CW, 4634-001, H35/2;
Figure 11. Adnatosphaeridium tutulosum (Cookson & Eisenack 1960) Morgan 1980, LC, 33.53 m (110 ft), S30/2;
Figure 12. Two specimens of possible placoderm desmid-like microalgae (cf. Schwab et al. 2011), indicated by the arrows, LC, 36.12 m (118.5 ft), U30/4;
Figure 13. Bosedinia cf. sp. 3 (40 μm) of Prauss (2012b), Iona-1, 127.31 m;
Figure 14. Ascodinium cf. ovatum Prössl 1990 ex Prössl 1992, CW, 4634-002, V35/1;
Figure 15. Botryococcus braunii Kützing 1849, LC, 13.41 m (44 ft), M25/0;
Figure 16. Complexioxopollis spp., angiosperm (Normapolles) pollen, LC, 28.50 m (93.5 ft), S20/0;
Figure 17. Chatangiella spp., LC, 44.04 m (144.5 ft), Q42/4;
Figure 18. Bosedinia cf. sp. 1 (< 40 μm) of Prauss (2012b), CW, 4634-004, L19/4;
Figure 19. Subtilisphaera cf. pirnaensis (Alberti 1959) Jain & Millepied 1973 sensu Davey (1970) = Alterbidinium ‘daveyi’ (Stover & Evitt 1978) Lentin & Williams 1985, LC, 44.81 m (147 ft), H28/4;
Figure 20. Atlantopollis reticulatus Krutzsch 1967, CW, 4634-004, J43/4.

4.9. Top Adnatosphaeridium tutulosum (33.53 m; Iona-1 event P5)

This event occurs in the same stratigraphical position at Lozier Canyon and localities further north in the KWIS, at the GSSP in Pueblo (top Bed 78; Dodsworth 2000, figs 6, 12) and Bunker Hill in Kansas (Bed 78 equivalent; Harris & Tocher 2003), i.e. above top Lithosphaeridium siphoniphorum but below the influx of terrigenous pollen. However, specimens of A. tutulosum were only recorded from one sample in Iona-1 (104.18 m; Eldrett et al. 2015), below top L. siphoniphorum, so the astronomical age calibration in Iona-1 (94.59 Ma; Figure 2) will be older than the wider range top reported here. At locations in Europe, top A. tutulosum also occurs within the uppermost Cenomanian, above top consistent/frequent L. siphoniphorum in southern England (Plenus Marl, Bed 8 and 6 respectively; Dodsworth 2000; Pearce et al. 2009), eastern England (Dodsworth 1996, 2000), northern Germany (Marshall & Batten 1988), southern France (cf. Courtinat et al. 1991; Jarvis et al. 2011) and at a comparable stratigraphical level in northern France (Foucher 1983) and Crimea (Dodsworth 2004a).

4.10. Influx abundant terrigenous palynomorphs (34.32 to 36.12 m; pollen event not ranked in Iona-1)

The base of persistent abundant terrigenous palynomorphs, mainly angiosperm (Normapolles) and gymnosperm pollen within the uppermost Cenomanian is
an event that can be correlated around basal sections in the KWIS. At the GSSP in Pueblo, the event occurs in Beds 82 to 83 (Dodsworth 2000), within the planktonic foraminiferal *Heterohelix* shift (Beds 78 to 85; Leckie 1985; Keller & Pardo 2004). This is also the case at Lozier Canyon (Figure 2), where the latter is reported from 33.53 m upwards (Donovan et al. 2012). In Iona-1, abundant terrigenous pollen occur between 103.44 and 98.82 m, the base of the influx being slightly stratigraphically lower than that of the *Heterohelix* shift (100.90 m, Eldrett et al. 2015).

### 4.11. Cenomanian–Turonian boundary (CTB) (39.78 m) (ca. 94 Ma)

The CTB, i.e. the base of the Turonian Stage, is picked at the base of Bed 86 at the Pueblo GSSP (Kennedy et al. 2005). The $\delta^{13}$C excursion that spans the interval adjacent to the stage boundary has a distinctive profile of six peaks and troughs (Pratt & Threlkeld 1984; Gale et al. 1993) that can be correlated inter-regionally. Lowery et al. (2014) and Eldrett et al. (2015) noted that these component peaks and troughs are present in the $\delta^{13}$C excursion at some Eagle Ford Group sections, including Iona-1. However, they observed that the upper part of the $\delta^{13}$C excursion is missing at Lozier Canyon, including the IE-C peak of Pratt & Threlkeld (1984), which occurs immediately prior to the stage boundary at Pueblo. The Cenomanian–Turonian stage boundary level is therefore probably not preserved at Lozier Canyon, missing the unconformity at the base of the Langtry Member (ca. 39.78 m, Figure 2). Donovan & Staerker (2012) suggested that much of the lower and middle Turonian was eroded along this surface. Eldrett et al. (2015) estimated a 1.65-million-year hiatus, based on a comparison of nannofossil distributions (Donovan et al. 2012; Lowery et al. 2014) with Iona-1. Ewing (2013) and Denne et al. (2014) correlated and interpreted the unconformity in a regional context.

### 4.12. *Top Eurydinium glomeratum* (Iona-1 event P8)

This taxon was not recorded at Lozier Canyon. It is common in the upper Cenomanian to middle Turonian in Alberta, western Canada (e.g. Bloch et al. 1999). From published records, *E. glomeratum* is relatively rare and has a more stratigraphically-restricted occurrence further south in the KWIS, within lower Turonian strata at localities in Colorado and Kansas (Harris & Tocher 2003) and Iona-1 (98.88 to 70.45 m; Eldrett et al. 2015). It may occur in strata missing in the unconformity at the base of the Langtry Member at Lozier Canyon.

### 4.13. *Base Chatangiella spp.* (39.93 m; Iona-1 event P9)

At Lozier Canyon, base *Chatangiella* spp. occurs at 39.93 m, in the first sample analysed above the base of the Langtry Member, at the same level as the base of the Turonian calcareous nannofossil markers *Quadrum gartneri* and *Eprolithus eptapetalus* (Donovan et al. 2012). In Iona-1, *Chatangiella* spp. and *Chatangiella spectabilis* first occur in lower Turonian strata, sporadically from 74.50 m and consistently from 53.75 m upwards (Eldrett et al. 2015). Harris & Tocher (2003) recorded the basal occurrence of *C. spectabilis* in the upper part of the lower Turonian *Watinoceras* Ammo-nite Zone at three locations farther north, in Colorado, Utah and Kansas, but did not comment on whether any other species belonging to the genus ranged lower in these sections.

### 4.14. *Base Heterosphaeridium difficile* (42.52 m; Iona-1 event P11)

Rare and sporadic, broken specimens of *Heterosphaeridium difficile* are recorded between 42.52 and 46.70 m at Lozier Canyon; complete specimens are recorded from middle Turonian to Coniacian strata in Iona-1 (65.12 to 12.84 m; Eldrett et al. 2015). Specimens were recorded stratigraphically lower, in lower Turonian strata, at the Pueblo GSSP (Bed 95; Dodsworth 2000; Kennedy et al. 2005). In Europe, the taxon ranges from lower or basal middle Turonian to lower Santonian (e.g. Foucher 1980, 1981, 1983; Jarvis et al. 1988; Costa & Davey 1992; Fitzpatrick 1995; Pearce et al. 2003). The paucity of specimens in the KWIS Turonian renders its range base of limited practical use in biostratigraphical correlation between sections.

### 4.15. *Base consistent Senoniasphaera turonica* (Iona-1 event P12)

This taxon was not recorded in the Upper Eagle Ford Formation at Lozier Canyon. In Europe, *Senoniasphaera rotundata* is an established zonal marker fossil, its base occurring close to the lower–middle Turonian boundary in France, southern England and Spain (e.g. Foucher 1979, 1980, 1981, 1983; Tocher & Jarvis 1987; Lamolda & Mao 1999). Its inception may be later, close to the Turonian–Coniacian boundary farther north in the boreal North Sea region (Costa & Davey 1992). It is common in Coniacian, Santonian and Lower Campanian deposits in southern England (Prince et al. 1999, 2008). Pearce et al. (2003, 2011) and Olde et al. (2015a) differentiated a related species by a thicker endophragm, *Senoniasphaera turonica*, and indicated that *S. turonica* is the more common
morphotype in the Turonian of northwest Europe while specimens close to the holotype of *S. rotundata* (Clarke & Verdier 1967, pl. 14, fig. 2) are more typical in Coniacian deposits. In Iona-1, the first consistent occurrence (60.93 m) and subsequent frequent/common occurrence (58.74 to 52.57 m) of *S. turolica*, within the middle Turonian (Eldrett et al. 2015), may occur in strata missing in the unconformity at the base of the Langtry Member at Lozier Canyon.

4.16. Base frequent *Senoniasphaera rotundata* (44.04 m; Iona-1 event P13)

At Lozier Canyon, specimens were recovered from two adjacent samples at 44.04 m (rare) and 44.81 m (frequent), in the Langtry Member. As noted below, the base of frequent/common *S. rotundata* occurs in the presumed stratigraphically higher Austin Chalk Formation in Iona-1, where it is dated as upper Turonian (i.e. 90.17 Ma, Eldrett et al. 2015).

4.17. Turonian–Coniacian boundary (ca. 89.7 Ma)

At Lozier Canyon, Donovan et al. (2012) recorded the range top of calcareous nannofossil *Eprolithus eptapetalus* at 42.98 m. They interpreted it as a proxy for the top of the Turonian Stage and assigned the overlying part of the Langtry Member to a Coniacian age. Lowery et al. (2014) argued for a late Turonian rather than Coniacian age for the section of Langtry Member from 42.52 m and above, on grounds of the range base of the nannofossil *Lithastrinus septenarius* at 42.52 m, and subsequent range bases of *Eiffellithus eximius*, *Lucianorhabdus maleformis* and *Marthasterites furcatus*, and the range top of *Stoverius acylohous* at 44.04 m (Figure 2). These taxa have been documented from Turonian and Coniacian strata outside the KWIS area, e.g. Burnett (1998), Burnett & Whitham (1999), Crux (1982), Lees (2002, 2008), Sissingh (1977) and Wiese et al. (2004). The range bases mentioned are dated as late Turonian in Iona-1, but the range top of *S. achylohus* in Iona-1 is dated as early Coniacian (89.52 Ma; Eldrett et al. 2015). The ages of the upper Langtry Member and lower Austin Chalk Formation therefore remain controversial at Lozier Canyon, and a ranged assignment is given in Figure 2.

In Iona-1, the range bases of *L. maleformis* (nannofossil event N16), *M. furcatus* (nannofossil event N17), and the range top of *S. acyloohus* (nannofossil event N18), are recorded within the Austin Chalk Formation. Frequent occurrences of the dinoflagellate cyst *Senoniasphaera rotundata* are also restricted to the Austin Chalk Formation in Iona-1 (Eldrett et al. 2015). However, at Lozier Canyon, these events occur in the Langtry Member (Figure 2). It is unclear whether the ranges of the taxa are diachronous or the boundary between Langtry and Austin Chalk facies is diachronous within the Maverick Basin (e.g. Iona-1) and adjacent shelfal area (e.g. Lozier Canyon; Figure 1).

4.18. *Top Isabelaedinum magnum* (57.15 m; Iona-1 event P14)

Specimens of *Isabelaedinum magnum* are sporadically recorded at Lozier Canyon, up to the highest sample analysed from 57.15 m. In Iona-1, it is frequent between 18.70 m and the shallowest rich palynological sample analysed at 7.91 m (Eldrett et al. 2015). In NW Europe, *I. magnum* ranges from upper Cenomanian to Coniacian and has a common upper Turonian occurrence in the boreal North Sea, but can be absent from contemporary sections in southern England and France (Costa & Davey 1992). Its true range top probably occurs above the sampled section in Lozier Canyon and Iona-1. Its presence supports macrofossil data for an Austin Chalk Formation age not younger than Coniacian (Cobban et al. 2008).

5. Discussion

5.1. Palaeoenvironments

Modern gonyaulacacean dinoflagellates are mostly photosynthetic with high abundances usually related to lower productivity (Harland 1988). Almost all modern peridinioid dinoflagellates are heterotrophic, and are common in waters rich in dissolved nutrients. The peridinioid to gonyaulacacean ratio has been found to be a good measure of the proportions of living heterotrophic and autotrophic dinoflagellates, and hence of productivity in upwelling zones, and has been used as a measure of palaeoproduction in the KWIS (Harris & Tocher 2003). According to Wall et al. (1977), dinoflagellate cyst diversity is a function of environmental stress, with lower stress resulting in a higher diversity. Generally, environmental stress decreases and species richness increases from near-shore to distal-shore areas (e.g. Olde et al. 2015b).

Cornell (1997) reported diversified, mainly gonyaulacacean dinoflagellate cyst assemblages from the massive limestones of the Buda Formation in Dona Ana County, New Mexico. Ten samples analysed from the Buda Formation in Iona-1 yielded comparable assemblages (Eldrett et al. 2015). The assemblages are consistent with deposition under relatively open-marine, well-oxygenated conditions.

Deposition under restricted marine conditions with oxygen-deficient, probably anoxic bottom waters is indicated by the black, organic-rich (ca. 1 to >6% TOC) shales of the overlying Lower Eagle Ford
Formation at Lozier Canyon (Donovan et al. 2012, fig. 4). Prasinophytes phycomata and peridinioid dinoflagellate cysts are the dominant palynomorphs. It has been suggested that the input or availability of reduced nitrogen from the denitrification zone into photic-zone waters may have selectively stimulated groups of green algae like prasinophytes in the Cenomanian–Turonian organic-rich shales of Germany and Tarfaya, Morocco (Prauss 2006, 2007, 2012a and references therein). In Tarfaya, significant water-column oxygen depletion has been inferred, episodically reaching up into the photic zone (Kolonic et al. 2005). During deposition of the Lower Eagle Ford Formation, the introduction of waters from respectively deeper denitrification zones into photic zone waters by upwelling, or vertical expansion of the oxygen-minimum zone, may have fostered the prosperity of peridinioids and prasinophytes by enhanced availability of nitrite (peridinioids) and ammonium (prasinophytes; cf. Prauss 2007).

Prauss (2012a, 2012b) recorded sporadically common/abundant occurrences of the peridinioid taxon Bosedinia sp. 1 & sp. 3 in the Cenomanian and Turonian of Tarfaya. He suggested it may have a fresh/brackish-water affinity due to its association with common Botryococcus spp. Bosedinia cf. sp. 1 & sp. 3 are common in the Lower Eagle Ford Formation at Lozier Canyon and superabundant at Comstock West and Iona-1. In these west Texas localities, the influxes are not associated with increases in fresh/brackish-water algae such as Botryococcus, or with an increase in ter-rigenous pollen and spores. As noted in section 4.2, its abundant occurrence, in association with relatively high TOC and redox sensitive trace metals, may alternatively indicate eutrophic water, and possibly nitrite availability in the photic zone.

Terrigenous palynomorphs at Lozier Canyon generally compose less than one fifth of palynomorph assemblages (Figures 3 and 4), consistent with a distal marine palaeoenvironment, as envisaged by Donovan & Staerker (2010) and Donovan et al. (2012). They are mainly angiosperm and gymnosperm taxa. These assemblages are in contrast to those from an un-released well that was drilled on the margin of the East Texas Basin (Figure 1), located in a depositional setting relatively close to a fluvial–deltaic source. The lateral equivalent of the Lower Eagle Ford Formation in the well contains assemblages that are dominated by terrigenous palynomorphs (more than 75% of the assemblages), mainly pteridophyte/bryophyte spores and gymnosperm pollen, associated with relatively rare angiosperm pollen (Dodsworth, unpubl. data). Dinoflagellate cysts and freshwater algae, including the genera Ovoidites/Schizosporis and Concentricystes (taxa not recorded at Lozier Canyon or Comstock West), are frequent in many samples. Comparable palynomorph assemblages, mainly composed of terrigenous taxa, predominantly spores, associated with freshwater algae and rare dinoflagellate cysts, have been recorded from a continental to fluvial–deltaic depositional setting in Turonian sediments from farther north in the KWIS, in Utah (Akyuz et al. 2015). It is possible that the hydrodynamic properties of relatively small and therefore light angiosperm pollen, and relatively buoyant gymnosperm bisaccate and Clas sopriss tetrad taxa, may have facilitated their preferential transport to, and accumulation in, distal marine sediments (cf. Muller 1959).

5.2. Sequence stratigraphy

The Eagle Ford Group comprises a third-order stratigraphical sequence (e.g. Pessagno (1969) that shows an overall diminishing gamma log response from base to top (Slatt 2013). Superimposed on this third-order sequence are four fourth-order depositional sequences; K63 (Lozier Canyon Member), K64 (Antonio Creek Member), K65 (Scott Ranch Member) and K70 (Lantry Member). In general, each fourth-order sequence consists of a lower portion dominated by organic-rich carbonate mudstones and an upper portion consisting of carbonate mudstones with limestone interbeds, which are interpreted respectively as transgressive and highstand deposits (Donovan & Staerker 2010). Donovan et al. (2012) correlated these sequences between Lozier Canyon and other west Texas outcrops with subsurface sections in south and east Texas using geochemical and petrophysical data (e.g. gamma ray logs). In the following section, standard abbreviations for lowstand systems tract (LST), transgressive systems tract (TST), highstand systems tract (HST) and sequence boundary (SB) are used.

5.2.1. Lower Eagle Ford Formation: Sequences K63 & K64

A regional unconformity between the Buda and Lower Eagle Ford Formations occurs at the base of Sequence K63. A shallow-water succession at the base of the Lower Eagle Ford formation, with hummocky cross stratification and disarticulated oyster shells (facies A), slowly gives way to an anoxic, offshore mudstone facies (B; Donovan et al. 2012; Lowery et al. 2014). Prasinophytes are dominant in most samples from the lower part of Sequence K63 (facies A to basal B), 0.99 to 9.6 m (Figure 3). Influxes of peridinioid dinoflagellate cysts, mainly Palaeohystrichophora fusiformioides, are recorded at 6.25 and 8.69 m, while a diversified gonyaulaccean dinoflagellate cyst assemblage occurs at 1.52 m. The latter may be reworked from the underlying Buda Formation. In the upper part of K63 (facies
5.2.2. Upper Eagle Ford Formation: Sequences K65 & K70

The K65 SB at ca. 28.19 m is marked by an abrupt change in the physical and geochemical character of the Eagle Ford Group, including a decrease in organic carbon content and increase in carbonate content. These strata probably record a change from highly anoxic conditions below the surface to a more oxygenated environment above (Donovan et al. 2012). In terms of palynology, diversified dinoflagellate cyst assemblages appear from 28.50 m upwards (Figure 4), including taxa with inter-regional distributions (Section 4). This is consistent with a relatively well-oxygenated, open marine palaeoenvironment, in connection with oceanic water masses. The changes probably reflect the onset of eustatic sea level maxima leading up to the CTB (e.g. Sloss 1963; Haq et al. 1988).

Van Helmond et al. (2014) interpreted the range of the areoligeracean dinoflagellate cysts Cyclonephelium compactum-membraniphorum (28.62 m at Lozier Canyon; section 4.4) to reflect the southward migration of boreal waters during the ‘Plenus Cold Event’. The time interval is named for the belemnite Actinocamax plenus that migrated southwards in Europe during a relatively short-lived colder interval, ca. 3–5 °C, immediately prior to the CTB global temperature rise and maxima (Jefferies 1963; Gale & Christensen 1996; Huber et al. 2002; Pearce et al. 2009; Jarvis et al. 2011).

An inter-regional δ13C excursion around the CTB (see section 4.11) occurs in the interpreted TST and HST of Sequence K65 at Lozier Canyon (facies C2–C3, 32.61 to 39.78 m). The highest TOC values (ca. 1–3%) for the Upper Eagle Ford Formation are also recorded from C2–C3 (Donovan et al. 2012, fig. 8), suggesting this level is the regional expression of the global CTB OAE (OAE-2; see Jenkyns 2010 for a recent review). The influx of terrigenous pollen from 34.32 to 36.12 m (Section 4.10) may reflect an intensified hydrological cycle, i.e. increased evaporation, precipitation and run-off to the KWIS associated with global warming after the Plenus Cold Event (cf. van Helmond et al. 2014; Young et al. 2014). At Lozier Canyon, the pollen influx occurs within the K65 TST. Reworking of mud to the basin (e.g. Jenkyns 1980) and/or the formation of swamps due to drowning of land masses (cf. Ioannides et al. 1976) during transgression could also account for the increase in pollen.

In the upper part of Sequence K65 and the basal part of K70, from 37.03 to 39.93 m, palynomorph assemblages are dominated by peridinioid dinoflagellate cyst taxa, mainly Subtilisphaera spp. and Palaeohystrichophora infusorioides. The K70 SB (ca. 39.78 m), i.e. the unconformity at the base of the Langtry Member (section 4.11), is marked by a colour transition from light grey shales interbedded with grainstones to tan-coloured, highly bioturbated marls and a lag bed with pebble-sized rip-up clasts. The similarity in assemblages below and immediately above the K70 SB may be due to reworking. Sequence K70 is characterised by a coarsening-upward succession and increasing wave-ripple grainstones toward the contact with the Austin Chalk Formation, with rip-up clasts again marking the boundary to wackestones interbedded with thin black mudstones of the basal Austin Chalk Formation (Donovan et al. 2012; Lowery et al. 2014).

The reappearance of diversified gonyaulacacean dinoflagellate cyst assemblages from 42.52 to 44.81 m is consistent with open marine conditions during the K70 TST–HST. The highest samples analysed from Lozier Canyon, 45.42 to 57.15 m, are dominated by prasinophytes. The preparations appear to have been affected by weathering, with overall low recovery of palynomorphs, and are heavily contaminated with
vegetative matter. The high relative abundance of prasinophytes is probably an artefact of their preferential preservation in weathered material. Donovan et al. (2012, fig. 8) recorded negligible organic carbon content in samples from this level. Diversified dinoflagellate cyst assemblages are recorded throughout the Langtry Member and Austin Chalk Formation in the Iona-1 core (Eldrett et al. 2015).

6. Conclusions

(1) The four component members/sequences of the Eagle Ford Group can be recognised using standard industrial palynological analytical techniques. Dinoflagellate cyst range tops, bases and semi-quantitative abundance events facilitate comparable stratigraphical resolution to micropalaeontology and nannopalaeontology. Broad trends amongst different palynomorph botanical groups are interpreted to reflect major palaeoenvironmental changes during deposition of the Eagle Ford Group. These can also potentially be correlated within Texas.

(2) Deposition of the Eagle Ford Group at Lozier Canyon in a distal marine setting, on a submarine platform within the Cretaceous Western Interior Seaway (KWIS), is corroborated by palynology, including the high ratios of marine to terrestrial palynomorphs and angiosperm/gymnosperm pollen to pteridophyte/bryophyte spores.

(3) The Lower Eagle Ford Formation at Lozier Canyon contains two prasinophyte algal-dominated intervals that can be correlated with Iona-1. At Lozier Canyon, they are coincident with sedimentological evidence for relatively shallow sea levels during deposition of the lower parts of Sequences K63 (Lozier Canyon Member) and K64 (Antonio Creek Member). They may reflect encroachment of the photic zone by ammonium-enriched waters of the denitrification zone during relatively shallow sea level across the region. The intervening peridinioid dinoflagellate cyst-dominated assemblage, in the upper part of Sequence K63 at Lozier Canyon, differs in composition from those at Comstock West and Iona-1, including lower proportions of Bosediniella spp., suggesting significant lateral peridinioid assemblage variation.

(4) In the Upper Eagle Ford Formation, Scott Ranch Member (Sequence K65) at Lozier Canyon, upper Cenomanian dinoflagellate cyst marker events are recorded, including base and acme Cyclonephelium compactum-membraniphorum, top consistent and frequent Litospheridium siphoniphorum, and top Adnatosphaeridium tutulosum. The marker events in conjunction with planktonic foraminifera, calcareous nannofossils and geochemistry ($\delta^{13}$C) are consistent with the Pueblo, Colorado, international Cenomanian–Turonian Stage boundary (CTB) stratotype, and localities in Europe. An influx of terrigenous pollen immediately below the CTB at Lozier Canyon can be correlated with other sections in Texas (e.g. Iona-1 core) and Colorado (e.g. Pueblo). The base of C. compactum-membraniphorum may reflect the southward migration of colder boreal waters into the KWIS, around the time of commencement of deposition of the Upper Eagle Ford Formation. The overlying pollen influx may reflect an intensified hydrological cycle, i.e. increased evaporation, precipitation and run-off to the seaway associated with subsequent global temperature rise and maxima close to the CTB.

(5) Palynology complements nannopalaeontology in assessment of the amount of strata missing in unconformity at the base of the Langtry Member (Sequence K70). The absence of Eurydinium glomeratum and Senoniasphaera turonica at Lozier Canyon gives an indication of the amount of lower to middle Turonian sediment missing relative to more stratigraphically complete Eagle Ford Group sections, such as Iona-1. Nannopalaeontology and palynology, i.e. the basal occurrence of frequent Senoniasphaera rotundata, may indicate diachronous facies around the Langtry Member–Austin Chalk Formation boundary.

(6) There is potential for future operational (‘geosteering’) application of palynology to the drilling of long-reach ‘horizontal’ wells in the unconventional Eagle Ford Group reservoirs of south Texas. Commercial wells penetrate the Eagle Ford Group at depths from 1200 to 3700 m (Railroad of Texas 2015). Shallower shale oil wells may have comparable palynomorph preservation to west Texas outcrops but deeper shale gas wells may exhibit poor preservation and palynomorph loss due to thermal maturity of host sediments.

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No potential conflict of interest was reported by the author.

Supplemental data
Supplemental data for this article can be accessed here.

Author biography
PAUL DODSWORTH is a consultant palynologist/director at StrataSolve Ltd and an associate PhD supervisor at Kingston University, London. He obtained his PhD in Cenomanian–Turonian palynology from the University of Sheffield in 1997. His consultancy work focuses on the Cretaceous and Cenozoic stratigraphy of Europe, the Middle East, North America and Africa. He has undertaken stratigraphical studies of the Eagle Ford Group in Texas for three major oil companies. Since 2008, he has regularly organised and supervised offshore biostratigraphy teams for the drilling of ‘horizontal’ oil wells in the Lista Formation (Paleocene) of the UK sector.

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Appendix 1

A list of all palynomorph taxa recovered from the Eagle Ford Group at Lozier Canyon and Comstock West, grouped according to botanical affinity. The dinoflagellate cyst nomenclature and generic classification of Fensome et al. (1993) and the generic classification of Fensome & Williams (2004) are followed. The earlier taxonomic name of Cyclonephelium membraniphorum is retained purely for convenience of comparison with the Cyclonephelium compactum-membraniphorum complex of Marshall & Batten (1988). Taxa prefixed with a '?' indicate questionable identification(s).

Division Dinoflagellata (Bütschli 1885) Fensome et al. 1993
Subdivision Dinokaryota Fensome et al. 1993
Class Dinophyceae Pascher 1914
Subclass Peridiniphycidae Fensome et al. 1993

Order Gonyaulacales Taylor 1980
Suborder Gonyaulacinae (autonym)
Family Gonyaulacaceae Linde mann 1928

Achomosphaera ramulifera (Deflandre 1937) Evitt 1963
Apteodinium spp.
Atopodinium haromense Thomas & Cox 1988
Cassiculosphaerida reticulata Davey 1969
Chlamydophorea spp.
Coronifera oceanica Cookson & Eisenack 1958
Cribroperidinium spp.
Desmoscysta plekta Duxbury 1983
Dissiliodinium spp.
Florentinia clavigera (Deflandre 1937) Davey & Ver dier 1973
Florentinia deanei (Davey & Williams 1966) Davey & Ver dier 1973
Florentinia laciniata Davey & Ver dier 1973
Florentinia radiculata (Davey & Williams 1966) Davey & Ver dier 1973
Florentinia resex Davey & Ver dier 1976
Florentinia spp.
Haplocysta peridictya (Eisenack & Cookson 1960) Davey 1979
Kiokansium unituberculatum (Tasch in Tasch et al. 1964) Stover & Evitt 1978
Kleithriasphaeridium lufronsense Davey & Ver dier 1976
Litosphaeridium sipho phorum (Cookson & Eisenack 1958) Davey & Williams 1966
Nomatospaeropsis spp.
Oligosphaeridium complex (White 1842) Davey & Williams 1966
Oligosphaeridium? spp.
Oligosphaeridium toton Brideaux 1971
Pervosphaeridium paucispinum (Eisenack & Cookson 1960) Jan du Chêne et al. 1986
Pervosphaeridium pseudostri chodinium (Deflandre 1937) Yun Hyesu 1981
Pterodinium cingulatum cingulatum (Wetzel 1933) Below 1981
Pterodinium cingulatum granulatum (Clarke & Ver dier 1967) Lent in & Williams 1981
Sentisidiunm spp.
Spiniferites ramosus (Ehrenberg 1838) Mantell 1854
Spiniferites twistri ngiensis (Maier 1959) Fensome et al. 1990
Surculosphaeridium longifaccatum (Firtion 1952) Davey et al. 1966
Trichodinium castanea Deflandre 1935 ex Clarke & Ver dier 1967

Other chorate dinoflagellate cysts of uncertain supra-generic affinity, usually found in association with gonyaulacacean taxa

Cleistosphaeridium Downes sp.,
Dapsilidinium laminaspinosum (Davey & Williams 1966) Lent in & Williams 1981
Dapsilidinium? pumilum (Davey & Williams 1966) Lent in & Williams 1981
Dapsilidinium spp.
Downespheraidium armatum (Deflandre 1937) Islam 1993
Exochosphaeridium bifidum (Clarke & Ver dier 1967) Clarke et al. 1968
Exochosphaeridium phragmites Davey et al. 1966
Sepispinula? ambigua (Deflandre, 1937) Masue in Fauconnier & Masue 2004
Sepispinula pertusa (Davey 1969) Masue in Fauconnier & Masue 2004
Tanyosphaeridium spp.

Suborder Gonyaulacinae
Family Areoligeraceae Evitt 1963

Adnatosphaeridium? chonetum (Cookson & Eisenack 1962) Davey 1969
Adnatosphaeridium tutulosum (Cookson & Eisenack 1960) Morgan 1980
Canningia reticulata Cookson & Eisenack 1960
Circulodinium colliveri (Cookson & Eisenack 1960) Helby 1987
Circulodinium distinctum (Deflandre & Cookson 1955) Janssens 1986
Circulodinium spp.

Cyclonephelium compactum Deflandre & Cookson 1955
Cyclonephelium longispinatum (Davey 1978) Fauconnier in Fauconnier & Masure 2004
Cyclonephelium vanhophorum Davey 1969
Heterosphaeridium difficile (Manum & Cookson 1964) Ioannides 1986
Heterosphaeridium heteracanthum (Deflandre & Cookson 1955) Eisenack & Kjellström 1972
Heterosphaeridium? spp.
Senoniasphaera rotundata Clarke & Verdier 1967
Tenua hystrix Eisenack 1958

Suborder Goniodominae Fensome et al. 1993
Family Goniodomaceae Lindemann 1928

Dinoptrygium cladoideas Deflandre 1935
Hystrichosphaeridium recurvatum (White 1842) Lejeune-Carpentier 1940
Xiphophoridium alatum (Cookson & Eisenack 1962) Sarjeant 1966

Suborder Ceratinae Fensome et al. 1993
Family Ceratiaceae Willey & Hickson 1909

Endoceratium spp.

Endoceratium turneri (Cookson & Eisenack) Stover & Evitt 1978
Odontochitina operculata Deflandre & Cookson 1955
Odontochitina singhi Morgan 1980
Xenascus ceratioides (Deflandre 1937) Lentin & Williams 1973

Order Peridiniales Haeckel 1894
Suborder Peridiiniae (autonym)
Family Peridiniaeae Ehrenberg 1831

?Alterbidinium ioannidesii Pearce 2010
Alterbidinium spp.
Ascodinium cf. ovatum Prössl 1990 ex Prössl 1992

Comments: A plexus of peridiinoid taxa, including forms close to A. ovatum and forms grading toward a small variety of Trithyrodinium rhomboideum Singh 1983, are combined as A. cf. ovatum in the present study.

Bosedinia spp. cf. Bosedinia sp. 1 & sp. 3 of Prauss (2012b)

Comments: Smaller specimens (20–40 μm) with sub-spheroidal shape, lack of cavation, combination intercalary–apical archaeopyle with fused paraplate operculum, are comparable to the Tarfaya specimens of ‘Bosedinia sp. 1’, informally described by Prauss (2012b). Larger specimens (>40 μm) are comparable to his ‘Bosedinia sp. 3’. The Eagle Ford Group specimens contain fewer omphali (usually one or none) and lack any ornament features such as verrucae. N.B. Omphali = bio-polymeric ‘accumulation bodies’ of Evitt (1985).

Chatangiella spp.
Chatangiella victoriensis (Cookson & Manum 1964) Lent & Williams 1976
Chicchauxadinium? cf. vestitum (Brideaux 1971) Bujak & Davies 1983
Corculodinium inaffectum (Drugg 1978) Courtinat 2000 sensu Harris & Tocher 2003
Epelidiosphaeridium cf. spinosiformis Cookson & Hughes 1964 ex Davey 1969
Ginginodinium spp.
Isabelidinium cooksoniae (Alberti 1959) Lent & Williams 1977
Isabelidinium magnun (Davey 1970) Stover & Evitt 1978
Isabelidinium spp.
Laciniodinium biconicum McIntyre 1975/L. firmum (Harland 1973) Morgan 1977
Laciniodinium spp.
Palaeohystrichophora infusorioides Deflandre 1935
Spinidinium? spp.
Subtilisphaera pontis-mariae (Deflandre 1936) Lentin & Williams 1976
Subtilisphaera spp.
Trithyrodinium evittii Drugg 1967
Trithyrodinium spp.
Trithyrodinium spectacum (Manum & Cookson 1964) Davey 1969

Miscellaneous dinoflagellate cysts

?Codiocycla campanulata (Cookson & Eisenack 1960) Downie & Sarjeant 1965
Impletosphaeridium spp.
Membranilarnacia polycladiata Cookson & Eisenack in Eisenack 1963
Pareodinia ceratophora Deflandre 1947
Palaeotetradinium spp.
?Rhizoporus veligera (Deflandre 1937) Lejeune-Carpentier & Sarjeant 1983
Trigonopyxidia ginella (Cookson & Eisenack 1960) Downie & Sarjeant 1965
Vesperopsis nebulosa Bint 1984
Wallodinium anglicum (Cookson & Hughes 1964) Lentin & Williams 1973

Subclass Gymnodiniphyceae Fensome et al. 1993
Order Ptychodiscales Fensome et al. 1993
Family Ptychodiscaceae Willey & Hickson 1909
Subfamily Ptychodiscoideae Willey & Hickson 1909

Fensome et al. 1993
Alisogymnium spp.
Dinogymnium acuminatum Evitt et al. 1967
Dinogymnium albertii Clarke & Verdier 1967
Dinogymnium spp.

Other marine palynomorphs:
Prasinophyte phycomata
Crassosphaera spp.
Cymatosphaera spp.
Leiopsosphaera spp.
Leiosphaeridia spp.
Pterospermella aureolata (Cookson & Eisenack 1958)
Eisenack 1972
Pterospermella australiensis Deflandre & Cookson 1955
Pterospermella spp.
Pterosphaeridia spp.

Miscellaneous acritarchs/algae
Diplofusa gearlensis Cookson & Eisenack 1960
Eyrea nebulosa Cookson & Eisenack 1970
Palambages spp.
Paralecaniella indentata (Deflandre & Cookson 1955) Cookson & Eisenack 1970
Wuroia spp.

Acanthomorph acritarchs
Micrhystridium spp.
Veryhachium spp.

Foraminiferal chamber & (spiral) test linings
Fresh/brackish-water algae
Botryococcus braunii Kützing 1849
Possible placoderm desmid-like microalgae
Pediasstrum spp.

Terrestrially derived spores & pollen
Angiosperm pollen

Pteridophyte/bryophyte spores

Aquilapollenites spp.
Atlantopollis reticulatus Krutzsch 1967
Atlantopollis spp.
Atlantopollis verrucosus (Groot & Groot 1962) Krutzsch 1967
Complexiopollis complicatus Goczán 1964
Complexiopollis spp.
Normapolles pollen undifferentiated
Proteacidites spp.
Retiriculopites spp.
Tricolpites spp.

Gymnosperm pollen
Alisporites microsaccus (Couper 1958) Pocock 1962
Bisaccate pollen undifferentiated
Callialasporites dampieri (Balme 1957) Dev 1961
Classopollis spp.
Classopollis spp. (tetrads)
Exesipollenites spp.
Rugubivesiculites rugosus Pierce 1961

Fungal spores & hyphae