Refining palaeoenvironmental analysis using integrated quantitative granulometry and palynology

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Abstract

Accurate palaeoenvironmental analysis is at the heart of producing reliable interpretations and depositional models. This study demonstrates a multivariate statistical approach to facies analysis based on relationships between grain size and quantitative palynology. Our methodology has the advantage that it can be used on small amounts of sample, such as core or well cuttings, as the basis for facies analysis.

Proof of concept studies involving collection of grainsize and palynological datasets from well exposed outcrops of the Middle Jurassic, Lajas Formation of the Neuquén Basin, Argentina, demonstrate that canonical correspondence analysis can be used to consistently recognize facies and aid in the determination of depositional environments. This study demonstrates the link between depositional facies, grain-size distribution, palynomorph hydrodynamics, and assemblage taphonomy of palynomorphs. This knowledge can be transferred into a semi-automated statistical facies prediction technique for the subsurface in complex depositional settings, particularly when calibrated against conventional sedimentary facies analysis.

Supplementary material: The full set of grain size data and statistical scores are available at: http://www.geolsoc.org.uk/SUP0000

Introduction

Palaeoenvironmental interpretation is at the core of effective reservoir characterization and sequence stratigraphic analysis. While significant advances have been made with integrated palaeontological/sedimentological facies analysis of highly heterolithic deltaic facies in outcrop and core (McIlroy 2004, 2008), the same analysis from drill cutting material would be problematic. Detailed in this study is the analysis of two primary datasets that can be obtained from well cuttings (grain size attributes and palynology) from a well-documented outcrop framework (Brandsæter *et al.* 2005; McIlroy *et al.* 2005; McIlroy *et al.* 1999).

Significant advances in the understanding of tide-dominated deltas have been made in recent years through study of the Lajas Formation of the Neuquén Basin in Argentina (McIlroy *et al.* 2005; McIlroy 2007; McIlroy 2004; Martinius *et al.* 2000; Ichaso & Dalrymple 2009; Brandsæter *et al.* 2005; Rossi & Steel 2016). The significance of tide-dominated and tide-influenced deltas stems from their importance as petroleum reservoirs, especially offshore Mid-Norway (McIlroy 2004; Martinius *et al.* 2000; Ichaso & Dalrymple 2009) and the Northern North Sea (Maxwell *et al.* 1999).

Facies characterization and palaeoenvironmental interpretation is notoriously difficult in tide-influenced deltaic deposits, requiring the full breadth of palaeontological and sedimentological tools to be applied (Martinius *et al.* 2011; van Cappelle 2016). Sedimentological, ichnological and palaeobotanical data has already been integrated into facies analysis in the studied sections (McIlroy *et al.* 2005; Morgans-Bell & McIlroy 2005). The linkage between the palynology and palaeoenvironment of the hinterland floras, and its application to the understanding of the coastal depositional system has been investigated previously (Stukins *et al.* 2013). This study aims to build on this earlier work by developing an understanding of the depositional dynamics of palynomorphs in differing environments within a tide-dominated depositional setting.

Geological context

Middle Jurassic strata of the Lajas Formation crop out extensively in the Sierra de Chacaico of Neuquén Province, Argentina (Fig. 1a). The Lajas Formation (Fig. 2) has been widely studied in this region and is interpreted as marginal marine, deltaic unit with a strong tidal influence, high sediment supply, and rapid subsidence (McIlroy *et al.* 1999; McIlroy *et al.* 2005; Zavala 1996), though there is ongoing debate regarding the relative contribution of fluvial, wave and tidal processes through the succession (Gugliotta *et al.* 2015; Rossi & Steel 2016).

Four stratigraphic sections, chosen to encompass a range of depositional facies at different stratigraphic positions within the Lajas Formation (Fig. 1b), were logged and the fine-grained facies were sampled for palynology and granulometry (Stukins *et al.* 2013).

1) The ~40m thick progradational “Perigrina” parasequence set is dominated by mudstones and siltstones and inter-bedded with tabular sandstones in upward coarsening parasequences capped by distributary channel sandstones. These fine-grained facies are interpreted as pro-delta mudstones inter-bedded with prodelta turbidites associated with the first pulse of progradation of the Lajas Formation into the offshore facies of the Los Molles Formation (McIlroy *et al.* 2005).

2) The Quilmez Parasequence is dominated by a mud-rich facies succession that varies in stratigraphic thickness laterally from 2.8 m to 11.1 m, and is associated with heterolithic sandstones and mudstones. The thick, mudstone-dominated bayfill facies passes stratigraphically and laterally into tidal flat and abandoned channel fill deposits related with the bay-margin, and intertidal depositional environments (McIlroy *et al.* 2005).

3) The Norwegian Parasequence is a highly heterolithic package of sandstones and mudstones that is capped by oyster banks, which are in some places reworked by processes concurrent with the Owl Sequence boundary (McIlroy *et al.* 1999). The tidal flat dominated parasequence (sensu McIlroy *et al.* 1999) includes facies from sand/mud/mixed tidal flats, tidal channel fills, abandoned tidal channel fills, bayfills, mouthbar, as well as both autochthonous and allocthonous shell beds (McIlroy *et al.* 2005; McIlroy *et al.* 1999; Brandsæter *et al.* 2005).

4) The Dagna Parasequence marks the transition between the marginal marine Lajas Formation and the dominantly fluvial Challacó Formation at the northern end of the Sierra de Chacaico. The studied section is composed of upward coarsening heterolithic sandstones and mudstones inferred to have been deposited in river-dominated mouthbar settings. These mouthbar deposits pass distally into organic rich micaceous mudstones of lagoonal/bayfill character (McIlroy *et al.* 2005). The fine-grained mouthbar facies are cut by very coarse grained sandstones interpreted as delta top weakly tide-influenced river channels cutting older progradational lagoonal/bayfill facies. High in the section, but below the main Challacó Formation fluvial sandstones, there is a palaeosol horizon with a rooted horizon overlain by a thin coal.

Previous studies, based on macroflora and palynofloral data (Stukins *et al.* 2013; Quattrocchio *et al.* 2007), have proposed palaeoecological models for the floras of the Jurassic of the Neuquén Basin. The palaeofloral ecological dynamics have previously been published for the studied sections (Stukins *et al.* 2013) and are used as a point of reference for this study.

Methods

For palynological analysis the samples were processed using 40% hydrofluoric acid and the resulting residue sieved through a 7μm mesh then, where necessary, boiled in 40% hydrochloric acid to remove any precipitate. The residues were applied to cover slips using 2% polyvinyl alcohol and then onto slides using two part epoxy medium. The sample slides were counted using transmitted light microscopy for a minimum of 250 specimens per slide, abundance permitting, to create a raw data-set. The raw count data was converted into abundance percentages to normalize the data.

All of the fine-grained samples analysed for their palynological content had their grain size distributions determined using a Beckman Coulter LS 13 320 LS Particle Size Analyzer. Grain size and grain sorting were identified as the most useful factors for comparison with the sedimentological facies recognised in the field, and for linkage with the palynological data collected herein. The parameters used as proxies for grain size and grain sorting are the <50 percentile (%<50) and the mean/median ratio (m/m ratio) respectively (adapted from (Friedman 1962; Inman 1952)).

Canonical correspondence analysis (CCA)

The possibility of linking granulometric analysis results with palynological data through canonical correspondence analysis (CCA) to help determine palaeoenvironment of deposition is explored in this study using the integrated palynological and granulometric datasets. Correspondence analysis (CA) is an ordination method that can display ecological information inferred from axes of eigenvalues representing directions of variation in the dataset from given species assemblage data. The eigenvalues derived from the statistical analysis are a coefficient reflecting the degree of species dispersion along an axis, hence, a measure of relative importance of the given axis in explaining the species variation (Ter Braak 1986; Kovach 1993; Dale *et al.* 2005). Similar eigenvalues are interpreted to show a relationship based on the variant of the given axis.

Canonical correspondence analysis is an extension of CA, in which an additional matrix of environmental data is incorporated into the analysis. Ordination axes (represented by vectors) are added for these known environmental variables (Ter Braak 1986; Kovach 1993). In this study, these ordination axes are the sedimentological properties of the fine-grained sediment that the palynomorphs were recovered from.

In this study, a matrix of samples against palynomorph assemblage data and also the sedimentological properties provide the raw data. CCA of this data was analysed using the software package MVSP (Kovach 1993). The output of which are eigenvalues (degrees of variance) for the samples and palynomorph species identified within them. Canonical coefficient scores were produced for the sedimentological properties to form linear combinations of the environmental variables. These form the environmental vectors that can be projected onto cross-plots of the eigenvalues.

We approach the development of an understanding of the dataset by first compiling the whole Sierra de Chacaico dataset in order to analyse broad-scale trends in granulometric and palynomorph assemblage data. Once the coarse-scale trends have been determined, we then focus in on a subset of data from the Norwegian Parasequence in Rhea Gorge (cf. Brandsæter *et al.* 2005) to identify more detailed relationships between potential sedimentological processes in a progradational tidal flat rich succession and the palynological assemblages.

Grouped Sierra de Chacaico dataset analysis

Canonical correspondence analysis, applied to the palynological and granulometric datasets, calculated a five axes solution for the data, where the third and fourth axes have the greatest percentage variance. In this analysis however, constrained by the software, the known palaeoenvironmental variables are constrained only to the first two axes. Nevertheless, there is enough confidence in the statistics that there is adequate variance in the first two axes (eigenvalues of 0.027 and 0.008 but cumulative constructive percentages of 76.041% and 100%) to represent grain size related relationships for analysis.

When the data from the first two axes are presented on a cross plot (Fig. 3), the relationships between the samples/inferred facies, palynological data and the grain size data can be determined. CCA reveals that most of the samples from the same reported depositional environment cluster together as is expected (Fig. 3).

There is a facies-related characteristic represented in the multivariate dataset in the form of the linear trend within samples identified from the field as being bayfill mudstone deposits (Fig. 3). The linear trend is the approximate bisector of the two environmental vectors. It is not possible to determine whether this trend implies that grain size and grain sorting have an almost equal control on the palynological assemblages of bayfill mudstones, or whether that there is another unknown palaeoenvironmental factor that cannot be described directly from the data collected.

A trend is also observable in the data from the prodelta mudstone samples. The samples from all prodelta settings trend with an inverse relationship relative to the environmental vectors. This implies that neither grain size nor grain sorting controls on the sediment-palynomorph relationship. Fine-grained sediment was delivered to the prodelta environments of the Lajas Formation either by suspension settling from buoyant plumes, or from hyperpycnal slurries flowing down the delta slope.

The other facies described from the Sierra de Chacaico generally follow trends relating to the grain size proxy vector. The mudstones from mouth bar deposits show the strongest positive correlation with the grain size vector, and have seemingly little relationship to the grain-sorting vector, which could be considered an inverse relationship. Mouthbars as a whole are typically composed of well-sorted sand-grade sediment, though the processes responsible for depositing mud-rich drapes are less well constrained. Since there is little relationship between palynology and grain sorting, it may be that different processes operate at different portions of mouthbars. The mudstones sampled from the base of these mouthbar deposits, for example may be more prone to suspension settling than those on the accreting foresets of the mouthbar, and as such the sampling may need to be refined to determine real trends.

The tidal flat mudstone samples are not tightly grouped as a whole, but generally share a relationship with the grain size trend. The strongly progradational tidal flat environments of the Lajas Formation were extensive in aerial extent widespread and concomitantly diverse in character (McIlroy *et al.* 2005). Mudstones are typically present either as slack-water drapes (McIlroy *et al.* 2005) or as widespread fluid mud events (Ichaso & Dalrymple 2009). Tidal flats encompass a diverse range of depositional environments with subtle differences in depositional mechanisms (e.g. variable degrees of river, wave and tide influence). The absence of a distinctive relationship between the palynology and grain size variations is therefore perhaps to be expected.

Lagoonal mudstone samples from the Lajas Formation are weakly correlated with the grain size vector, but with some possible relationship to the grain-sorting vector since the entire samples plot between the two vectors (Fig. 3). Fine-grained sediment is inferred to have been transported to, partially restricted, coastal depositional environments associated with the Lajas Formation deltas by a combination of suspension settling and lateral transportation from hyperpycnal mud flows.

Abandoned tidal channel deposits have a complex relationship that is not simply described by the two granulometric parameters. There appears to be a greater concentration of data along the grain size vector, but there are definite outliers plotting with a relationship towards the grain-sorting vector. Mud-rich abandoned tidal channel environments typically fall along a continuum that grades either: laterally into tidal flats (once the fluvial influence of the tidal channel has been removed by channel abandonment); or distally into the basinal waters. After abandonment, tidal channels gradually fill with a combination of sediment from the adjacent tidal flats, and pelagic material from the marine system (McIlroy 2007).

The palynomorph data, when presented on a cross plot (Fig. 4), can show trends that can be used to compare and relate to the facies. The most obvious relationship between palynomorphs and sedimentological proxies is that *Classopollis* spp. plots with an inverse relationship to both palaeoenvironmental vectors. This trend corresponds to the same position as the prodelta mudstone samples (Fig. 3). The prodelta samples also have the highest dominance of *Classopollis* of all facies. We consider that this is due to the buoyancy of *Classopollis* pollen grains (Carvalho *et al.* 2006; Traverse 2008) that allows them to bypass the higher energy shallow marine settings before eventually settling, often as intact tetrads, in the relatively quiescent prodelta (Fig. 5). Therefore, transportation and deposition can be demonstrated to systematically control the distribution of majority of palynomorphs, with the exception of the *Classopollis*, which dominates prodelta mudstones.

Practical applications

When minimal sample material is available, such as from drill cuttings, this~~e~~ integration of palynology and grain-size analysis provides a semi-automated methodology for determining depositional facies from a suite of samples within complex marginal marine settings. Given that facies by their very nature grade into one another, there is bound to be overlap in the statistically derived facies groupings (Fig. 6). Where there is overlap, it may be that depositional facies/palaeoenvironment may be better determined by detailed palynological/palaeoecological characterization (cf. (Stukins *et al.* 2013).

Taphonomy and depositional processes on tidal flats

The CCA technique was performed on the subset of data from the Norwegian parasequence at Rhea Gorge (Brandsæter *et al.* 2005), to characterize potential trends in a tidal flat dominated succession. The resulting cross plot (Fig. 7) shows a distinct correlation between the tidal flat deposit samples and the grain size proxy vector with the samples forming a tight cluster. To investigate whether a model could be created that links depositional environment with palynological assemblage, the palynomorph data was plotted against the environmental variables (Fig. 8).

Two groupings are identified in the tidal flat dataset that relate closely to the environmental vectors. *Inaperturopollenites hiatus* and *Deltoidospora* spp. are found to closely relate to grain sorting (m/m ratio) and Araucariaceae pollen, *Vitreisporites* *pallidus* and *Classopollis* spp. are in close relation to grain size (%<50). No other taxa have a significant relationship to either of the two vectors.

When the abundance of the two groups of palynomorphs are plotted against each other (Fig. 9), and the samples are sorted by their inferred depositional environments—based on field characterization of facies—there is a strong trend within the tidal flat samples. In samples from tidal flat facies there is a higher abundance of the grain size related palynomorph taxa, and lower abundance of grain-sorting related taxa. The pattern shown in this assemblage is considered to reflect the sedimentation processes that deposit fine-grained sediment in tidal flat environments. The grain size related taxa both have good buoyancy since Araucariaceae pollen have a large air sac, and *Classopollis* have buoyant pollen morphologies (Carvalho *et al.* 2006; Traverse 2008). In contrast, the grain sorting group of taxa are dominated by *Deltoidospora* spores, that are simple trilete spores with little to no airborne or hydrodynamic transportation potential (Salter *et al.* 2002). Such spores are considered to rely almost entirely on fluvial processes to act as transport mechanisms into the shallow marine environment. Due to the minimal influence of distributary channel systems and the dominance of tidal reworking as the primary sedimentary process in tidal flat deposits, the grain sorting related taxa are represented in a far smaller proportion than the grain size related taxa.

Conclusions

Our exploration of the relationship between palynomorph assemblage and grain size of mudstones in the Lajas Formation shows that different facies, when plotted with grain size data proxies for grain sorting (m/m ratio) and grain size (%<50), have consistent spatial relationships (Fig. 6). This insight could be used to allow the palynology and grain-size data from samples, such as drill cuttings of unknown facies, to aid in palaeoenvironmental interpretation using the canonical correspondence analysis method.

A link between the palynomorphs present in fine-grained samples from tidal flat dominated successions has been established through canonical correspondence analysis of the Norwegian parasequence data from Rhea Gorge. There is a greater proportion of palynomorphs related to the grain size proxy (%<50) than grain sorting (m/m ratio). This indicates that the process of deposition within tidal flat environments is dominated by fallout from suspension, inferred from the palynomorph physiology, rather than current controlled processes that could be expected from other environments such as channels and mouthbars. This methodology could be directly translated for use in any tidal flat dominated subsurface reservoir or outcrop. The results of this study also demonstrate a link between depositional facies, grain-size distribution, hydrodynamics, and assemblage taphonomy of palynomorphs. This knowledge can be transferred into a semi-automated statistical facies prediction technique for the subsurface in complex marginal marine settings. With further investigation, this technique also has the potential to be applied to a broader range of depositional settings.

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Figure 1a: Location diagram of study area. A shows the location of map B in the context of South America. B shows the Neuquén Province and map C. C is a map south of Zapala showing the Sierra de Chacaicó study area.

Figure 1b: Location of sampled sections within the Sierra de Chacaico outcrops.

Figure 2: Simplified stratigraphic column of the Cuyo Group (Based on Howell *et al.* (2005), McIlroy *et al.* (2005) and dates from Gradstein *et al.* (2004)). Lajas Formation sequences and parasequences after McIlroy *et al.* (2005).

Figure 3: CCA cross plot of eigenvalue scores for the samples calculated from palynological and granulometric data from all Sierra de Chacaico sections. The samples are coded by facies interpretation.

Figure 4: CCA cross plot of eigenvalue scores calculated from data from all Sierra de Chacaico sections showing the palynomorph variables.

Figure 5: *Classopollis* spp. tetrad from the “Peregrina” parasequence set (Sample 4o9 Leica DMRX coordinates 42.8 103.0)

Figure 6: Model of the relationship between lithofacies/palaeoenvironment and palynological and granulometric data using CCA.

Figure 7: CCA plot of eigenvalue scores from the Norwegian parasequence samples and relationship with palynological and granulometric data. Samples are facies coded.

Figure 8: CCA cross plot of eigenvalue scores of the palynomorphs variables from the Norwegian parasequence and their relationship to the granulometric parameters. Circled are the two taxa groupings associated with the environmental vectors (m/m ratio and %<50).

Figure 9: Percentage abundance of the grain size (%<50 taxa) and grain sorting (m/m ratio) taxa per sample, grouped in lithofacies/palaeoenvironment.