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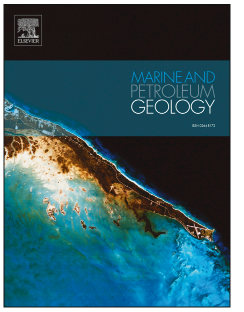

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Reconstruction of linear dunes from ancient aeolian successions using subsurface data: Permian Auk Formation, Central North Sea, UK

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Abstract

A series of well logs and cores penetrating the predominantly aeolian Auk Formation, Permian Rotliegend Group, Central North Sea, UK, have been evaluated to determine the morphology and style of migratory behaviour of the original dune bedforms, the overall depositional environment, and to assess implications for reservoir heterogeneity. This has been achieved by detailed facies analysis of subsurface datasets and by comparison of the observed sedimentary styles of accumulation to analogous modern aeolian dune fields. Aeolian bedform type, morphology, detailed migratory behaviour, and the nature of the accumulation surface have been interpreted. Analysis of the facies architecture of preserved cross-bedded sets and cosets indicates accumulation on a dry substrate via the migration and climb of large linear bedforms that possessed low-angle inclined lower plinths, up to 15 m thick. Dune plinth elements are dominated by wind-ripple and reworked wind-ripple strata, and were preferentially preserved as successive bedforms migrated over one another at low angles. Packages of grainflow-dominated strata representative of accumulation on the higher part of the bedform lee slope are less common and tend to be preserved mostly in the upper parts of large cosets of strata (~30 m thick). Large linear bedforms were separated by dry interdune areas. Although the primary direction of sand transport was along the elongated crests of the bedforms, a secondary component of transverse motion enabled the lateral migration and preferential preservation of lee-slope deposits that arose from a minor oblique component of bedform migration. In places, the architecture records the preservation of small barchanoid dune deposits, either within interdune depressions or superimposed on the lower flanks of the large linear bedforms. The preserved aeolian facies types exert a primary control on reservoir quality. Few previous studies have documented linear dunes in ancient successions; these findings represent a valuable case example.

Keywords

Aeolian; North Sea; sedimentology; Auk; Rotliegend; linear dune

Highlights

Cores and well logs from the subsurface aeolian Auk Formation have been analysed and interpreted;

Bedform type, morphology, and migratory behaviour have been reconstructed using novel and innovative techniques in aeolian facies analysis;

Novel criteria have been established for the recognition of linear bedforms in ancient preserved aeolian successions known only from subsurface data;

Auk Formation is shown to have arisen via the accumulation of linear draa and smaller barchanoid dunes that climbed over one another in a complex manner;

Represents a rare study of subsurface linear dune deposits.

1 – Introduction

An integrated well-log and core interpretation case study is presented to demonstrate how observations from a subsurface dataset can be used to reconstruct dune type, morphology and temporal migratory behaviour of large bedforms within an aeolian dune and interdune succession known only from the subsurface. The method employed outlines objective criteria for interpreting changes in the style, rate and direction of aeolian bedform migration through recognition of stratigraphic evidence for temporal changes in bedform migration behaviour, lee-slope steepness and asymmetry, and by comparison to analogous outcropping successions and currently active aeolian dune fields.

Determination of original aeolian bedform type and migratory behaviour from ancient aeolian successions known only from subsurface intervals is problematic because such successions exhibit lithological heterogeneity at a number of scales. Such heterogeneity develops in response to both the varied arrangement of lithofacies arising from complex autogenic bedform behaviour (e.g. Heward, 1991), and potentially also from allogenic controls on stratigraphic accumulation and preservation (e.g. Howell and Mountney, 1997). As such, the deposits of such accumulations may be highly variable over short lateral distances; elucidating the three-dimensional architecture of the deposits and interpreting their significance in terms of original formative processes are not straightforward.

Aeolian dune successions of the Permian Rotliegend Group of the southern and central North Sea, and surrounding area have previously mostly been interpreted as the accumulated deposits of transverse bedforms (e.g. Glennie et al., 1978; 1998a; Heward, 1991), including barchanoid forms. However, linear aeolian bedforms have been also reconstructed from some parts of this succession (e.g. Steele, 1983). Although spatial variations in bedform type across large aeolian dune fields are widely documented such that transverse and linear forms are known to commonly co-exist (e.g. Namib Desert, Lancaster, 1983; Rub' Al-Khali, Al-Masrahy and Mountney, 2013), there remain few documented examples of such variability from ancient preserved aeolian successions.

Despite linear bedforms accounting for >50% of dunes present in modern active dune fields, the deposits of such bedforms are rarely interpreted from the ancient record (Rubin and Hunter, 1985; Rodríguez-López et al., 2014). This is, in part, because linear bedforms tend to develop where sand is being transported over deflation surfaces and the potential for long-term aeolian accumulation is therefore limited (Mainguet and Chemin, 1983). As such, there are very few published descriptions relating to the internal facies and bounding-surface distributions of ancient linear dune successions, though one such example is the Permian Yellow Sands of Coutny Durham, England (Steele, 1983). However, more generally, qualitative and quantitative data sets relating to the stratigraphy of successions generated by the accumulation of linear bedforms – which might serve as valuable analogues for the Auk Formation – are few. The modest number of accounts that have been published are from successions that are either not especially close in terms of their analogy, or are not sufficiently well exposed to yield useful dimensional data.

Figure 1 depicts a schematic representation of a simple (*sensu* McKee, 1979) linear draa (large scale aeolian bedform) that has undertaken migration and aggradation at a low angle-of-climb. Vertical successions located at various positions along an accumulated stratigraphic section depict typical vertical lithofacies profiles. This schematic illustration demonstrates the expected presence of a marked lateral variability in facies arrangements that is typically encountered over lateral distances of 100 to 300 m within aeolian dune deposits accumulated by the same migrating bedform. Individual vertical profiles within the same set (or coset) can be composed solely of wind-ripple and wind-ripple-dominated facies, whereas only a relatively short distance away, the same stratigraphic section might be represented by a suite of different aeolian dune facies types, including grainflow and grainflow-dominated units. Figure 1 demonstrates how core and log data are dependent on the exact position of a well, and illustrates the difficulty of attempting to correlate laterally between even closely spaced wells in aeolian successions represented by these types of deposits. For effective reconstruction of aeolian paaleoenvironments from subsurface core and well-log data, an underlying assumption is that, given a number of wells, the unit as a whole is represented by the available data, and an interpretative model can be developed to account for the expected three-dimensional facies arrangements.

The complexity in facies arrangements in aeolian successions is dependent on a number of autogenic factors including, for example, how far down the lee slope of the migrating bedform grainflow avalanches extended before terminating. Given this intrinsic complexity in facies arrangements, care must be taken when interpreting individual one-dimensional graphic logs, especially those recorded from cores taken from subsurface aeolian successions; this is especially important for aeolian successions where the ability to reliably correlate between neighbouring logs – even those spaced only a few hundred metres apart – is severely hindered by the absence of beds or bounding surfaces that can demonstrably be shown to serve as reliable markers for correlation purposes (Mountney, 2006). In many cases, the inability to even establish the presence of features regarded to be reliable indicators of palaeo-horizontal in subsurface aeolian successions is highly problematic (Kocurek, 1988; 1991).

Despite these problems, reconstruction of aeolian dune type from subsurface data remains important because many aeolian successions are known wholly or principally only from the subsurface, yet understanding these systems is important for improving palaeoenvironmental understanding. Examples include the Pennsylvanian-Permian Weber Sandstone of the Rangely Field, Colorado, USA (Fryberger, 1979b; Bowker and Jackson, 1989), the Permian Leman Sandstone of the UK Southern North Sea (Glennie et al., 1978; Weber, 1987), the Permian Auk Formation of the UK Central North Sea (Heward, 1991), the Permian Unayzah Formation of Saudi Arabia (Melvin et al., 2010), parts of the Triassic Ormskirk Sandstone of the UK East Irish Sea Basin (Meadows, 2006), the Jurassic Norphlet Sandstone of the Gulf of Mexico (Mancini et al., 1985), and the Cretaceous Kudu Sandstone, offshore Namibia (Wickens and McLachlan, 1990). From an applied perspective, these successions form important reservoirs for hydrocarbons and understanding dune type is a fundamental step in predicting lithofacies distribution and therefore determining lithological heterogeneity and the arrangement of packages of favourable reservoir quality.

The aim of this study is to demonstrate how a detailed palaeoenvironmental reconstruction of an aeolian system can be made from an ancient preserved succession known only from a subsurface dataset. Specific objectives of this study are as follows: (i) to identify a range of aeolian lithofacies types present in core data from the subsurface Auk Formation; (ii) to establish criteria for determining the type, morphology and migratory behaviour of the aeolian bedforms that gave rise to the Auk succession through analysis of preserved stratigraphic architecture and palaeocurrent data; and (iii) to demonstrate a methodology for reconstructing the depositional environment of an ancient aeolian succession based on key observations from subsurface datasets coupled with comparison to modern analogous aeolian dune systems.

This research is novel and significant because deposits of the Auk Formation studied here are considered to represent the preserved remnants of large linear aeolian bedforms; this study therefore documents an example of an important aeolian dune system type that is rarely recognised in ancient successions.

2 – Geological Setting

The Permian Auk Formation of the Rotliegend Group is present in the subsurface around the southern edge of the North Permian Basin in the UK sector of the Central North Sea (Figure 2). The succession accumulated in a subsiding basinal area in response to transtensional collapse following the Variscan Orogeny (Glennie, 1998a; Glennie et al., 2003). The Auk Formation underwent initial accumulation in the Early Permian: Capitanian to Wuchiapingian (Glennie et al., 2003; Figure 3). Thin grey claystone beds within the upper part of the formation have yielded spores of Late Permian age (Heward, 1991). The overlying Zechstein Group accumulated during the Late Tatarian (Taylor, 2009).

The aeolian system of the Auk Formation was constructed from wind-blown detritus that was derived from both the Caledonian Uplands that lay to the northwest (Glennie et al., 2003) and from the Variscan uplift of the Mid-North Sea High to the south (Bifani et al., 1987), based on analysis of regional palaeowind patterns determined from preserved palaeocurrent data including foreset dip-azimuths in cross-bedded sets and sediment provenance studies. Sediment transport pathways were complex and were likely influenced by both regional palaeodrainage and palaeowind patterns.

The Auk Field is a producing oil reservoir that forms a fault-bounded horst block located close to the western edge of the Central Graben of the North Sea (Trewin et al., 2003). Oil has been produced from both the Permian Auk Formation itself and from the overlying Zechstein Group.

2.1 – Stratigraphy and reservoir layering

Previous stratigraphic studies of the Rotliegend Group in the Central North Sea region have yielded a five-fold layering scheme, which are numbered from stratigraphic top to bottom as Unit 1 to Unit 5, respectively (Heward, 1991). Unit 5 comprises a basal conglomerate layer that is rarely penetrated by wells. Units 4, 3 and 2 are interpreted as aeolian dune sands, which form effective net reservoir in varying proportions. Units 2 and 1 are significant reservoir layers above the oil-water contact (OWC); Unit 2 forms a lower net:gross reservoir interval than Unit 3. Unit 1 is a distinct stratigraphic layer which comprises massive and slumped sandstones, interpreted to be the products of reworking and slumping of the large aeolian dunes in a wet climatic phase directly preceding the Zechstein transgression (Glennie and Buller, 1983), or possibly as a result of the initial transgression itself. The interval studied here is Unit 2 from the upper part of the Auk Formation. The seismic character of the Auk Formation is internally rather opaque; the surface at the boundary between Unit 3 and Unit 2 is generally well imaged but individual bounding surfaces representing large dune sets cannot be resolved due to the low acoustic impedance contrast. Although some wells that penetrate the Auk Formation are only a few hundred metres apart (e.g. 30/16-2, 30/16-A12 and 30/16-A14; Figure 4), no direct correlation can be reliably established between cored sections thought to represent the same stratigraphic intervals.

3 – Data and Methods

Core and well-log data from 14 wells (Figure 4) from Unit 2 of the Auk Formation totalling 1140 m in length have been logged to record the detailed sedimentology of the succession. Logging was carried out on the predominantly well-conserved reference slabbed sections held by the field operator (Talisman Energy UK Limited – now Talisman Sinopec Energy UK Limited). Less well-conserved sections are available on open-release from the British Geological Survey. Core logs record lamination and bedding style, apparent depositional dips and textural properties of the sediments; this information has been used to assign the deposits to 6 lithofacies. A review of all previously published sedimentological studies of the Auk Formation was also undertaken to supplement the primary dataset. Interpretations of the subsurface data were made on the basis of comparison with observed textural characteristics and patterns of aggradation of the sediments and depositional environments of recent aeolian sediments. Foreset dip-azimuth values from dipmeter data and from oriented core were analysed to determine original aeolian bedform migration direction and to relate this to regional palaeowind directions.

The following parameters were recorded from the 14 studied wells (Figure 4).

Top and base depths of facies units. Depths were recorded of tops and bases of all facies units, sample gaps, rubble zones and core gaps. Depths were recorded to the nearest 15 mm.

Nature of basal contact of units. For all facies boundaries, the following attributes of the basal contact of the unit were recorded: (i) angle of contact surface (relative to true horizontal in deviated wells); (ii) relationship of overlying laminae to bounding surface (concordant, downlapping, onlapping); (iii) relationship of underlying laminae to bounding surface (concordant, sub-parallel truncation, angular truncation). These attributes collectively allow recognition of different types of aeolian bounding surface (Figure 5), including interdune migrations surfaces, superimposition surfaces and reactivation surfaces (Kocurek, 1991, 1996).

Facies. Six facies types were recognised: non-reworked wind-ripple, reworked wind-ripple, grainflow, grainfall, massive sands and conglomerates, of which the first 4 mentioned are considered in detail herein.

Bedding style. A description of the nature of the lamination, comprising both lamina thickness, grain size, and an indication of the generalised nature of the sorting as expressed by the degree and nature of bimodality of grain size was undertaken. Four classes of bedding style were recorded: mm-bedded; mm-bedded with subordinate cm-bedding; bedding arising due to bimodal sediment grain sorting; bedding due to unimodal sediment grain sorting. Of these, bimodal sediment grain sorting is very common and four types are identified (Figure 6): bimodal framework, bimodal within framework and between laminae; bimodal between laminae with unimodal framework; and unimodal. The distinct grain sorting types are important for the recognition of different syn- and post-depositional processes that operated, especially on the lower and middle flanks of aeolian bedforms.

Apparent dip angle, corrected for well deviation. Dip angles of laminae were systematically recorded. A template cut to the angle of well deviation was used to obtain corrected apparent dips in cores cut in deviated wells, where the combination of well-path inclination and azimuth, and orientation of the slabbed core surface allowed this.

Grainsize, sorting and bimodality. With a few exceptions, the modal grainsize of the sandstones in the studied Auk Formation ranges from fine sand (upper) to medium sand (lower). Thus, as a parameter, grainsize has little facies diagnostic value. Rather than record modal grainsize, a record has been made of visual estimates of the minimum and maximum grainsizes (“GSmn” and “GSmx”), expressed in phi units. A visual estimate of sorting (“Srt”) has been made, using a four-level scale (poor, moderate, good, very good). For analysis of the succession, the range of grainsize present (GSmx-GSmn, expressed in phi units) represents a simple way to describe the peakedness of the grainsize distribution. Much of the Auk Formation shows strong bimodality; an estimate has been made of the nature of this (“Bimod”). The scale employs a four level scale (Figure 6) to summarize the extent to which the framework of the rock comprises a random mixture of two grainsize populations (the “framework bimodality”) and the extent to which the rock contains finely alternating laminae of contrasting grainsize, each laminae being in itself unimodal (the “lamina bimodality”).

Colour. The dominant colours in the studied interval of the Auk Formation (red and drab) are recorded. In many sections, these are too finely interlaminated to record on a bed-by-bed basis, and have instead been recorded in 4 classes: (i) all red; (ii) red with subordinate drab; (iii) drab with subordinate red; (iv) all drab.

Oil stain. The presence of oil in the studied interval of the Auk Formation is marked by black staining and by the occurrence of bleached laminae. The latter records the passage of reducing fluids and is not in all cases associated with live oil. In some older cores, the recognition of weak oil staining is ambiguous, owing to the loss of oil by evaporation. A four-fold scale of oil staining has been recorded: 0 – no stain; 1 – weak stain; 2 – moderate stain; 3 – strong stain. In addition, black impregnations of bitumen and residual oil have been recorded as a stain of type ‘R’. Type of oil staining is closely related to porosity and permeability (Prosser and Maskall, 1993; Follows, 1997; cf. Linquist, 1988), which are themselves controlled by primary lithofacies type. Thus, oil staining is an important indicator of primary sedimentological features.

4 – Sedimentology of the Auk Formation

The most detailed previously published study of the sedimentology and stratigraphy of the Auk Formation was conducted by Heward (1991) who proposed a four-fold facies scheme: aeolian wind-ripple sands, aeolian slipface sands, water-lain reworked sands of originally aeolian origin, and other water-lain conglomerates, breccias and sands. For this study, an extended and refined version of the scheme of Heward (1991) is employed. The lithofacies composition of the aeolian dune and interdune sets, and related deposits, are as follows: (i) predominantly fine-grained (rarely medium-grained) wind-ripple laminated sands, which typically exhibit bimodal sorting (Figure 7a); (ii) fine- to medium-grained reworked wind-rippled sands, which exhibit a coarse skew (Figure 7b); (iii) fine- to medium-grained sand of dune slipface (grainflow) origin, with generally the highest porosities (Figure 7c); (iv) fine-grained sands of grainfall origin; (v) fine- to coarse-grained sands that are predominantly massive (i.e. structureless), which occur at the top of the Rotliegend Group (named Weissliegend, Glennie and Buller, 1983); (vi) water-lain conglomerates, which occur locally at the base of the succession in the Argyll Field (Heward et al., 2003). Of these lithofacies types, only the first four are present in cores from this study of Unit 2 of the Auk Formation and these are considered in detail below.

4.1 – Wind-rippled facies

Description. Wind-rippled facies of the Auk Formation are composed of mm-scale laminated sandstone, with the grain size generally ranging from very fine, to medium (or rarely coarse) sand. This facies is characterised by strong bimodality (Figure 5), with a bimodal framework and segregation into laminae of contrasting grain size. The wind-rippled sandstone facies locally contains abundant pinstripe laminae (*sensu* Fryberger and Schenk, 1981), and in places contains discrete lenses of coarser-grained sand. Weak inverse grading can be discerned in some cases. In almost all cases this facies is red in colour, especially so in the finer grained parts. The reconstructed original depositional dip (i.e. inclination) of wind-rippled facies in the Auk Formation ranges from 0° to 26°.

Interpretation. Wind-ripple deposits record the migration of grains by creep or saltation, with a mixture of very fine sand and silt or clay material potentially also recording some fallout from suspension. Such transport processes are well documented in recent aeolian systems (e.g. Kocurek, 1991; Mountney, 2006), have been simulated in experimental wind tunnels (Fryberger and Schenk, 1981) and are identified in ancient deposits (Hunter, 1977). The pinstripe lamination represents interlaminations of very-fine and fine or medium sandstone and is generated by the accumulation of wind-ripple strata. Wind-ripple pinstripe laminae are generally inversely graded because of grain segregation on the ripples (Hunter, 1977). Although ripples on dune lee slopes commonly form where there is also active grainfall (Anderson, 1987; Sharp, 1963), the finer grains derived via suspension fallout are typically reworked into the migrating ripples. The finer-grained parts of the ripple-laminae tend to retain their deep red staining by virtue of their lower permeability.

4.2 – Reworked wind-rippled facies

Description. Reworked wind-rippled facies of the Auk Formation are characterised by mm-scale laminated sandstone as for the previously described wind-rippled facies, but additionally contain discrete laminae of better-sorted sand and that are either bimodal only between laminae, or are unimodal (Figure 6). Depositional dips range from 0° to 26°, but are usually greater than 7°. In places, where reworked wind-rippled strata occur above the OWC, the reworked laminae may be bleached to a drab colour or may be oil-stained.

Interpretation. The improved sorting and organisation of these laminae indicate reworking of the primary wind-rippled sands. Reworked wind-rippled facies are the product of post-depositional winnowing of wind-rippled facies. Although the transport processes involved are the same as for wind-ripple generation – creep and saltation – slower deposition or exposure to stronger winds resulted in the loss of the finer fractions by winnowing and transport in suspension. Sand grains greater than 0.5 mm diameter (medium sand) were mainly transported by creep processes (Lancaster, 1995); aeolian transport of grains of this size tends to be restricted to interdunes and to the plinths and lower (less steeply-inclined) flanks of dunes. As such, this reworked wind-ripple facies is not expected in the higher parts of topographically elevated bedforms. This reworked wind-rippled facies has not previously been explicitly recognised in ancient aeolian dune deposits but the significance of the distinction between reworked and non-reworked wind-rippled facies is implicit from the descriptions of textural parameters and depositional processes in studies of modern dune systems (cf. studies of sands from the Namib Desert, Lancaster, 1981, Fryberger et al., 1992). Reworked wind-rippled facies similar to this are common on the lower flanks of large aeolian bedforms in the Great Sand Sea of the Sahara Desert (Besler, 2008).

4.3 – Grainflow facies

Description. Grainflow facies of the Auk Formation comprise cm-scale laminated, fine- to medium-grained sandstone, with individual sediment packages usually having a massive appearance and a looser grain packing structure than the wind-rippled facies. Weak inverse grain-size grading is discernable in some cases. The depositional dips of grainflow facies are usually greater than 20° but no more than 30°. Where the grainflow facies occurs above the OWC, it is almost always bleached to a drab colour or oil-stained.

Interpretation. Grainflow strata are deposited by avalanching of sand grains down steeply dipping dune slipfaces (Hunter, 1977; Kocurek, 1991; 1996). Grainflow processes are associated with sets composed internally of laminations that indicate primary depositional dips of more than 17°, and typically up to 26° in buried and compacted sandstone. This reflects deposition from avalanches that were triggered by failure that occurred when the slope built to the angle of initial yield, and, following failure, came to rest at the critical angle of repose for dry sand. On modern dunes, this angle is between 32-34° for loose, dry sand (Allen, 1970; Carrigy, 1970): preserved inclinations are reduced as a result of post-depositional compaction. Grainflow-covered dune lee slopes inclined at the angle of repose for loose sand are common in modern dunes (e.g. Namib Sand Sea, Lancaster, 1981).

In the case of large linear aeolian bedforms, slipfaces on which grainflows occur tend to be preferentially located on the middle and upper parts of the lee slopes (e.g. Sneh and Weissbrod, 1983) because such dune types tend to have large, low-angle inclined plinths at their bases where wind-ripple strata preferentially accumulate (McKee and Tibbitts, 1964). By contrast, other types of large dunes (e.g. transverse and barchanoid forms) commonly have slipfaces that extend close to the base of the lee slope, and therefore close to the bottom of the preserved set. In such dune types, grainflow facies will tend to be present close to the base of preserved sets (Kocurek and Dott, 1981; Romain and Mountney, 2014). This has implications for preservation potential in cases where bedforms accumulate via climbing over one another: only the lowermost toes of bedforms might typically be expected to be preserved via a bedform-climb mechanism, meaning that grainflow deposits are expected to be less common in preserved linear dunes that possess large, low-angle-inclined plinths dominated by wind-ripple facies. However, exceptions to these general trends abound. For example, some barchanoid dunes of the Sonoran Desert have lee slopes that are repeatedly modified by winds that change direction, sometimes reversing; here, grainflows tend to terminate several metres above the interdune floor due to the presence of low-angle inclined plinths constructed at the dune toes.

4.4 – Grainfall facies

Description. Grainfall facies in the Auk Formation consist of mm-scale laminae of very-fine grained sandstone, occurring as pinstripe laminae in two distinct settings: (i) as laminae interbedded with wind-ripple laminated sand, in which case the facies is usually dark red in colour; and (ii) as laminae separating successive grainflow deposits, in which case the facies is usually bleached but not oil-stained, if occurring above the OWC.

Interpretation. Grainfall facies are formed when very-fine and fine sand is entrained into suspension, and later deposited in bedform slipface, plinth and interdune areas (Hunter, 1977). These facies are seldom found associated with reworked wind-rippled facies due to the winnowing associated with grain reworking. Rather, grainfall facies are present more commonly draping the deposits of grainflow facies on the lower parts of dune lee slopes where the grainflow deposits are themselves entirely depositional. Here, thin grainfall laminae highlight boundaries between successive grainflow avalanche deposits (cf. Hunter, 1977). However, unequivocally distinguishing grainfall deposits from adjacent grainflow deposits is not always possible because grainflow deposits typically incorporate and rework grainfall deposits as they pass downslope over them. Grainfall deposits tend to be absent from the upper parts of dune slipfaces because in such settings zones of grainflow failure are characterszed by an erosional scarp and the reworking of any grainfall deposits. Furthermore, grainfall deposits tend not to accumulate on the upper parts of dune lee slopes because sand is carried in saltation or incipient suspension on the stoss slope, but then overshoots the brinkline and is buoyed along by lee-side eddies (e.g., McDonald & Anderson, 1995; Eastwood et al., 2012) before falling from suspension onto the lower parts of the dune lee slope. Where accumulations of grainfall facies are recorded in interdune areas, such deposits record sustained fallout from suspension due to airflow deceleration downwind from the zone of turbulence associated with flow separation in the lee of large aeolian bedforms (Anderson, 1988; McDonald and Anderson, 1995). Accumualted intervals of grainfall facies tend to occur interbedded with wind-rippled sand deposits (cf. Hunter, 1981), commonly after wind storm events.

4.5 – Composite facies types

Facies descriptions used in this study are not based solely on discrete and individual facies types; additionally they incorporate combinations of two or more of the basic facies types described above in varying proportions: *grainflow-dominated* units are composed of >50% grainflow facies but additionally incorporate a secondary component of reworked wind-rippled strata; *wind-ripple-dominated* units are composed of >50% wind-rippled facies but additionally incorporate a minor component of reworked wind-rippled strata.

5 – Depositional Environment

5.1 – Nature of accumulation surface

Observation. In the studied succession, the facies types recognised are wind-ripple, reworked wind-ripple, grainflow and grainfall. Wind-ripple strata occur predominantly within flat- or near-flat-lying packages of strata between thicker cross stratified sets and cosets (Figure 8 – Well 30/16-2, core runs 6 and 7).

Interpretation. The studied part of the Auk Formation represents the preserved remnant of a dry aeolian system (*sensu* Kocurek and Havholm, 1993). The facies types recognised collectively demonstrate accumulation without the presence of significant surface moisture and indicate aeolian sedimentation on a dry substrate. Wind-ripple strata inclined at low angles occur predominantly within interdune elements and indicate that, even in the lowest topographic depressions of the main palaeo-dune-field system of the studied interval (Unit 2), the substrate remained dry, such that there is no significant evidence of contact with a palaeo-water table or its capillary fringe (cf. Mountney, 2006). However, examples of wet (ponded) interdune deposits of restricted thickness and lateral extent are known from other parts of the Auk Formation (Heward, 1991), as well as deposits of potential fluvial origin in the lower part of the succession. The Weissliegend facies of the uppermost part of the succession (Unit 1 of the Auk Formation) also preserves considerable evidence for marine reworking of aeolian sand, most likely in response to the Zechstein transgression of the palaeo-dune field (Glennie and Buller, 1983). However, such features are not present in the part of the succession studied here (Unit 2).

5.2 – Aeolian bedform type and morphology

Observation. Facies in the Auk Formation are dominated by wind-ripple and reworked wind-ripple strata (85%), whereas grainflow and grainfall strata are considerably less common (15%) (Figure 8). The characteristic vertical arrangement of facies most common in the Auk Formation takes the form of thick sets (10-30 m; average = 12 m), each characterised internally by low- to moderate-angle inclined, wind-ripple dominated stratal packages at their base. Packages of wind-ripple strata within sets gradually steepen up-section and packages of reworked wind-ripple strata become more abundant 2-5 m above the basal set bounding surface. In the uppermost 20-40% of many sets, wind-ripple dominated packages of strata steepen further (18-20°) before merging with packages of grainflow-dominated avalanche strata near the top of the sets (Figure 9). Grainflow deposits in the Auk Formation rarely reach the base of preserved dune sets and in most cases are confined to the uppermost 50% of sets.

Interpretation. The vertical arrangement of recorded facies – notably the occurrence of thick packages of wind-ripple and wind-ripple-dominated strata of various types, plus the upward-steepening within the sets, and the angle of inclination of the set bounding surfaces – are typical of deposition on large linear bedforms (e.g. Tsoar, 1982, 1983; Bristow et al., 2000), especially on the lower and middle flanks of such forms (Lancaster, 1981; Livingstone, 1987, 1989; McKee, 1982; McKee and Tibbitts, 1964; Sneh and Weissbrod, 1983). The steepening of the cross-strata upward within a set, plus the transition of ripple strata to grainflow is consistent with a plinth transitioning upward to a slipface. This configuration is typical of an oblique lee face where the middle and upper portion was dominated by gravity processes (flow and fall) because of a high sedimentation rate, and the lower portion was dominated by traction transport (ripples) where an along-slope-directed secondary flow was able to rework the deposited grains. This morphology is characteristic of linear dunes. However, from the available data, it is not clear whether the bedforms represented by the Auk Formation were true linear bedforms or might alternatively have been three-dimensional bedforms modified from a linear morphology and migratory behaviour, possibly compound or complex draa that supported superimposed bedforms (see later).

By contrast, the majority of transverse bedform types (including barchans, straight-crested transverse ridges and barchanoid dune ridges) observed in modern dune fields tend to be characterised by a single, downwind-facing slipface element. In the case of most such simple bedforms (*sensu* McKee, 1979), active avalanching tends to occur down to a level within the bottom-most few metres of the bedform lee slope (Hunter, 1985). This records the accretion of sediment on a dune lee-slope that migrated consistently in a favoured direction (thereby giving rise to a tightly clustered range of foreset dip-azimuths). This is contrary to the dominant pattern observed in the Auk Formation. However, where compound or complex bedforms (*sensu* McKee, 1979) are developed or where migrating scour pits are present on the bedform lee slope, distributions of foreset dip-azimuths will typically be more complicated and varied (see Rubin, 1987a, b).

More than 50% of bedforms within modern dune fields are of a linear type (Rubin and Hunter, 1985; Rodríguez-López et al., 2014), and they are by far the most abundant single bedform type in the central parts of large, dry aeolian dune systems, such as the Central Namib Sand Sea of South West Africa (Lancaster, 1982; Bristow et al., 2007), large parts of the Rub' Al-Khali erg of the Arabian sub-continent (Glennie, 1998b; Al-Masrahy and Mountney, 2013), in the Qarhan region of northwest China (Li et al., 2016), and in the Strzelecki Desert, Australia (Fitzsimmons, 2007).

Bedform climbing – whereby successive migrating bedforms slowly migrate over and scour into one another to leave behind only the bottom-most parts of their predecessors as they do so – is the most common mechanism responsible for enabling the accumulation of thick sets of aeolian strata in the rock record (e.g. Kocurek, 1991), and is herein considered the most likely mechanism responsible for accumulation of the Auk succession. However, there are several alternative mechanisms for the accumulation and preservation of sets of aeolian strata of the type observed in the Auk Formation, including the infilling of localised accommodation space present between existing bedforms (e.g. Langford et al., 2008; Luzón et al., 2012), accumulation around relic aeolian topography (e.g. Fryberger, 1986), and exceptional bedform preservation following rapid inundation by water or other fluids (e.g. Glennie and Buller, 1983; Mountney et al., 1999; Benan and Kocurek, 2000). However the 'bedform climbing' mechanism remains the most convincing explanation for the origin of the majority of ancient preserved aeolian dune successions (Mountney, 2012) and is the most plausible explanation for the observed set architecture in the Auk Formation, given that the formation comprises multiple vertically stacked cosets of strata. Each of these cosets is likely to represent the migration, accumulation and subsequent partial truncation of a single draa-scale bedform.

The process of bedform climb only commences once the bedforms have grown to such a size that the intervening interdune flats have been reduced to small, isolated topographic depressions (Wilson, 1971; 1972; 1973; Mainguet and Chemin, 1983; Kocurek, 1996; Mountney, 2012). This, together with the presence of only limited occurrences of flat-lying wind-ripple interdune strata between thick cosets of cross strata, suggests the presence of only isolated interdune depressions – rather than wide, open interdune corridors – in most of the studied Auk aeolian system. Linear dunes in modern deserts are commonly separated by wide interdune flats; such dunes are not climbing as sand-accumulating bedforms but are sand-transporting bedforms (see Mainguet and Chemin, 1983). However, there are examples from the modern Namib Desert where linear dunes are not separated by interdune flats and such dunes are likely to climb over neighbouring dunes at low angles as they migrate.

Based on the points above, the bedforms represented by the deposits of the Auk Formation are interpreted to have been of a linear type due to the preserved facies arrangement, which is typical of deposition on large linear bedforms. The crest-lines are interpreted to be aligned within 15° to the resultant sand drift direction, based on the classification of Hunter et al., (1983) whereby dunes are classified as longitudinal if their crestlines are aligned within 15° either side of perfectly parallel to the vector mean of the sand-transport direction (see Hunter et al., 1983, their Figure 2).

5.3 – Compound bedforms

Observation. A small but significant proportion of what are interpreted to be linear dune flank facies (~15%) show a vertical succession that diverges from the 'simple' vertical cycle depicted in Figure 9; a representative example of these is shown in Figure 11. Although a cyclicity similar to that seen in the 'simple' linear dune model (Figure 9) is present (upward-steepening dips, upward increase in amounts of reworking and occurrence of slipface facies), the pattern is subtly different. The basal unit in Figure 11, which defines a 10 m-thick coset, demonstrates the arrangement of dominantly non-reworked wind-rippled sands, with an upward increase in dip passing directly into a slipface complex developed low on the dune flank. Above this, a number of minor sets composed internally of cross beds with upward-steepening dip are present, but there is no reversion to typical interdune or dune-plinth sediments, and the flat-lying depositional dips are rare.

Interpretation. Thicker units, dominated by dune flank facies, are interpreted as compound linear draa deposits, formed by superimposed dunes migrating over the flanks of linear draa. A possible modern example from the Central Namib Desert is illustrated in Figure 12. Bedforms may migrate at different speeds, resulting in superimposed dunes migrating over more slowly moving parent draa. These forms allow for juxtaposition of middle or upper dune-flank and slipface elements in complex geometric arrangements (Rubin, 1987a).

5.4 – Aeolian bedform scale and nature of dune flanks

Observation. The distribution of facies observed in core is typically characterised by 10 to 30 m-thick cosets of strata that are each made up of a series of nested sets, together with their delineating bounding surfaces (Figure 9). The facies types within these cosets commonly occur in a predictable order, such that apparently horizontal or near-horizontal, 2 to 10 m-thick packages of wind-ripple strata are overlain by low angle-inclined, 2 to 10 m-thick packages of partly reworked wind-ripple strata (Figure 8). Foresets within these facies types typically dip at low angles that rarely exceed 8-14°. The combined thickness of these two elements represents the majority (up to 65%) of the preserved cosets.

Interpretation. Preserved 10 to 30 m-thick cosets were likely generated by large bedforms. The 2 to 10 m-thick packages of wind-ripple strata at the base of these cosets are representative of interdune-flat elements (cf. Kocurek and Nielson, 1986). For example, in Figure 8 the section at core depth 2357 to 2349 m (7733 to 7707.5 ft) represents an interdune flat and the overlying packages of partly reworked wind-ripple strata at core depth 2332 to 2335 m (7650 to 7662 ft) are indicative of lowermost dune plinth elements (cf. Lancaster, 1981).

The facies types and distributions described above indicate that the bedforms possessed very thick, low-angle-inclined toeset and plinth regions. Comparisons with modern linear dunes where this arrangement of facies has been observed (e.g. Sneh and Weissbrod, 1983; Lancaster, 1988) suggests that the original Auk bedforms were likely to have been more than 100 m high. This is based on comparisons of rates of upward-steepening of dune foresets from large modern linear bedforms, such as those in the Rub' Al-Khali desert in Saudi Arabia (Al-Masrahy and Mountney, 2013) and the Namib Desert (Bristow et al., 2000). Data from these studies record gradual upward-steepening in the lowermost plinth areas of the bedforms, and dune heights for the Auk Formation have been reconstructed based on measured relationships documented in these published accounts. Modern linear bedforms that are 150 to 250 metres high are common in the central parts of many modern dry aeolian systems, including the Central Namib Sand Sea (Breed et al., 1979). The lateral inter-bedform spacing of adjacent bedforms of this size (from crest-to-crest) typically varies from 1500 to 2500 metres (Lancaster, 1988; Al-Masrahy and Mountney, 2013).

5.5 – Bedform migratory behaviour

Observation. The arrangement of facies within the Auk succession and their delineation by bounding surfaces records the preservation of 15 to 30 m-thick cosets of cross strata, many with multiple internal bounding surfaces. Facies within these cosets are typically arranged into a predictable succession that indicates the preservation of the interdune flat, basal-most dune plinth and lower dune flank, with only rare occurrences where the middle and upper dune flank is preserved (Figure 9).

Interpretation. Preserved lithofacies successions in the Auk Formation record a stacked series of sets that likely originated via the coeval migration and accumulation of bedforms via a bedform climb mechanism. As adjacent bedforms migrated over one another at low angles, they preferentially preserved solely their lowermost parts (cf. Mountney, 2006) and, for large linear bedforms with low-angle inclined flanks, such deposits are dominated by wind-ripple strata.

There are now many published studies that recognise that it is usual for linear aeolian dunes to undertake a minor component of transverse motion in addition to their primary along-crest component of motion (e.g. Hesp et al., 1989; Rubin, 1990). In particular, the work of Bristow et al. (2000) demonstrates unequivocally that linear dunes slowly creep laterally (relative to the primary sand migration direction) over long episodes. Rubin and Hunter (1985) and Rubin (1987a) demonstrated that it is this component of transverse motion that plays an important part in controlling the preserved architectural style of the accumulation.

The large linear bedforms responsible for generating the Auk Formation underwent accumulation that was coincident with bedform migration. The primary component of sediment transport over these large linear draa was via the along-crest migration of the plan-view sinuosities (see discussion above). In addition, a secondary component of transverse bedform migration translated these bedforms sideways, but most likely at a much slower rate. The result of these two components of migration provides an approximate indication of the resultant drift direction (*sensu* Fryberger, 1979a). Results from 2 zones in the studied portion of the Auk Formation – where zones are defined as groups of linear-dune growth cycles determined by bounding surfaces in the wells which are formed by dune migration – are shown in Figure 13. The dip-azimuths in Dune Cycle Zone 20-25 are between 050° and

120°, with the resultant drift direction between NE and ESE (Figure 13a). The dominant dip-azimuths for Dune Cycle Zone 40-50 are towards ENE and SSW (Figure 13b).

5.6 – Detailed morphology and behaviour of bedforms responsible for generating the bed-sets preserved in the Auk Formation

Although the gross morphology and temporal behaviour of the bedforms recorded in the Auk Formation has been outlined above, there exist several examples of facies distributions in the Auk cores that cannot be readily explained by a relatively simple morphology and migration style (Figure 14): more complicated arrangements of bedforms need to be invoked to account for such stratigraphic expressions. It is likely that a range of both simple and more complex bedform arrangements were variously responsible for the evolution of the Auk succession and that these types are likely to have developed and operated coevally and in close proximity to one another within the developing dune field.

5.6.1 – Morphology of interdune flats

Observation. Although the original morphology of interdune flats cannot be measured directly from the primary data recovered from the Auk Formation, general comparisons can be made between the interpretations of bedform type made above and the morphological relationships observed in analogous modern dune-field systems. One of the closest modern analogues envisaged for the Auk Formation is the part of the Rub' Al-Khali studied by Al-Masrahy and Mountney (2013). Based on comparisons between dunes and interdunes in this modern system, interdune flat areas between neighbouring linear draa represented by accumulations of the Auk Formation would have been best developed where two re-entrants in neighbouring bedforms were aligned adjacent to each other. Given the variability in the foreset dip-azimuths, and from the presence of inclined erosional bounding surfaces that represent scour surfaces in cosets of the Auk Formation, it is envisaged that the bedforms responsible for generating the preserved architecture must have had sinuous crestlines. It therefore follows that the interdunes must have varied in width and may have formed isolated elliptical flat areas between the major dunes.

Interpretation. Where two spurs (protruding ridges) present in adjacent bedforms were aligned with one another, interdune flats would have potentially been eliminated completely. In such circumstances, open elongate interdune corridors would have been replaced by elliptical-shaped, enclosed interdune flats in a direction parallel to the crests of the adjacent linear draa. The surface of interdune areas developed between the major linear bedforms was likely to have been covered largely by wind-rippled sand.

5.6.2 – Superimposed barchanoid dune fields

Observation. (i) In some parts of the Auk succession, stacked 1 to 5 m-thick sets of grainflow facies are preserved (Figures 9 and 13) and these are associated with thicker intervals of wind-ripple strata and reworked wind-ripple strata. (ii) In other rarer cases, thin sets of grainflow cross strata (1-5 m thick) are found *within* larger cosets that are themselves interpreted to be the deposits of large linear bedforms. However, the cross strata of grainflow origin are not necessarily associated with reworked wind-ripple facies in these cases (Figure 15).

Interpretation. (i) The stacked sets of grainflow facies described above are interpreted to be representative of accumulation via the migration and climb of relatively small and simple barchanoid dunes. The thicker intervals of wind-ripple and reworked wind-ripple strata represent deposits of the bottom-most parts of large linear dunes. This implies that fields of small barchanoid dunes occupied some of the interdune depressions between neighbouring linear bedforms (cf. Figure 1). Barchanoid dune fields lying between larger linear bedforms are common in modern dry aeolian systems, including many parts of the Central Namib Sand Sea (McKee, 1982; Figure 12). (ii) The presence of thin sets of grainflow cross strata within larger cosets implies that such grainflow-dominated units are the product of superimposed dunes developed on the lower or middle flanks of the larger bedforms, and that the bounding surfaces which delineate these units are therefore superimposition surfaces (*sensu* Kocurek, 1991). Parts of the aeolian system were therefore likely characterised by superimposed dunes (possibly transverse, barchanoid in form) which migrated obliquely over the middle flanks of the large, non-slipfaced linear bedforms in response to along-slope directed, possibly deflected, secondary winds (cf. Mountney et al., 1999). One present-day system containing dunes of a type similar to those envisaged for the Auk Formation is in the Kumtagh Desert of north-western China where linear draa have superimposed barchanoid dunes migrating along their lower flanks (Lü et al., 2017).

5.7 – The nature of the palaeowind responsible for generating the bedforms represented by the Auk Formation

Observation. The broad but unimodal spread of foreset azimuths present in the Auk succession (Heward, 1991 – his Figure 6; Figure 13 of this study) are consistent with the oblique migration of large linear dunes and their preservation through bedform climbing (Rubin and Hunter, 1985; Rubin, 1987a) – see discussion above and Bristow et al. (2000) for further discussion.

Interpretation. The azimuth of maximum foreset dip records the approximate direction of resultant sand drift, but not the trend of the bedform crest-lines (DeCelles et al., 1983; Rubin and Hunter, 1983). Most large linear bedforms develop in response to the convergence of two oblique wind directions, with alternations of wind direction typically occurring on a seasonal basis (e.g. Lancaster, 1983; McKee, 1982). The trend of the bedform crest-line will not usually be parallel to either of these wind directions and neither will the mean azimuth of the preserved foresets (Rubin and Hunter, 1987) because both wind directions are operating coevally over the entire depositional episode.

Although active linear dunes in present-day dune fields typically have two well-developed, opposing slipfaces, their preserved counterparts are unlikely to have preserved foresets that resemble this pattern. As linear dunes migrate, they undertake a modest component of lateral creep (technically rendering them oblique forms). It is this component that ultimately enables preferential preservation of lee-slope deposits from the face of the linear bedform that dip in the direction of this lateral creep (Rubin and Hunter, 1985). Thus, preserved linear bedform deposits do not necessarily preserve a bimodal pattern of palaeocurrent indicators.

The moderate to relatively broad range of foreset azimuths present in the Auk succession could be explained by a number of factors: (i) the bedforms shifted their migration trajectory over time; (ii) several contemporaneous bedforms had slightly different orientations; (iii) the bedforms had significantly curved crestlines, parts of which faced in the direction of the resultant drift direction. The presence of migrating scour pits in the form of concave-shaped re-entrants seen in plan-view would generate a series of erosional bounding surfaces aligned approximately in the direction of the resultant drift direction (Rubin and Carter, 2006; Rubin and Hunter, 1983). In the case of the Auk Formation, it is likely that the range of foreset azimuths seen in the dataset originated from a combination of the scenarios listed above and likely in response to linear dunes that undertook an additional minor component of transverse motion (cf. Bristow et al., 2000).

6 – Controls on reservoir quality and implications for reservoir modelling

Previous work on the sedimentology of the Auk Field has proposed general relationships between sedimentary facies and reservoir quality (Heward 1991; Prosser & Maskall 1993; Trewin et al., 2003), but the core-analysis data that have been published do not unequivocally demonstrate such relationships. It is clear from Figure 6 of Trewin et al. (2003) that much of the studied Auk Formation is of non-reservoir quality. Using an empirical cut-off permeability of 10 mD, controls exercised on reservoir quality by genetic depositional facies are subtle and poorly defined.

In the present study, it has been possible for the first time to accurately allocate depositional facies to a modern, high-quality set of core-analysis data on the basis of consistent description of very well preserved cores. The data come from development wells 30/16a-A12, A13, A14 and A16 (original operator's names Auk A06, A11S2, A06S1 and A06S2). The data (Figure 16) show clear relationships between depositional facies and reservoir quality. Net reservoir is effectively absent from the low-angle inclined wind-ripple facies of interdune flat and lower dune-plinth origin (Figure 16a), whereas the majority of the grainflow deposits do form net reservoir (Figure 16c). What is of most interest is the significant proportion of the reworked wind-rippled sand facies that forms net reservoir (Figure 16b). As reworked wind-rippled sands have not previously been differentiated as a distinct facies variant (see Figure 8 in Trewin et al. 2003) their importance has not hitherto been recognised. Thus, the four sub-populations based on gross depositional geomorphic elements identified by Trewin et al. (2003) all encompass wide ranges of porosity and permeability and cannot be used as an effective sedimentological basis for reservoir modelling (Figure 17, adapted from their Figure 6). For example, from comparison of Figure 17a with Figures 16a and b, the 'sand sheet' facies of Trewin et al. (2003) encompasses elements of both non-reworked and reworked wind-ripple deposits.

In this succession, analysis of reservoir properties and thence of geometries of permeable units clearly starts with the correct and consistent identification of sedimentary facies. However, the heterogeneous distribution of net reservoir facies within the genetic units formed by individual phases of dune migration means that simply dividing the succession into the deposits of successive dunes does not form a basis for the construction of a reservoir model that will allow a meaningful representation of the permeability structure of the reservoir as a whole. The highly permeable slipface facies forms a comparatively small proportion of the overall rock volume and has a patchy and unpredictable distribution reflecting the episodic and random occurrence of local slipface developments on the linear dune flanks (Figures 8 to 11). Much more consistent and predictable is the distribution of the reworked wind-ripple facies, which occurs with increasing frequency in the higher and more steeply dipping parts of individual bedform elements. In many cases, this facies acts as the matrix within which higher permeability slipface units occur. This previously undifferentiated facies acts as the "plumbing" for the oil reservoir: any static reservoir model must therefore explicitly acknowledge it. Given the variability of its distribution (Figures 8 to 11), it seems likely that construction of explicit sedimentological objects (e.g., dunes, interdunes) would be inappropriate in this linear dune succession.

7 – Conclusions

The studied interval of the Auk Formation represents the accumulated deposits of a series of linear aeolian dunes and draa that were present within a large dry aeolian dune-field system. The following conclusions relating to the reconstruction of original bedform type, size and style of migratory behaviour have been reached through a detailed core and well-log analysis coupled with comparison to analogous outcropping successions and modern dune systems: (i) the facies types noted from core data in the Auk Formation (wind-ripple, reworked wind-ripple, grainflow and grainfall) represent aeolian sedimentation on a predominantly dry substrate; (ii) the predominance of wind-ripple and reworked wind-ripple strata in the succession indicates deposition typical of large linear bedforms, with the lower and middle flanks of these being preserved; (iii) the upward-steepening of cross strata in sets indicates that a lee-side sinuosity was developed on the Auk bedforms; (iv) 15% of the linear dune flank facies do not show an upward reversion to deposits interpreted to be interdune or dune-plinth sediments within a preserved coset, which implies that there are instances of compound linear draa deposits within the Auk succession; (v) the occurrence of thick packages of wind-ripple and wind-ripple-dominated strata, which contribute to up to 65% of the preserved cosets in the Auk Formation, demonstrates that the bedforms had very thick low-angle inclined plinths, that they were originally between 150-250 m high, that possessed crest-to-crest spacing of 1500-2500 m, and that originated via a bedform climbing mechanism that resulted in preferential preservation of only their lowermost parts; (vi) the occurrence of 1-5 m-thick stacked sets of grainflow strata in some cores records the presence of small barchanoid dunes, either occupying interdune depressions where the grainflow units are associated with thick wind-ripple and reworked wind-ripple strata, or superimposed on the lower or middle flanks of linear draa where the grainflow units are found within larger cosets that are themselves interpreted to be deposits of these linear draa; (vii) the Auk Formation exhibits a broad but unimodal spread of foreset azimuths, which most likely record the migration of linear draa that undertook a minor component of transverse motion.

Sedimentary facies exert a primary control on reservoir properties. Yet, analysis undertaken here demonstrates that individual facies cannot be ascribed to formative dune types in a simple way. The recognition of reworked wind-ripple facies and demonstration of their preferential occurrence in dune-flank elements, is key to prediction of reservoir performance. This explains why the Auk Formation forms an effective reservoir succession, despite being characterised by a low proportion of slipface facies.

There are very few published accounts of ancient linear dune successions, yet linear dunes represent >50% of the dune types present in modern dune fields (Rubin and Hunter, 1985; Rodríguez-López et al., 2014). Given that linear aeolian dune systems can potentially accumulate via bedform climbing or other mechanisms, such system types must be significantly under recognised in the ancient rock record. This study therefore represents a valuable case study for a rarely recognised but important type of aeolian dune system.

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Figure Captions

Figure 1 – Schematic vertical successions deposited by a single episode of migration and aggradation of a ‘simple’ linear dune under conditions of moderate climb. Schematic lines on facies show dip-angle relationships. Note: a) the marked lateral variability over comparatively short distances of vertical successions deposited by the same migrating bedform; b) the persistence of the cleaning and steepening-upward cycle as seen in the typical vertical section (e.g. sections A, B and C); c) the uncertainty introduced in the recognition of this cyclicity where barchanoid dunes are present in interdune corridors (e.g. sections C, D and E); and d) the entire cycle deposited by a single dune migration episode may be represented by non-reworked wind-rippled facies (section F). The relationships depicted are conceptual and do not necessarily record any specific documented natural system.

Figure 2 – Permian paleogeography of the United Kingdom and North Sea region. Position of Auk Field highlighted. Modified from Smith and Taylor (1992).

Figure 3 – Regional depositional setting of palaeoenvironments represented by deposits of Rotliegend Group in the vicinity of the Auk Field, Central North Sea. Modified from Glennie et al. (2003). Eroding uplands within the region might not have existed until the late Triassic. A detailed maps of the Auk Field (hydrocarbon reservoir) is shown in Figure 4.

Figure 4 – Auk Field, Block 30/16, UK Central North Sea: well location map with position of cored wells used in this study. Well symbols mark well positions at Top Rotliegend Group. Well 30/16-1 (black circle) is the discovery well. The area considered in figure 4 is the Auk Field in Block 30/16 shown in Figure 3.

Figure 5 – Nature of bounding surfaces in the Auk Formation, with key to descriptive nomenclature for stratal relationships and typical occurrences of surface types. Note that many of the surface types may relate to either local or large scale stratal relationships, and that these cannot be differentiated in core. Abbreviations of stratal relationships: CON – concordant with bounding surface; OLP – onlapping lamination/bedding; DLP – downlapping lamination/bedding; SPT – sub-parallel truncation (i.e. small angular difference between dips in underlying and overlying); AGT – angular truncation. Together with assessment of lithofacies arrangements, these stratal relationships assist in the interpretation of the palaeoenvironmental significance of bounding surfaces observed in core, examples of which are shown in figures 8-11.

Figure 6 – Bimodal fabrics in the Auk Formation; explanation of scale used for recording bimodality. The bimodality of grain sizes in deposits of the Auk Formation is an important

indicator of syn- and post-depositional aeolian grain sorting processes. In particular, winnowing of finer grain fractions from deposits on the lower and middle flanks of dunes appears to have been a widespread process. A bimodality index is used to assess the palaeoenvironmental significance of facies observed in cores (Figures 8-11).

Figure 7 – Characteristic features of facies in the Auk Formation reservoir from core 30/16-2. Photographs of curated reference set of cores held by Talisman Sinopec Energy UK Ltd.

Figure 8 – Well 30/16-2, core runs 5, 6 and 7. Facies bar width proportional to perceived reservoir quality. Interpreted facies associations: i) simple linear dune or draa aggradation unit; ii) interdune or long-lived sandsheet (planar depositional sites dominated by sediment by-pass lacking significant dune development), iii) stacked slipface-dominated transverse dunes. See Figure 5 for explanation of the criteria used to determine the palaeoenvironmental significance of bounding surfaces. Gsmn = minimum grainsize; Gsmx = maximum grainsize. Sorting ("Srt") and bimodality ("Bimod") are described on a scale from 0-4. See methodology for further explanation. See Figure 6 for definition of the criteria used to assess bimodal grain fabrics in core.

Figure 9 – Typical vertical succession, showing aggradation of simple linear dune units, Auk Formation, Central North Sea: Well 30/16-A16, core runs 2, 3 and 4. Red dotted lines show positions of bounding surfaces; black dotted lines separate interpreted facies association boundaries: i) simple linear bedform (draa) aggradation unit; ii) aggradation unit of compound linear draa with superimposed dunes (see Figure 11). See Figure 5 for explanation of the criteria used to determine the palaeoenvironmental significance of bounding surfaces. See Figure 8 caption and Methodology for further explanation.

Figure 10 – Well 30/16-9, core run 4. Red dotted lines show positions of bounding surfaces; black dotted lines separate interpreted facies association boundaries: i) interdune with isolated barchanoid dunes; ii) simple linear dune (draa) aggradation unit. See Figure 5 for explanation of the criteria used to determine the palaeoenvironmental significance of bounding surfaces. See Figure 8 caption and Methodology for further explanation.

Figure 11 – Typical vertical succession, showing aggradation of compound linear draa units, Auk Formation, Central North Sea: Well 30/16-A14, core runs 6, 7 and 8. Red dotted lines show positions of bounding surfaces; black dotted lines separate interpreted facies association boundaries: i) compound linear dune (draa) aggradation unit. See Figure 5 for explanation of the criteria used to determine the palaeoenvironmental significance of bounding surfaces. See Figure 8 caption and Methodology for further explanation.

Figure 12 – Features contributing to the formation of composite linear draa, in places with and barchanoid dunes migrating over the draa lower flanks, Central Namib Desert (image

reproduced with permission courtesy of Bernhard Edmaier). Sinuous-crested star and linear draa, many with opposing slipfaces developed on their upper slopes and with broad, moderate angle-inclined, wind-ripple-dominated flanks. Slipface elements generally occupy only the uppermost halves of the bedforms. Bedforms up to 180 m high. 1) Close-spaced linear dunes: right-hand ridge overriding (?) left-hand ridge (as viewed); 2) Linear ridges diverging creating closely spaced ridges, one of which may override the other; 3) Ridge extending across interdune area; 4) Subordinate star elements; 5) Composite draa form created by amalgamation of linear ridges and barchanoid dune fields; 6) Large, mature star dune; 7) Barchanoid dunes migrating within interdune corridor; 8) Barchanoid dune fields associated with terminations and offsets of linear dune ridges; 9) Termination of linear ridge, with associated localised barchanoid dune field; 10) Barchanoid dunes migrating through nick points in linear dunes.

Figure 13 – Grouped dipmeter dip-azimuth data for well penetrations in the Auk Formation. Red well symbol indicate cored wells: a) Dune Cycle Zone 20-25, dip-azimuths dominantly between 050° and 120°, dominant wind direction WSW to ENE; b) Dune Cycle Zone 40-50, dominant dip-azimuths between dips to ENE and SSW, wind direction between NW to SE and NE to SW. Data record both cross-beds and bounding surfaces.

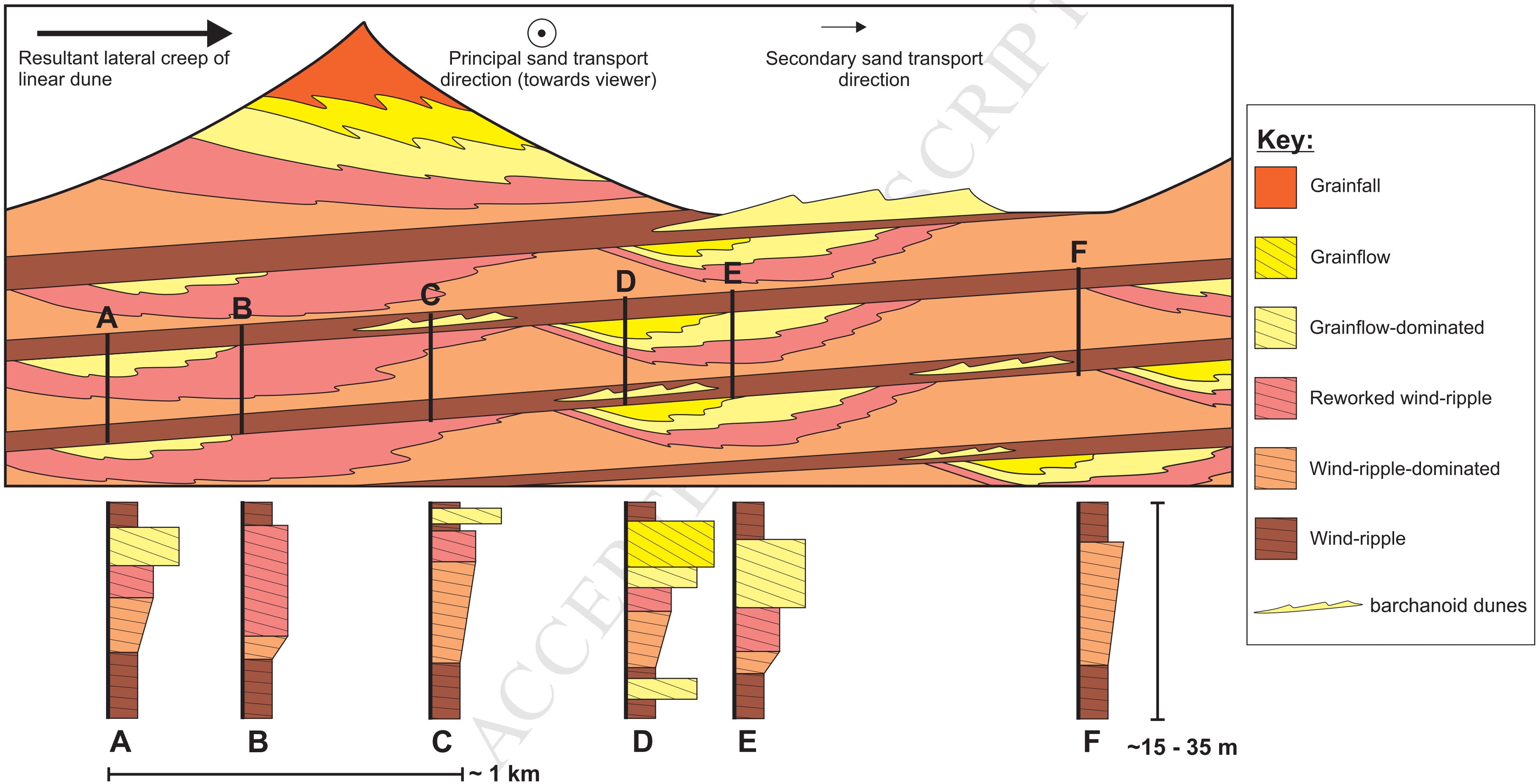
Figure 14 – Well 30/16-2, core run 7: 7743.5 ft – 7754 ft.; 1-5 m-thick sets of simple grainflow facies, representative of accumulation of small barchanoid dunes, occurring between intervals of wind-ripple strata. Core photographs provided by Talisman Sinopec Energy UK Limited.

Figure 15 – Well 30/16-3, core runs 8 and 9. Red dotted lines show positions of bounding surfaces; blue dotted lines mark positions of reactivation surfaces; black dotted lines separate interpreted facies association boundaries. i) Simple linear dune/draa aggradation unit with superimposed dunes; ii) simple linear dune/draa aggradation unit.

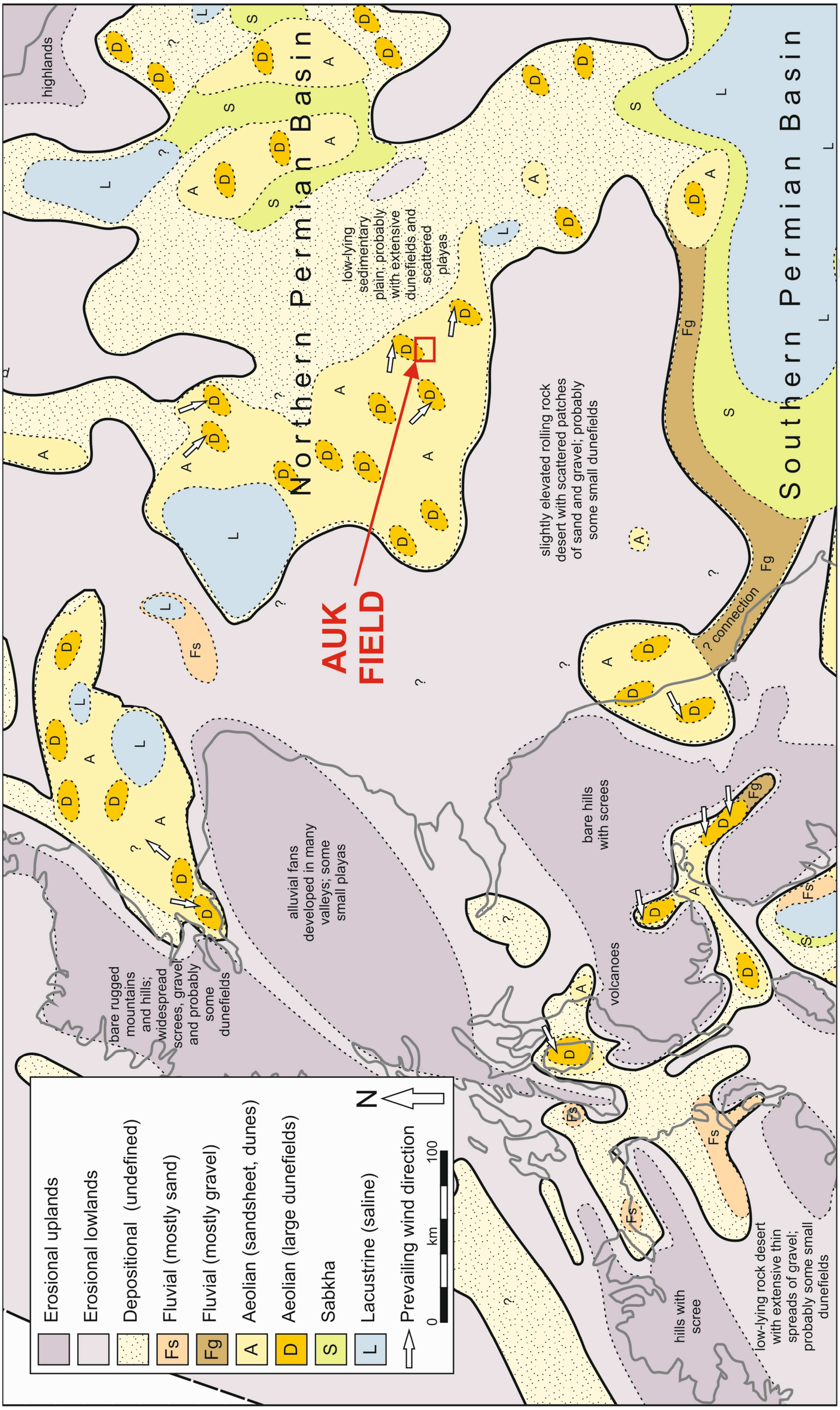
Figure 16 – Porosity and permeability data for sedimentary facies in the Auk Formation-conventional core analysis results from Unit 2 (Rot 2) in wells A13, A14 and A16. Long cored sections have good-quality, internally consistent core-analysis data sets: a), b) and c) porosity versus permeability cross plots for wind-ripple, reworked wind-ripple and grainflow facies; d) comparison of 95% confidence ellipses for the three facies. A strong sedimentological control on porosity and permeability is evident. Note that an insignificant proportion of the wind-ripple facies exceeds an empirical 10 mD cut-off for net oil reservoir, whereas most samples exceed this threshold in the grainflow facies.

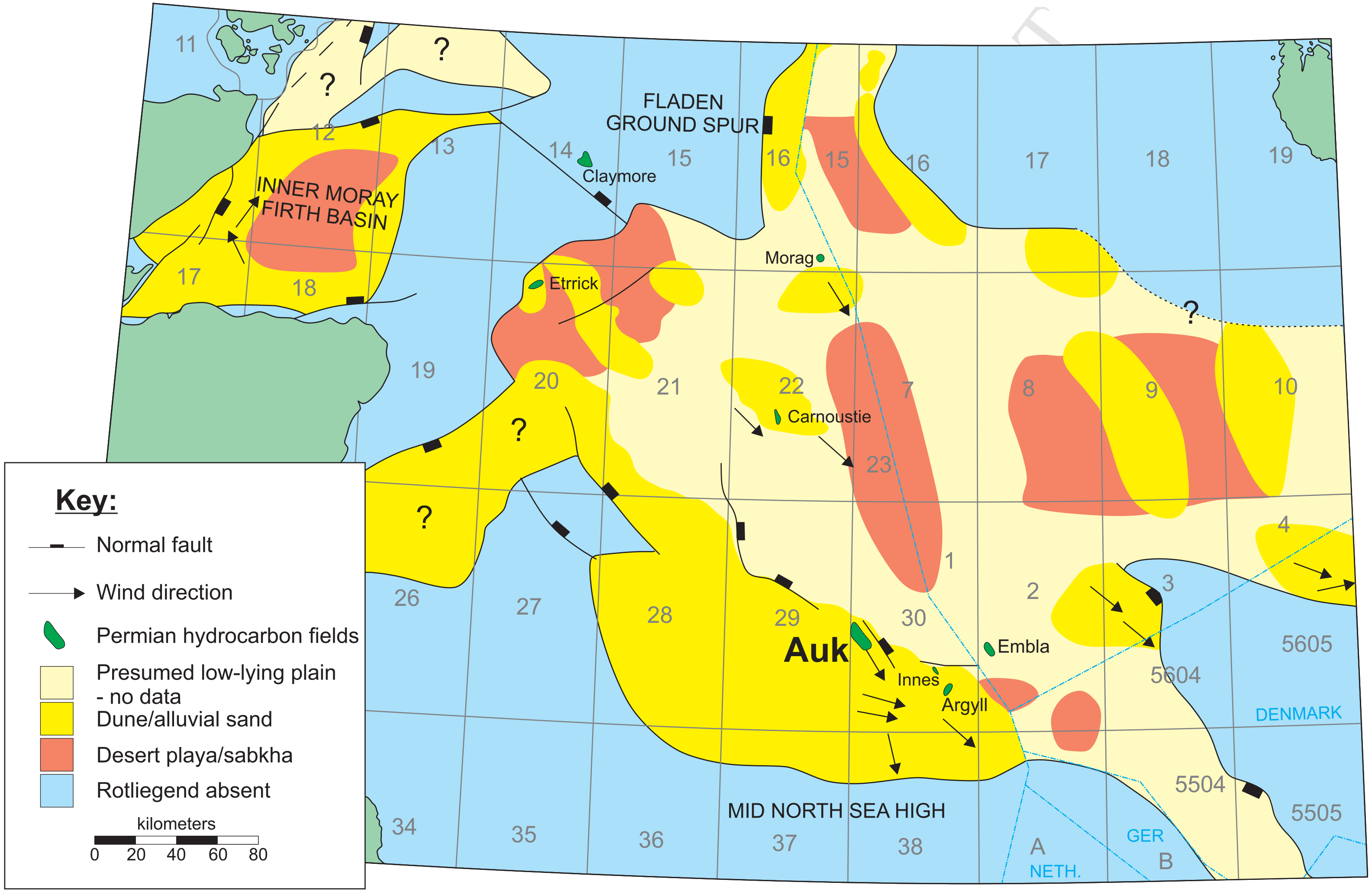
Figure 17 – Comparison of 95% confidence ellipses for the three facies (wind-ripple, reworked wind-ripple and grainflow) identified in this study with porosity-permeability

relationships of interpreted sub-environment types (grey dashed outlines) identified by Trewin et al. (2003). See text for explanation.



Resultant lateral creep of linear dune
Principal sand transport direction (towards viewer)
Secondary sand transport direction
A
B
C
D
E
F
~15 - 35 m
~ 1 km
Key:
Grainfall
Grainflow
Grainflow-dominated
Reworked wind-ripple
Wind-ripple-dominated
Wind-ripple
barchanoid dunes


Erosional uplands
Erosional lowlands
Depositional (undefined)
Fs Fluvial (mostly sand)
Fg Fluvial (mostly gravel)
A Aeolian (sandsheet, dunes)
D Aeolian (large dunefields)
S Sabkha
L Lacustrine (saline)
Prevailing wind direction
0 km 100
N
Northern Permian Basin
Southern Permian Basin
AUK FIELD
highlands
low-lying sedimentary plain; probably with extensive dunefields and scattered playas
slightly elevated rolling rock desert with scattered patches of sand and gravel; probably some small dunefields
? connection
bare rugged mountains and hills; widespread screes, gravel and probably some dunefields
alluvial fans developed in many valleys; some small playas
bare hills with screes
volcanoes
hills with scree
low-lying rock desert with extensive thin spreads of gravel; probably some small dunefields


FLADEN
GROUND SPUR
INNER MORAY
FIRTH BASIN
MID NORTH SEA HIGH
Claymore
Etrrick
Morag
Carnoustie
Auk
Innes
Argyll
Embla
DENMARK
GER
NETH.
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26
27
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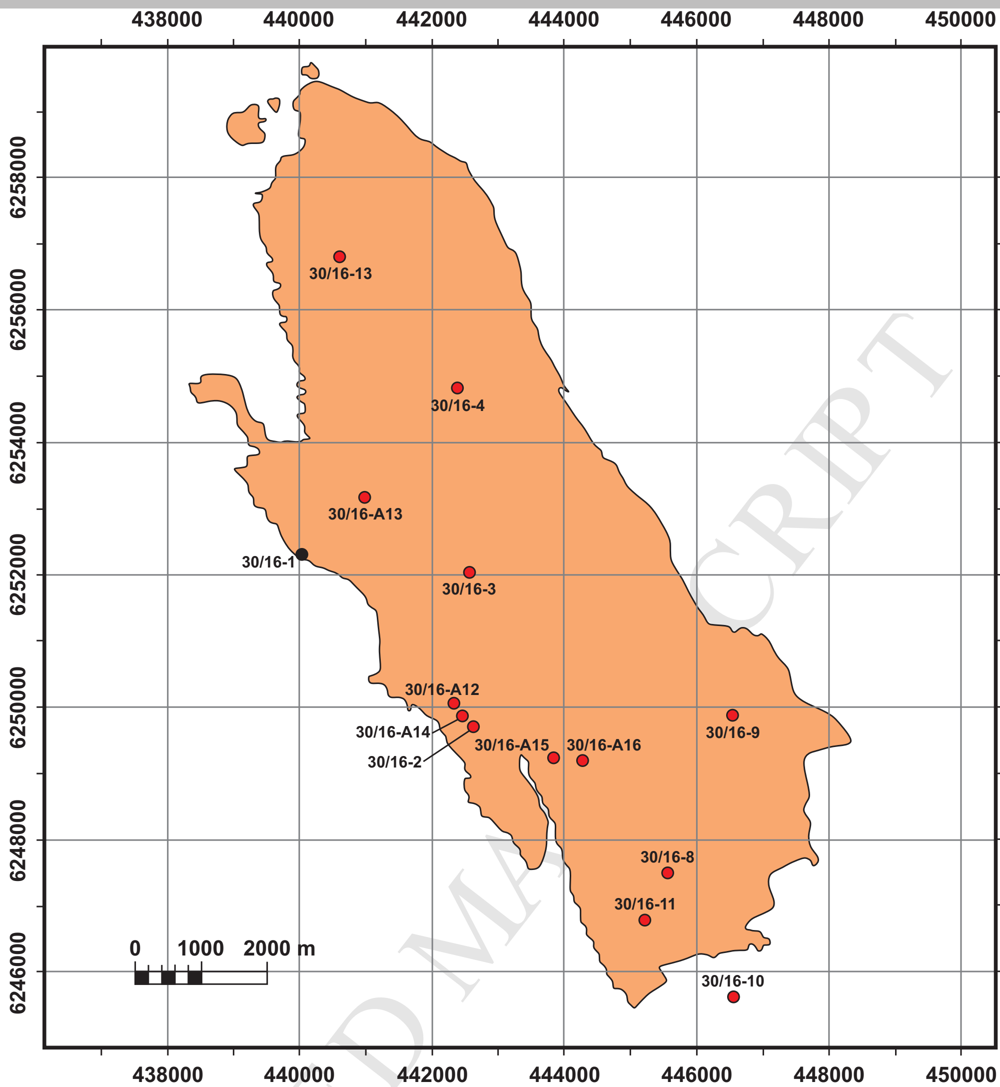
5605
5604
5504
5505
34
35
36
37
38
A
B
Key:
Normal fault
Wind direction
Permian hydrocarbon fields
Presumed low-lying plain
- no data
Dune/alluvial sand
Desert playa/sabkha
Rotliegend absent
kilometers
0
20
40
60
80



438000
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30/16-A13
30/16-1
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30/16-11
30/16-10
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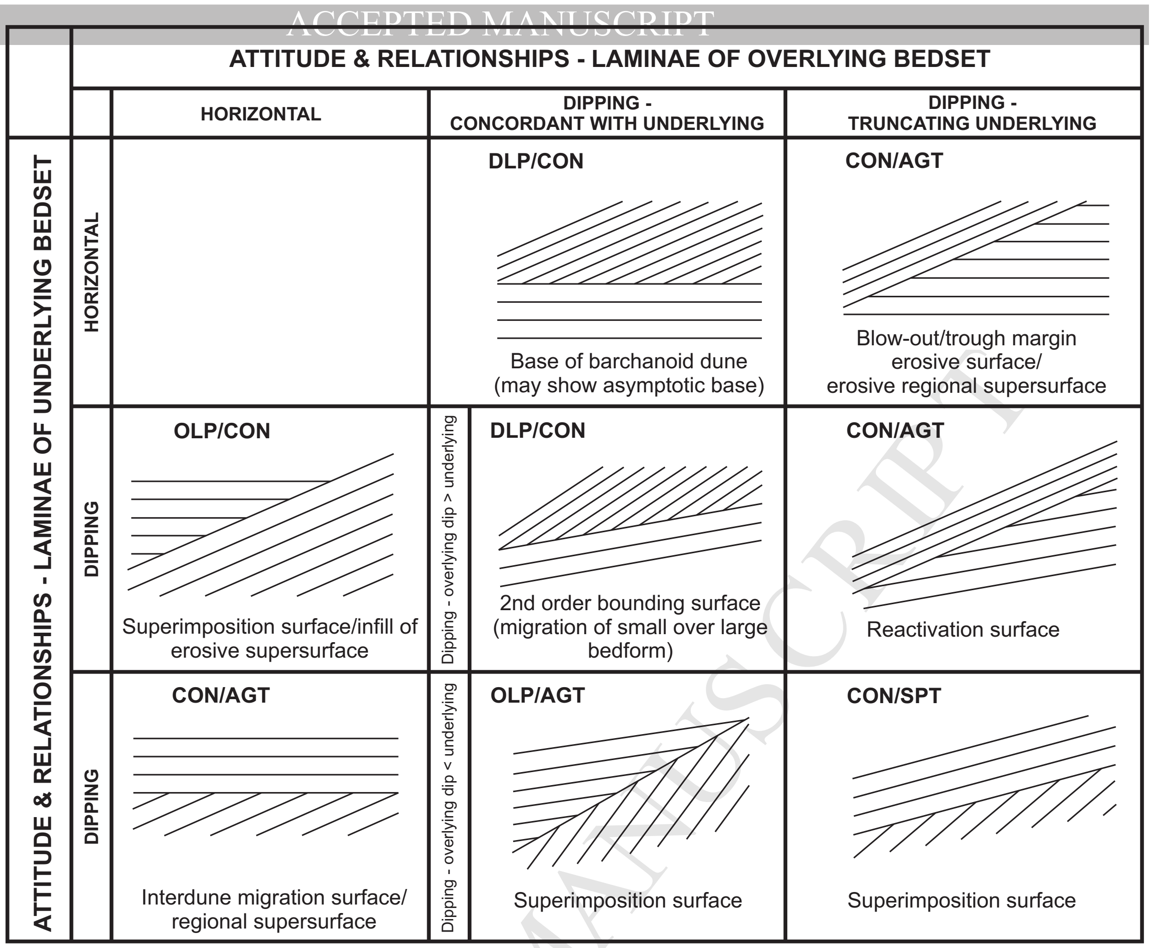
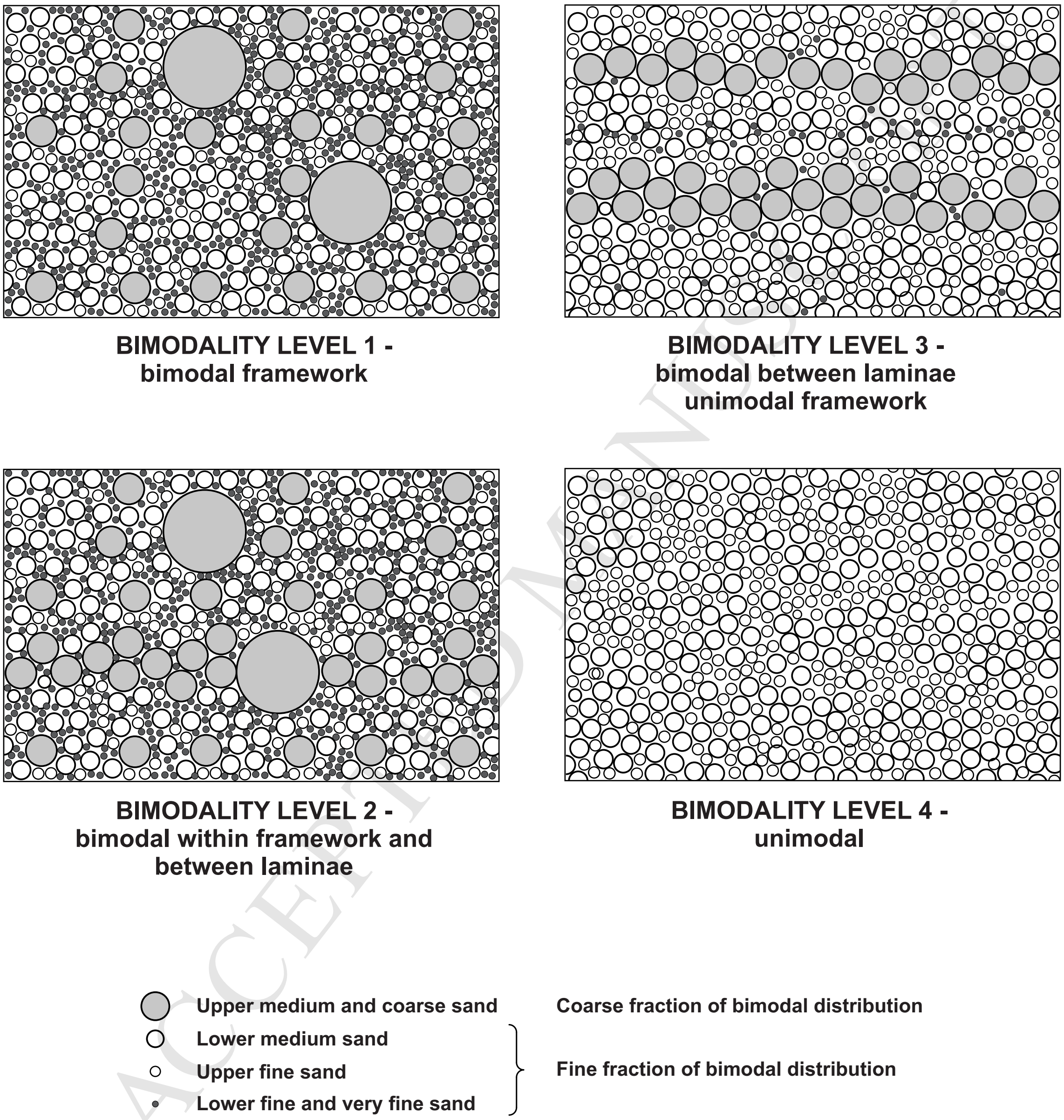
1000
2000 m

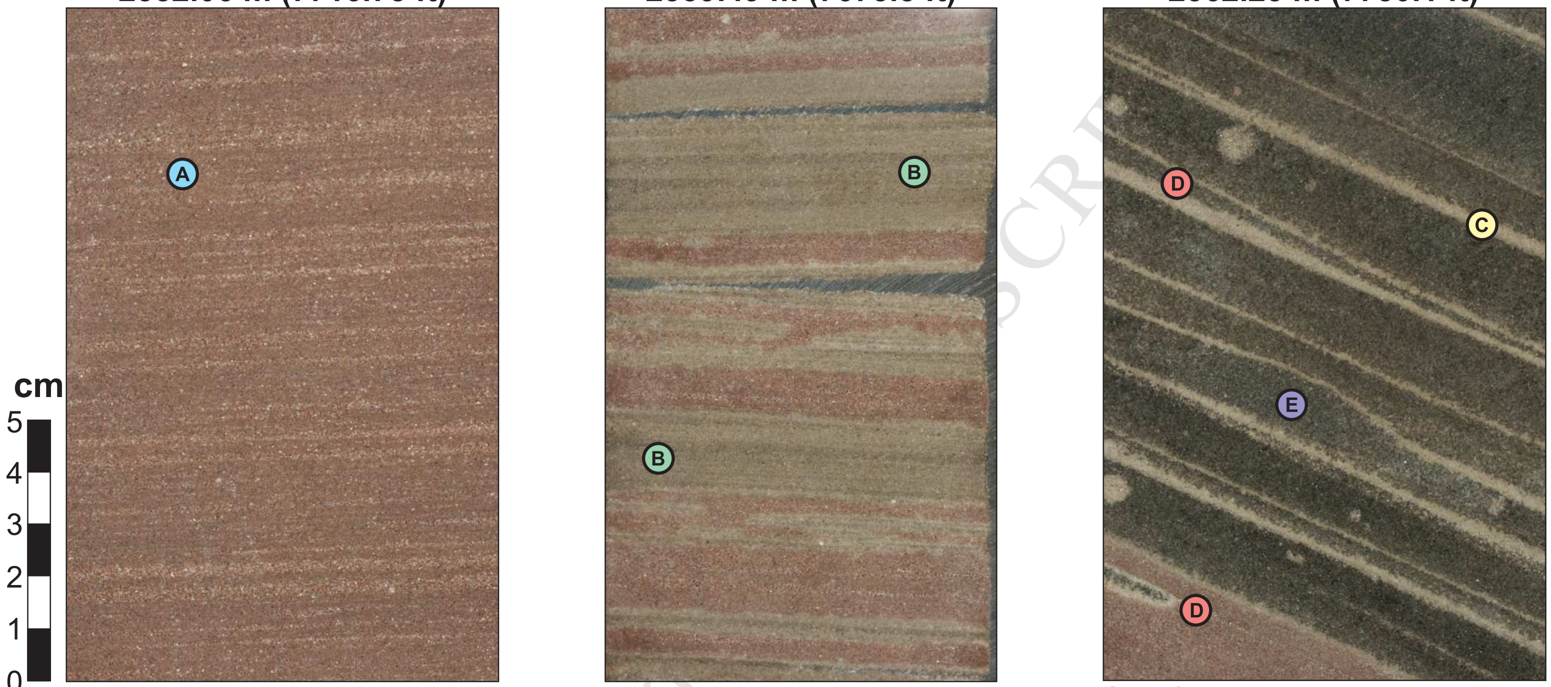

ATTITUDE & RELATIONSHIPS - LAMINAE OF OVERLYING BEDSET
HORIZONTAL
DIPPING - CONCORDANT WITH UNDERLYING
DIPPING - TRUNCATING UNDERLYING
ATTITUDE & RELATIONSHIPS - LAMINAE OF UNDERLYING BEDSET
HORIZONTAL
DIPPING
DIPPING
DLP/CON
Base of barchanoid dune (may show asymptotic base)
CON/AGT
Blow-out/trough margin erosive surface/ erosive regional supersurface
OLP/CON
Superimposition surface/infill of erosive supersurface
Dipping - overlying dip > underlying
DLP/CON
2nd order bounding surface (migration of small over large bedform)
CON/AGT
Reactivation surface
CON/AGT
Interdune migration surface/ regional supersurface
Dipping - overlying dip < underlying
OLP/AGT
Superimposition surface
CON/SPT
Superimposition surface


BIMODALITY LEVEL 1 -
bimodal framework
BIMODALITY LEVEL 3 -
bimodal between laminae
unimodal framework
BIMODALITY LEVEL 2 -
bimodal within framework and
between laminae
BIMODALITY LEVEL 4 -
unimodal
Upper medium and coarse sand
Lower medium sand
Upper fine sand
Lower fine and very fine sand
Coarse fraction of bimodal distribution
Fine fraction of bimodal distribution

core depth - 2352.06 m (7716.75 ft)

core depth - 2339.49 m (7675.5 ft)

core depth - 2362.23 m (7750.1 ft)



Wind-ripple laminated sand

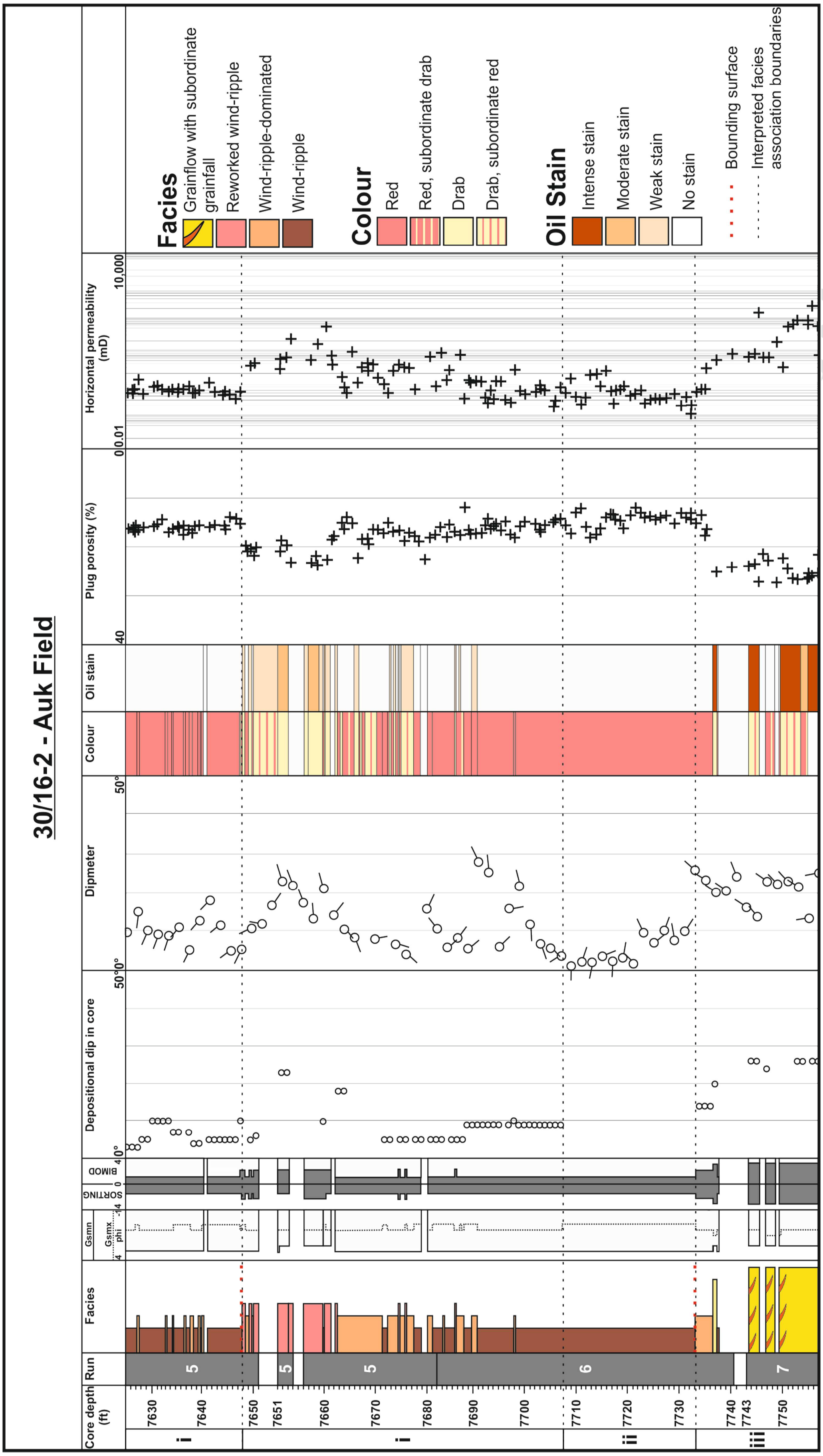
mm-scale laminated sand, poorly to moderately sorted bimodal framework, with sporadic lenticular laminae of coarser grains (wind-ripple crests - (A)); almost invariably red.

Reworked wind-ripple laminated sand

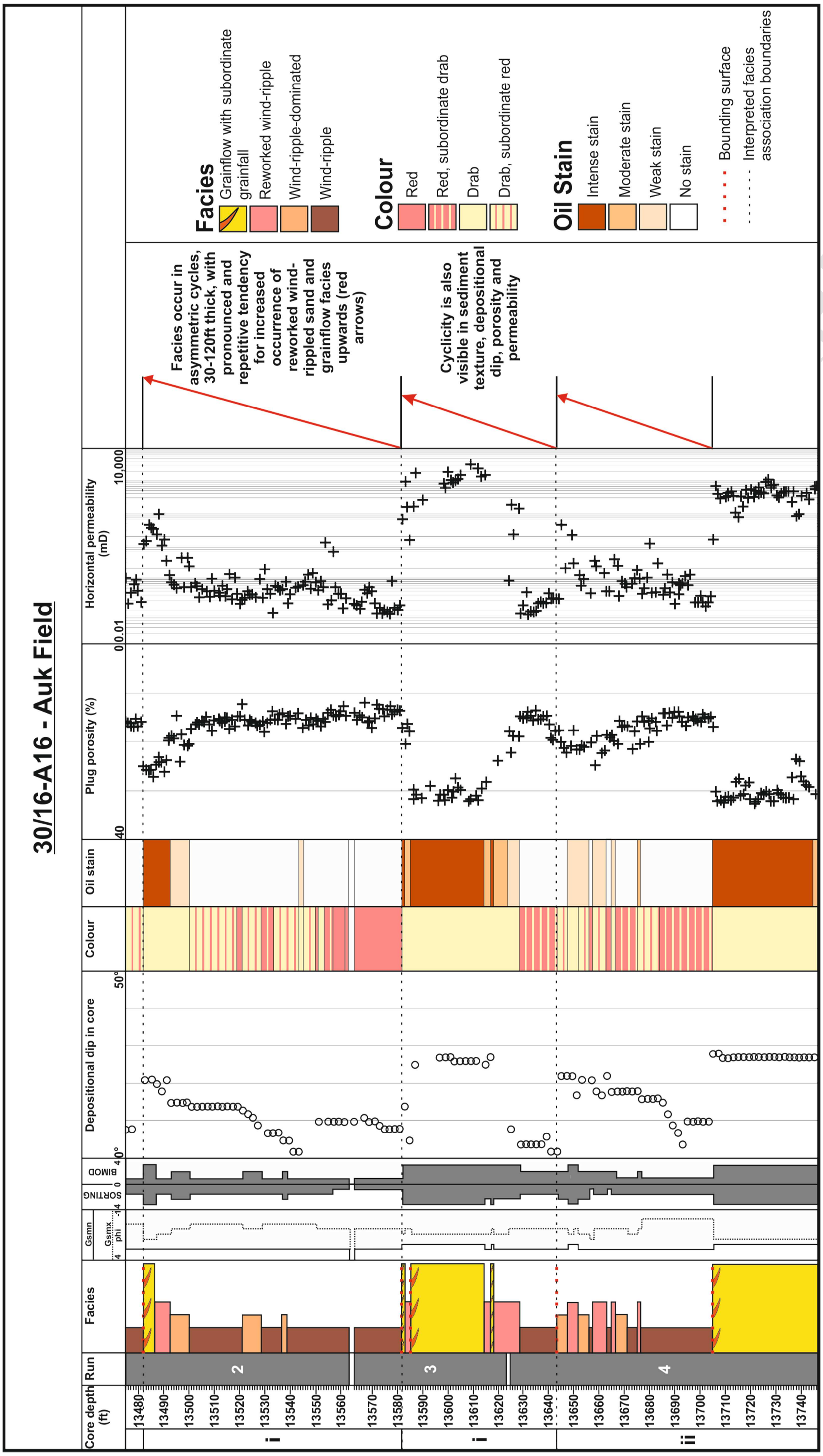
Wind-rippled sand in which a varying proportion of reworked laminae have smaller grain size range and better sorting ((B)). Reworked laminae comprise mm-scale laminated sand, moderately to well sorted, generally unimodal framework (locally unimodal), bimodal between laminae.

Grainflow laminated sand

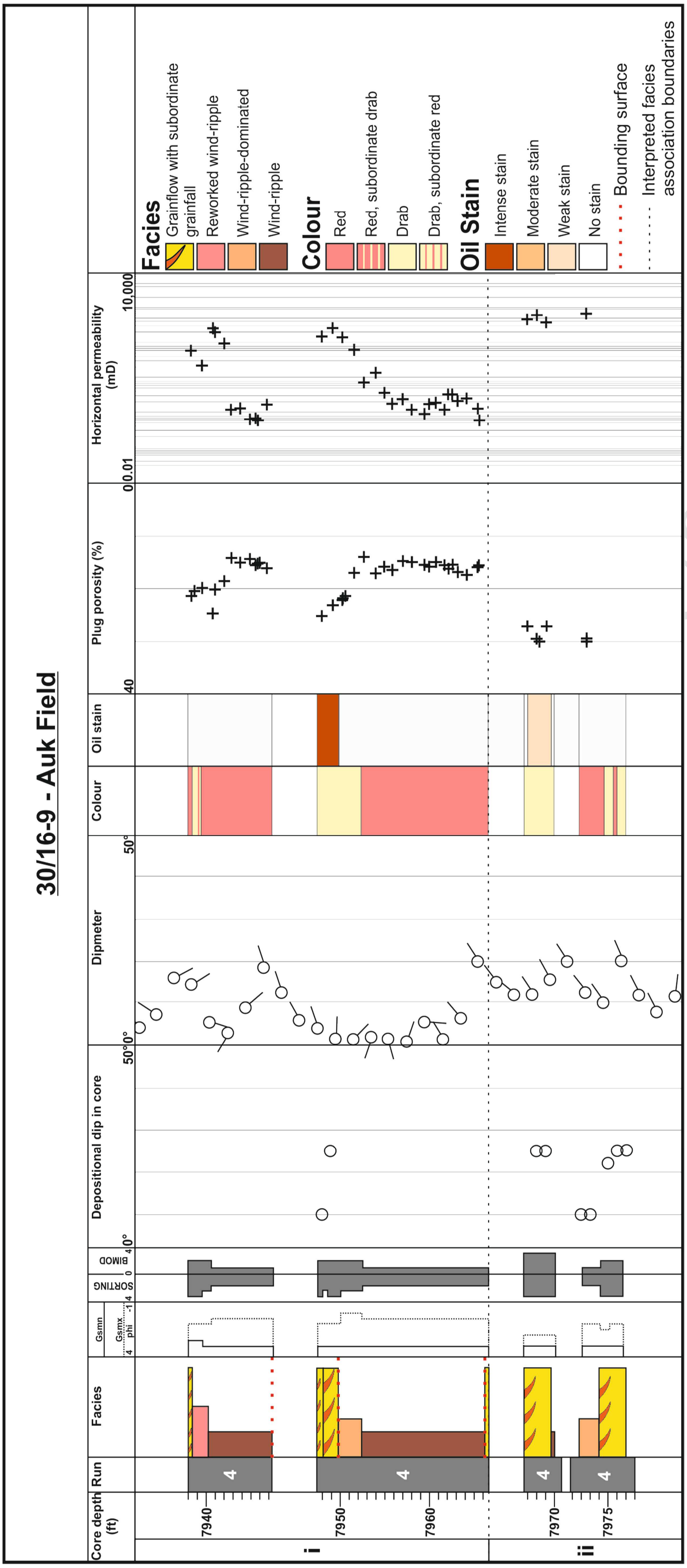
cm-scale laminated sand, with subordinate mm-scale lamination; well sorted upper fine to lower medium sand, unimodal framework, with local laminae of very fine grains (grainfall laminae (C)); generally bleached and oil-stained above OWC. Grainflow laminae locally pinch out marking toe of grainflow ((D)), or swell and/or show soft sediment deformation ((E)).

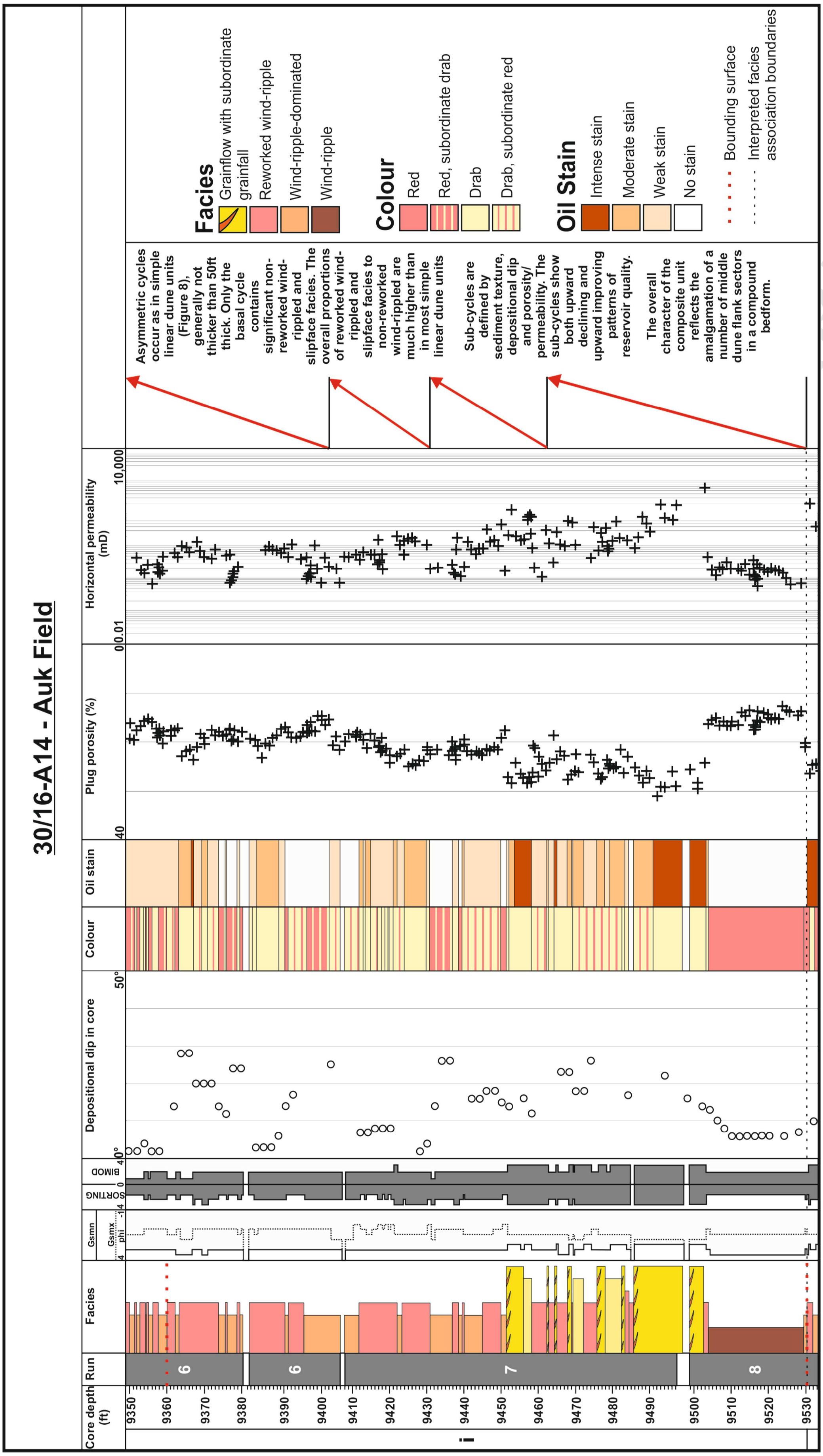


30/16-2 - Auk Field
Core depth (ft)
Run
Facies
Gsmn
Gsmx phi
SORTING
BIMOD
Depositional dip in core
Dipmeter
Colour
Oil stain
Plug porosity (%)
Horizontal permeability (mD)
7630
7640
7650
7651
7660
7670
7680
7690
7700
7710
7720
7730
7740
7743
7750
i
ii
iii
5
6
7
Facies
Grainflow with subordinate grainfall
Reworked wind-ripple
Wind-ripple-dominated
Wind-ripple
Colour
Red
Red, subordinate drab
Drab
Drab, subordinate red
Oil Stain
Intense stain
Moderate stain
Weak stain
No stain
Bounding surface
Interpreted facies association boundaries

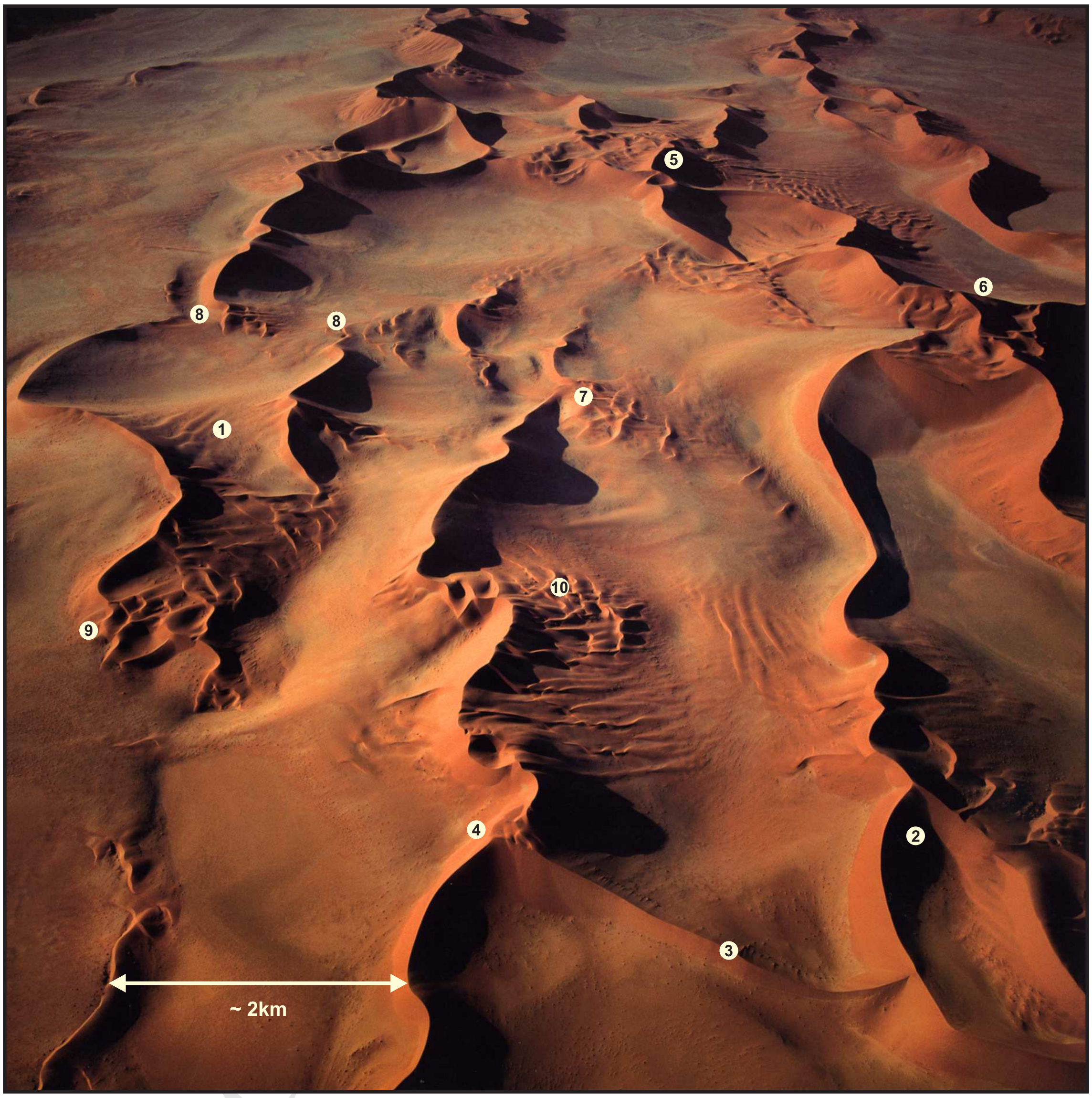


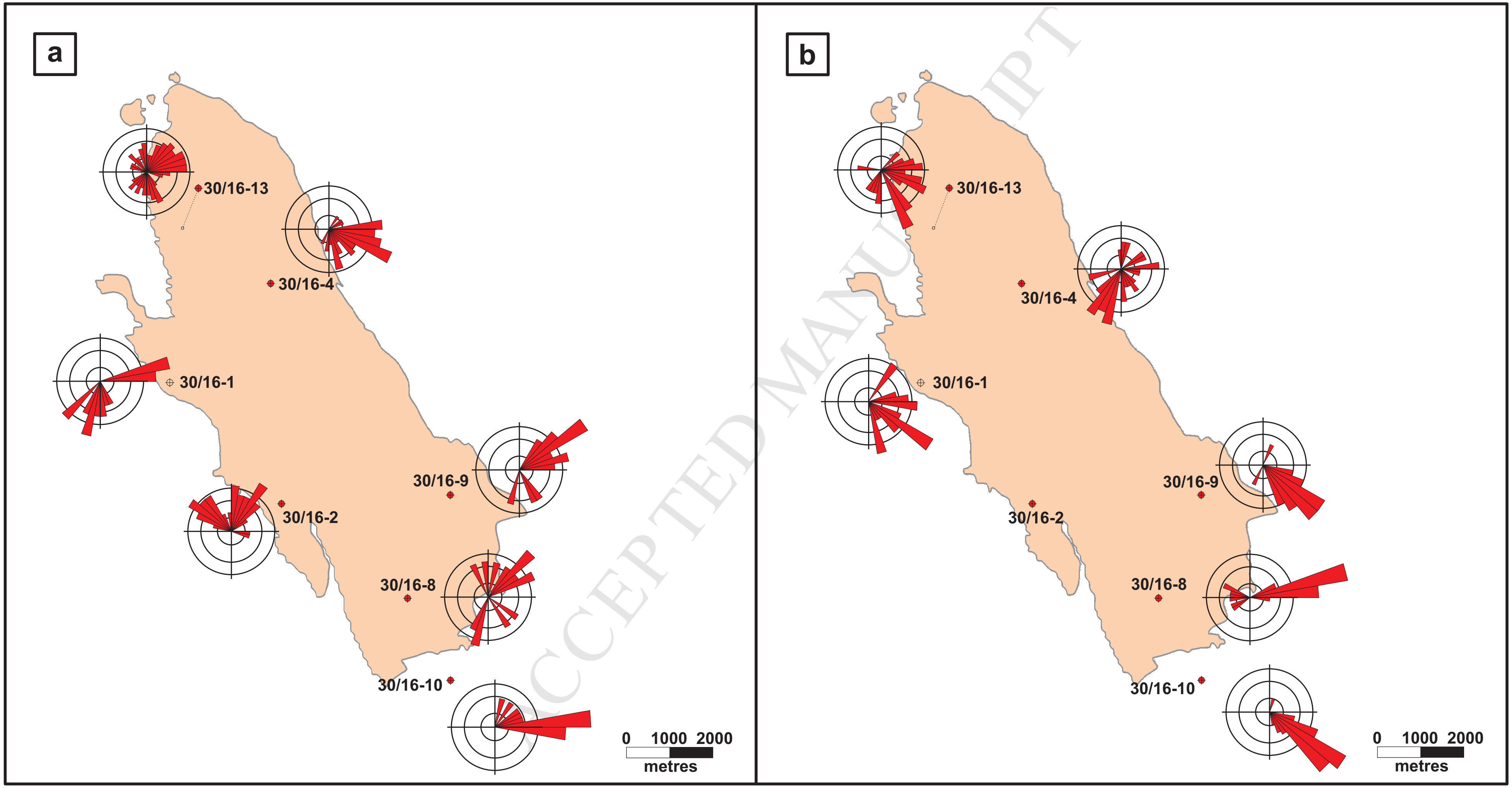
30/16-A16 - Auk Field
Core depth (ft)
Run
Facies
Gsmn
Gsmx phi
SORTING
BIMOD
Depositional dip in core
Colour
Oil stain
Plug porosity (%)
Horizontal permeability (mD)
Facies occur in asymmetric cycles, 30-120ft thick, with pronounced and repetitive tendency for increased occurrence of reworked wind-rippled sand and grainflow facies upwards (red arrows)
Cyclicity is also visible in sediment texture, depositional dip, porosity and permeability
Facies
Grainflow with subordinate grainfall
Reworked wind-ripple
Wind-ripple-dominated
Wind-ripple
Colour
Red
Red, subordinate drab
Drab
Drab, subordinate red
Oil Stain
Intense stain
Moderate stain
Weak stain
No stain
Bounding surface
Interpreted facies association boundaries

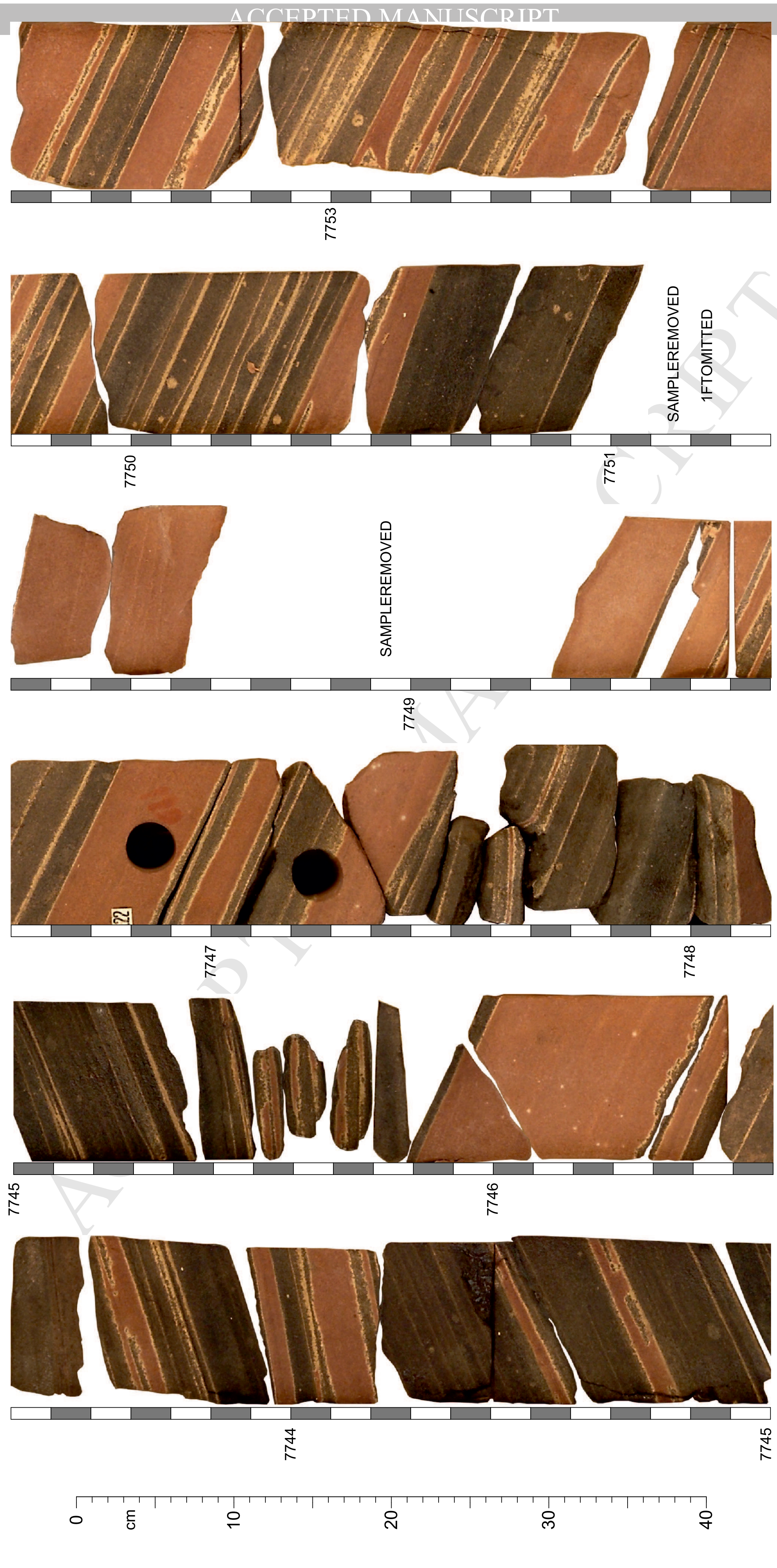

30/16-9 - Auk Field
Core depth (ft)
Run
Facies
Gsmn
Gsmx
phi
SORTING
BIMOD
Depositional dip in core
Dipmeter
Colour
Oil stain
Plug porosity (%)
Horizontal permeability (mD)
0°
50°
0
40
0.01
10,000
7940
7950
7960
7970
7975
4
i
ii
Facies
Grainflow with subordinate grainfall
Reworked wind-ripple
Wind-ripple-dominated
Wind-ripple
Colour
Red
Red, subordinate drab
Drab
Drab, subordinate red
Oil Stain
Intense stain
Moderate stain
Weak stain
No stain
Bounding surface
Interpreted facies association boundaries

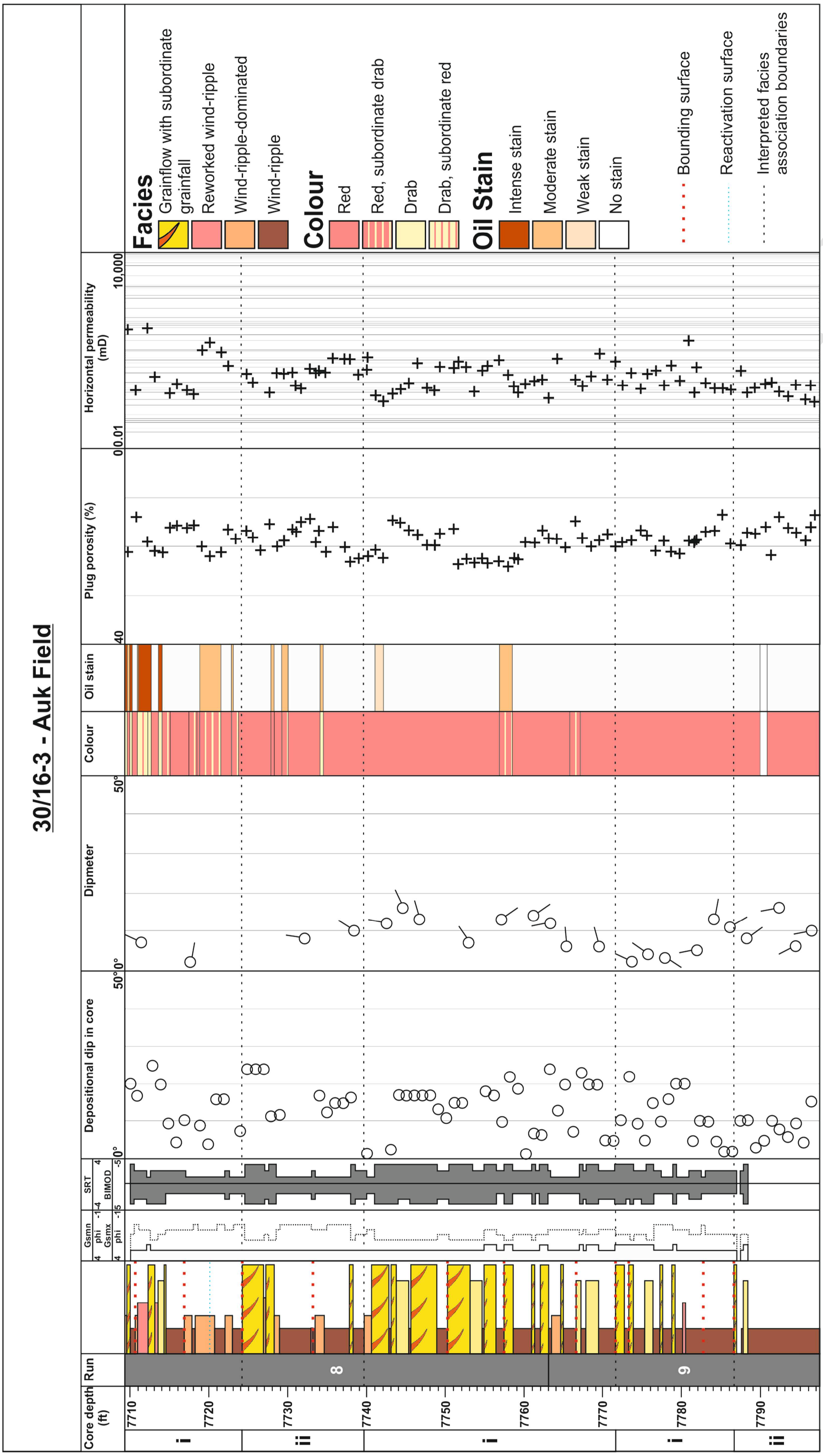


30/16-A14 - Auk Field
Core depth (ft)
Run
Facies
Gsmn
Gsmx
phi
SORTING
BIMOD
Depositional dip in core
0°
50°
Colour
Oil stain
Plug porosity (%)
40
0
Horizontal permeability (mD)
0.01
10,000
9350
9360
9370
9380
9390
9400
9410
9420
9430
9440
9450
9460
9470
9480
9490
9500
9510
9520
9530
6
6
7
8
Asymmetric cycles occur as in simple linear dune units (Figure 8), generally not thicker than 50ft thick. Only the basal cycle contains significant non-reworked wind-rippled and slipface facies. The overall proportions of reworked wind-rippled and slipface facies to non-reworked wind-rippled are much higher than in most simple linear dune units
Sub-cycles are defined by sediment texture, depositional dip and porosity/ permeability. The sub-cycles show both upward declining and upward improving patterns of reservoir quality.
The overall character of the composite unit reflects the amalgamation of a number of middle dune flank sectors in a compound bedform.
Facies
Grainflow with subordinate grainfall
Reworked wind-ripple
Wind-ripple-dominated
Wind-ripple
Colour
Red
Red, subordinate drab
Drab
Drab, subordinate red
Oil Stain
Intense stain
Moderate stain
Weak stain
No stain
Bounding surface
Interpreted facies association boundaries

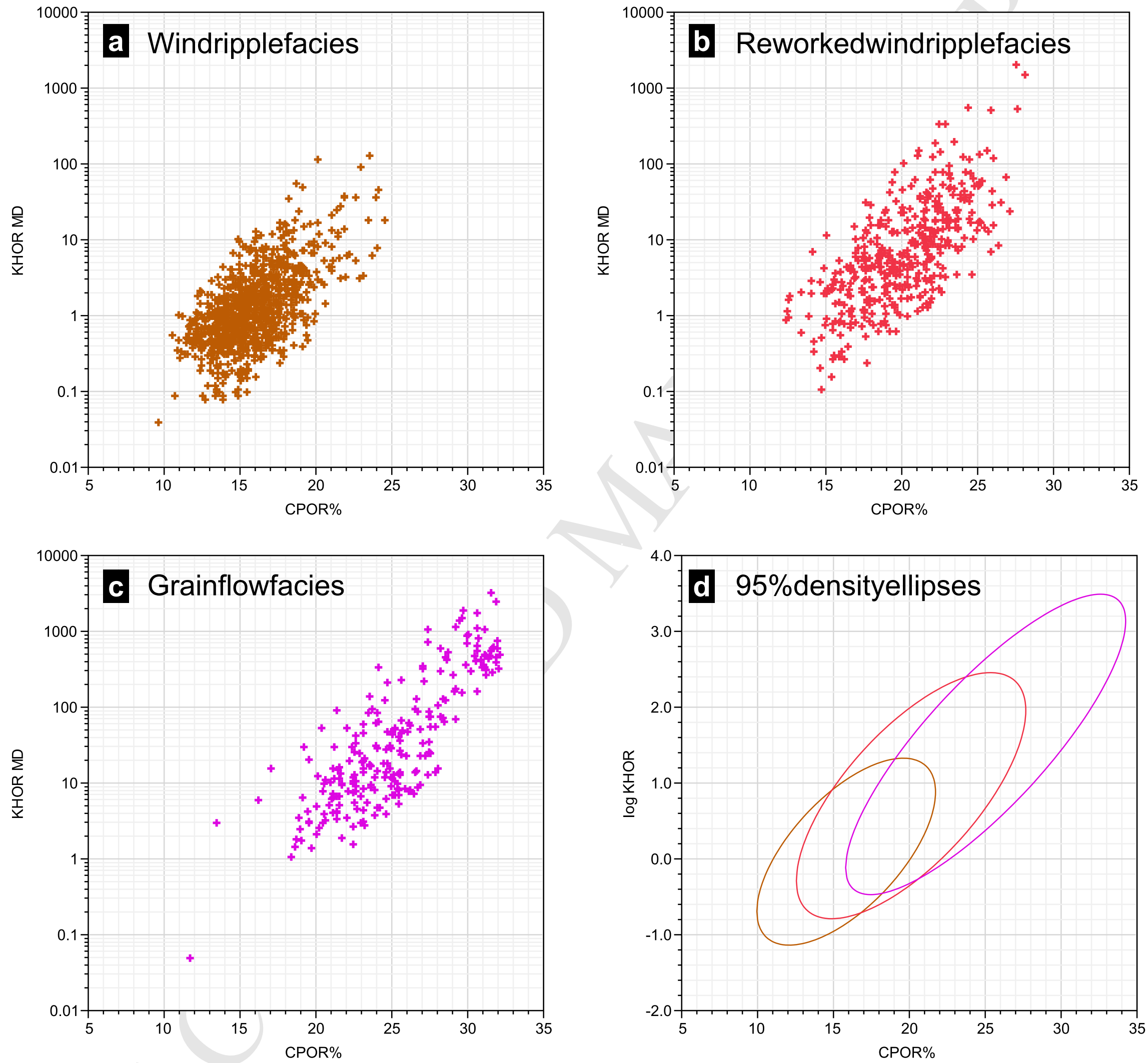

5
6
8
8
7
1
10
9
4
2
3
~ 2km


a
30/16-13
30/16-4
30/16-1
30/16-9
30/16-2
30/16-8
30/16-10
0 1000 2000
metres
b
30/16-13
30/16-4
30/16-1
30/16-9
30/16-2
30/16-8
30/16-10
0 1000 2000
metres

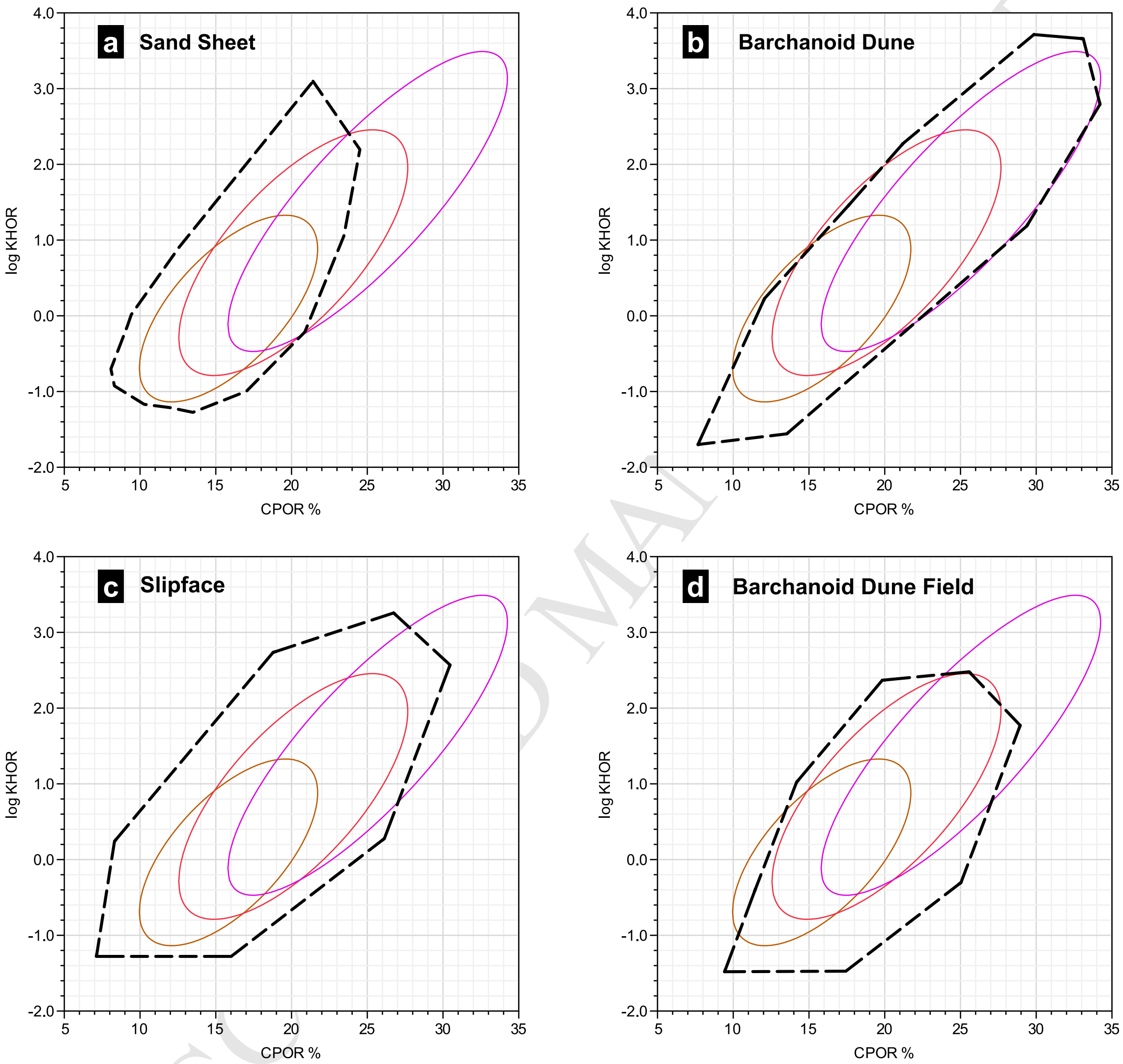

7753
7750
7751
SAMPLEREMOVED
1FTOMITTED
7749
SAMPLEREMOVED
7747
7748
22
7745
7746
7744
7745
0
cm
10
20
30
40



30/16-3 - Auk Field
Core depth (ft)
Run
Gsmn phi
Gsmx phi
SRT
BIMOD
Depositional dip in core
Dipmeter
Colour
Oil stain
Plug porosity (%)
Horizontal permeability (mD)
Facies
Grainflow with subordinate grainfall
Reworked wind-ripple
Wind-ripple-dominated
Wind-ripple
Colour
Red
Red, subordinate drab
Drab
Drab, subordinate red
Oil Stain
Intense stain
Moderate stain
Weak stain
No stain
Bounding surface
Reactivation surface
Interpreted facies association boundaries
7710
7720
7730
7740
7750
7760
7770
7780
7790
8
9
i
ii
0°
50°
40
0
0.01
10,000



a Windripplefacies
b Reworkedwindripplefacies
c Grainflowfacies
d 95%densityellipses
KHOR MD
log KHOR
CPOR%
10000
1000
100
10
1
0.1
0.01
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
5
10
15
20
25
30
35



a
Sand Sheet
b
Barchanoid Dune
c
Slipface
d
Barchanoid Dune Field
log KHOR
CPOR %
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
5
10
15
20
25
30
35

Highlights

Cores and well logs from the subsurface aeolian Auk Formation have been analysed and interpreted;

Bedform type, morphology, and migratory behaviour have been reconstructed using novel and innovative techniques in aeolian facies analysis;

Novel criteria have been established for the recognition of linear bedforms in ancient preserved aeolian successions known only from subsurface data;

Auk Formation is shown to have arisen via the accumulation of linear draa and smaller barchanoid dunes that climbed over one another in a complex manner;

Represents a rare study of subsurface linear dune deposits.