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Reconstruction of 3D eolian-dune architecture from 1D core data through adoption of analogue data from outcrop

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Introduction

Exploration and asset appraisal teams working in hydrocarbon companies typically have access to a varied set of data derived from core and well-log investigations relating to the sedimentology of deposits that make up potential subsurface reservoir intervals. However, at the sub-seismic scale, such datasets are almost exclusively one-dimensional in form, meaning that determination of sedimentary system type and elucidation of the three-dimensional geometry of the various architectural elements present in a reservoir volume, and their reciprocal relationships to one another, are usually highly subjective, resulting in potentially ambiguous interpretations and the postulation of equivocal depositional models (Kocurek 1988; Schenk, 1990; North & Prosser, 1993; North & Boering, 1999). This is especially true for eolian reservoir intervals where the ability to reliably correlate between neighboring wells – even those spaced only a few hundred meters apart, such as deviated sidetracks – 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, 2006a). In many cases, the inability to even establish the presence of features regarded to be reliable indicators of paleo-horizontal in preserved eolian reservoir successions is highly problematic (Kocurek, 1988, 1991). This presents difficulties when estimating volumetric sand content and regional porosity-permeability distributions for eolian reservoirs, where the geometries of the various dune, interdune and extradune elements present within the overall three-dimensional rock volume are poorly constrained in the subsurface (e.g. Nagtegaal, 1979; Heward, 1991).

The aim of this study is to demonstrate how a suite of predictable sedimentological features present in eolian successions can be used to relate detailed sedimentary architectural relationships observable in core and well-log data to the larger-scale sedimentological elements of eolian dune and interdune successions to enable the gross-scale reconstruction of eolian architecture, including estimates of bedform and interdune type, and bedform height, wavelength and spacing. Specific objectives of this study are as follows: (i) to describe the small-scale stratigraphic relationships expected for various different types of eolian bedform morphologies and their resultant preserved deposits arising as a product of eolian bedform migration and accumulation; (ii) to show how the sedimentological attributes of modern eolian systems and ancient outcrop successions can be used to quantify predictable trends in small-scale eolian architecture, and to demonstrate the style of occurrence of these features within larger scale elements (Figure 1); and (iii) to develop and demonstrate a workflow to enable first-order reconstruction of original dune and interdune morphology and preserved three-dimensional architecture from measurements made directly from the limited data provided by one-dimensional cores and well-logs through employment of a series of empirical relationships.

Eolian dunes of different morphological type exhibit varying yet predictable configurations of primary depositional facies (principally packages of grainflow, wind-ripple and grainfall strata) and associations of such facies (Hunter, 1977a, b, 1981; Kocurek & Dott, 1981). The distribution of associations of these facies tends to vary predictably over the surface of individual modern eolian bedforms as a function of the various eolian processes that operate on the flank, lee-slope, stoss-slope and brink areas of bedforms (Hunter, 1977a), meaning that primary lithological characteristics such as grain-size distribution, grain packing, and styles of small-scale lamination are also predictable (Livingstone, 1987).

In most systems, the mechanics by which eolian bedforms and their constituent stratal packages of associated facies undergo accumulation is dictated by the style by which bedforms undertake migration synchronously with a rise in the accumulation surface (Kocurek, 1988; Kocurek & Havholm, 1993), leading to bedform climbing (Rubin & Hunter, 1982) and the accumulation of sets of cross strata. Although several alternative mechanisms for the accumulation and preservation of sets of eolian strata have been proposed, including the infilling of localized accommodation space (e.g. Langford et al., 2008; Luzón et al., 2012), accumulation around relic eolian topography (Fryberger, 1986), and exceptional bedform preservation following rapid inundation by water or lava flows (e.g. Glennie & Buller, 1983; Mountney et al., 1999; Benan & Kocurek, 2000), the “bedform climbing” mechanism remains a convincing explanation for the origin of the majority of ancient preserved eolian dune successions (Mountney, 2012).

Importantly, accumulation of sets of eolian strata via the climbing of bedforms over one another means that typically only the lowermost flanks of migrating bedforms undergo accumulation and preservation into the long-term rock record, whereas the upper parts of bedforms (in most cases the upper 90% or more of a bedform) are truncated by the advance of the following bedform in the train (Rubin & Carter, 2006), with the majority of the original dune sediment being reworked (Figure 2). Thus, the proportion and distribution of primary lithofacies preserved in successions in the ancient record does not necessarily reflect the proportion and distribution of primary lithofacies present in modern bedforms. Care must therefore be exercised when using modern bedforms as analogues with which to make predictions about likely facies distributions in reservoir successions. Methods for the accurate prediction and characterization of zones of good reservoir quality in subsurface eolian successions require a clear understanding of the geometry of the various preserved architectural elements and the distribution of packages of facies associated within these elements.

Architectural elements (i.e. three-dimensional sediment bodies with specific internal facies characteristics) form the building blocks of eolian reservoir successions and, in most examples, both the elements themselves and the lithofacies of which they are composed internally exhibit a strong preferred directional heterogeneity due to the inherent preferred orientation of layering of laminations and beds of facies, often in a complex nested manner (Weber, 1987; Chandler et al., 1989; Krystinik, 1990). Understanding the detailed arrangement of the style of heterogeneity present in these elements is crucial for reservoir prediction as this exerts a primary control on porosity and permeability structure within eolian reservoirs and therefore dictates production flow rates and patterns within complex eolian reservoir bodies (Nagtegaal, 1979; Heward, 1991; Ellis, 1993; Stanistreet & Stollhofen, 2002; Garden et al., 2005; Bloomfield et al., 2006). In most eolian hydrocarbon plays, it is particularly important to target those intervals within a reservoir that contain a high proportion of grainflow laminae – the deposits of avalanching down dune lee slopes – as these tend to form packages of well-sorted, loosely-packed sandstone with permeabilities that are typically one or more orders of magnitude greater than those in packages of grainfall and wind-ripple strata that dominate in other eolian elements (Chandler et al., 1989; Prosser & Maskall, 1993; Howell & Mountney, 2001).

Background

Since the late 1970s, considerable eolian sedimentological research has focused on large scale stratigraphic relationships and the development of sequence stratigraphic models with which to account for the origin of the eolian record in terms of external controls on sedimentation (e.g. Brookfield, 1977; Kocurek, 1988; Kocurek & Havholm, 1993; Mountney, 2012). As a result of this emphasis, a wide variety of data have been published relating to large-scale stratigraphic architectures preserved in a number of ancient eolian successions (e.g. Glennie & Provan, 1990; Herries, 1993; Mountney & Thompson, 2002; Mountney & Jagger, 2004; Taggart et al., 2010). However, there remain relatively few studies that have investigated the sedimentary style of small-scale dune elements and the arrangement of facies present within preserved eolian sets originating from the migration of different types of eolian bedforms (Ellwood et al., 1975; Hunter, 1977a, b; Kocurek & Dott, 1981; Fryberger & Schenk, 1988). Although some explanation has been offered to account for how such types of small-scale stratification impact on reservoir quality (Lindquist, 1988; Chandler et al., 1989; Prosser & Maskall, 1993; Cox, 1994; Howell & Mountney, 2001; Stanistreet & Stollhofen, 2002; Garden et al., 2005; Bloomfield et al., 2006), an effective method to relate deposits seen in one-dimensional core to larger-scale architectural elements has yet to be fully developed.

Prediction of facies variability in three dimensions is a key requirement for quantitative reservoir characterization (e.g. Sweet et al., 1996; Fischer et al., 2007) because it enables reliable predictions to be made of the characteristics of a subsurface eolian reservoir bodies such as the extent, type and pattern of distribution of heterogeneities away from the points of data control provided by subsurface wells (Pryor, 1973). For the majority of eolian reservoirs, production behavior and characteristics are primarily influenced and controlled by original sediment fabric (grain size distribution), though secondary alteration of sediment fabric by diagenesis is also important (e.g. Mou & Brenner, 1982). A method to enable the prediction of the spatial occurrence of the original depositional processes that occurred on dunes and in interdunes, and the resultant distribution of lithofacies in preserved eolian architectural elements is therefore essential (Lewis & Couples, 1993).

Given that most eolian reservoirs are penetrated by a relatively small number of wells and that the typical spacing of these wells is many hundreds of meters to several kilometers, traditional subsurface lithostratigraphic correlation techniques involving the tracing of key stratal surfaces and depositional units are not typically possible. Instead, a commonly adopted method with which to adequately account for facies architecture and with which to predict the scale over which variations in architecture occur is to employ one or more outcrop analogues to provide proxy data (Weber, 1987; Lewis & Rosvoll, 1991, Howell & Mountney, 2001). Such outcrop-analogue studies are important because they provide a method by which regional three-dimensional facies distributions known from outcrop can be used to populate a reservoir volume and thereby inform detailed characterizations and minimize risk. Key to the successful application of this technique is the ability to fit the sedimentary architecture of the chosen outcrop analogue to available core and well-log data from the subsurface reservoir.

An inherent problem with reservoir modeling from core and well-log data alone is that such data-types are essentially one-dimensional in form and establishing the most likely three-dimensional sedimentary architecture from such data is typically equivocal (Lindquist, 1988; Luthi & Banavar, 1988; North & Boering, 1999). However, several parameters that effectively define the morphology and geometry of eolian bedforms and their preserved bedsets can be measured directly from subsurface core and these provide a method to directly relate the subsurface architecture present in reservoir successions to outcrop successions for which larger-scale three-dimensional architectural configurations can be determined.

Parameters that can be measured directly from core include: (i) preserved set thickness, which for bedsets that originated via bedform climbing is a function of both original bedform wavelength and the angle at which the bedforms climbed over one another as accumulation proceeded (Mountney & Howell, 2000); (ii) the thickness of grainflow units arising from individual sandflow avalanches, which is primarily a function of the length of the lee slope of the original bedform down which avalanching grains of sand cascaded to generate the deposit (Kocurek & Dott, 1981; Howell & Mountney, 2001); (iii) the shape of dune toesets and their style of interaction with deposits of underlying interdune elements, which is an indicator of the style of advance of the original bedform over a neighboring interdune area (e.g. Pulvertaft, 1985; Mountney & Thompson, 2002); (iv) the rate of upward steepening of foresets within a set, which is an indicator of the profile of the lower flanks of the original bedform (Rubin, 1987); (v) the distribution of primary lithofacies (grainflow, wind-ripple and grainfall) within sets, which is a function of processes that operated on the lee slope of the original bedform (Hunter 1977a, b; Kocurek & Dott, 1981); and (vi) the distribution of the occurrence of reactivation surfaces within cosets, which is an indicator of the periodicity with which the original bedforms undertook changes in lee-slope steepness, asymmetry, or migration direction (Rubin, 1987; Fryberger, 1993).

Within the remit of this study, detailed examination of the relationships arising between preserved set thicknesses and the thickness of preserved grainflow units has been undertaken. By relating quantitative measurements of these attributes from subsurface core intervals to equivalent sedimentary features observed in exposed outcrop successions, a workflow has been established for the quantification of larger-scale three-dimensional subsurface eolian architecture from limited one-dimensional core data through a suite of empirical relationships. Although the empirical relationships derived from this study serve as useful tools for generalized prediction of sedimentary architecture, application of such relationships should be undertaken with caution: relationships between many measured parameters record significant variability meaning that R^2 values determined for best-fit trend lines are low and not statistically significant in many instances, chiefly as a result of the variability inherent in natural depositional systems such as those studied in this work.

Despite these shortcomings, the data show a series of relationships that are nevertheless useful as a basis for a generalized technique to reconstruct the three-dimensional architecture from primary depositional facies in eolian successions. Specifically, the empirical relationships presented herein are useful for the determination of trends between features observable in core and several aspects of wider three-dimensional sedimentary architecture that cannot be determined by direct observation from subsurface datasets. Thus, such trends are useful for making first-order predictions of the likely internal three-dimensional sedimentary architectures of subsurface reservoir successions and can be used to assist in the construction of reservoir models for the prediction of porosity-permeability distributions and likely flow properties.

For example, in successions interpreted to have arisen in response to the migration and aggradation of large linear dune bedforms, a vertical stacking of thick packages of relatively low-angle-inclined, wind-ripple-dominated packages of strata is common, with only the uppermost parts of sets having foresets that steepen upward sufficiently to preserve grainflow strata (Krystinik, 1990). Determining the proportions of wind-ripple and grainflow strata and the distribution of their occurrence within preserved sets is key to understanding the three-dimensional configuration of packages of facies, and this is most readily achieved through comparison to analogous outcrop examples.

Data and Methods

To establish a suite of empirical relationships between eolian sedimentary parameters that can be measured directly from both one-dimensional core and from the larger-scale eolian architectural elements observable from outcrop successions, data have been collected from the Permian Cedar Mesa Sandstone and Jurassic Navajo Sandstone, two eolian successions that are well exposed in the South East Utah area, U.S.A. Four localities were studied in the so-called erg center region of the Permian Cedar Mesa Sandstone succession (Mountney, 2006b) in the White Canyon and Hite areas and an additional three localities were studied in the so-called erg margin region at Squaw Butte, Salt Creek Butte and Mosquito Butte (Figure 3a). Four localities were also studied in the Jurassic Navajo Sandstone in the area around the town of Moab, Utah (Figure 3b), which represents an erg center setting within the paleo-erg system (Blakey & Ranney, 2008).

Primary measurements of eolian bedset architectures were made at each study locality to determine three-dimensional relationships present in the successions of eolian dune sets. Aspects of eolian architecture measured included: (i) maximum preserved set thicknesses for 42 individual trough cross-bedded sets exposed in orientations both parallel and perpendicular to eolian transport direction (itself determined through analysis of dip-azimuth data relating to grainflow deposits representative of accumulation on the slipface of the original bedforms) – care was taken to account for set-thickness variations arising from the curved nature of trough cross-bedded sets; (ii) geometries of packages of grainflow strata representative of individual lee-slope sand avalanches, including thickness (932 readings in total), width (30 readings in total) and length (517 readings in total); (iii) measurements of bedform wavelength (42 readings in total) determined in directions parallel to eolian paleo-transport mostly by the measurement of the spacing between the points at which successive interdune migration surfaces climb off basal supersurfaces that are themselves inferred to represent paleohorizontal surfaces (see Mountney & Howell, 2000 and Mountney, 2006b for details of the methodology); (iv) measurements of angles of set climb (42 readings in total), determined trigonometrically in directions parallel to eolian paleo-transport (again determined through analysis of dip-azimuth data relating to grainflow deposits representative of accumulation on the slipface of the original bedforms) by evaluating the rate of rise of interdune migration surfaces relative to underlying supersurfaces (see Mountney, 2006b for methodology); (v) measurements of the rate of upward steepening of eolian dune toeset deposits with increasing height above the base of sets (36 readings in total).

Results

Grainflow Geometry

The mean lengths and widths of single units of grainflow strata in the Navajo Sandstone are 4.22 m (standard deviation = 2.43; n = 517) (Figure 4a), and 4.63 m (standard deviation = 1.58; n = 30) (Figure 4b), respectively. Grainflow width data were not measured from the Cedar Mesa Sandstone. The mean thicknesses of single units of grainflow strata (i.e. deposits representative of a single sandflow avalanche event) in the Navajo Sandstone and Cedar Mesa Sandstone are 23.77 mm (standard deviation = 7.32; n = 517), and 54.68 mm (standard deviation = 23.11; n = 415), respectively (Figure 4c). Individual grainflow units have been identified by their subtle inverse grading, which gives rise to a sharp grain-size contrast across unit boundaries that typically takes the form of a change from lower to upper fine-grained sand. Additionally, these units are in many instances identified by their style of interfingering and intercalation with thin accumulations of wind-ripple strata, especially in the lower parts of preserved sets, and with thin accumulations of grainfall strata, most notably in the upper parts of preserved sets.

Preserved Set Thickness

Preserved set thicknesses have been measured from the central axes of troughs (i.e. at the location of the thickest development of the set). The mean thicknesses of simple preserved sets (*sensu* McKee, 1979) of strata bounded by interdune migration bounding surfaces in the Navajo Sandstone and Cedar Mesa Sandstone are 3.10 m (standard deviation = 1.60; n = 25), and 4.71 m (standard deviation = 2.72; n = 17), respectively (Figure 4d). For the Cedar Mesa Sandstone, measured set thicknesses are representative of the succession overall, though considerable variability exists in some locations. For the Navajo Formation, which is exposed over large areas of Utah, Arizona and Colorado, preserved set thicknesses vary considerably and the sets measured as part of this study from parts of the succession exposed around the town of Moab, Utah, are not necessarily representative of the formation overall. Indeed, significantly thicker compound sets are known from other parts of this formation (see, for example, Herries, 1993 and Rubin, 1987), though these have not been examined for this study.

Bedform Wavelength Reconstruction

Original dune wavelengths were mostly determined via direct measurement. In directions parallel to eolian paleo-transport, the spacing between the points at which successive interdune migration surfaces climb off basal supersurfaces that are themselves inferred to represent paleohorizontal surfaces is a measure of bedform spacing, where bedform spacing is defined as the bedform wavelength plus the additional component of width of any adjoining interdune flat. Additional calculations of original dune wavelengths were derived trigonometrically from estimates of set thicknesses and angles of climb: see Mountney & Howell (2000) for details of the method. The mean reconstructed dune bedform wavelengths in directions parallel to inferred eolian bedform migration direction for studied parts of the Navajo Sandstone and Cedar Mesa Sandstone are 138.26 m (standard deviation = 70.75; n = 25), and 202.42 m (standard deviation = 159.19; n = 15), respectively (Figure 4e).

Based on relationships observed from Navajo Sandstone, where sets are seen to rise (climb) off supersurfaces, reconstructed dune bedforms are estimated to have had original wavelengths ranging from 80 to 340 m. The erg center region of the Cedar Mesa Sandstone exhibits a wider range of reconstructed dune wavelength values (65 m to 668 m). Overall, these data fall within the ranges determined previously for eolian dunes of the Cedar Mesa Sandstone in the White Canyon region of SE Utah (Mountney, 2006b). However, one exception is Set 1 from Mile 101 of Highway 95 (a 12.8 m-thick set climbing at an angle of 1.1°), which is estimated to represent the preserved deposit of a bedform that had an anomalously large wavelength of 668 m, considerably greater than values determined for other bedforms in the succession.

Angle of Climb

The Navajo Sandstone exhibits a narrow range of observed angles of climb, with the majority of sets climbing up through the stratigraphy in a downwind direction at angles between 1 to 1.5°. The mean angle of climb of studied sets in the Navajo Sandstone is 1.29° (standard deviation = 0.30; n = 25). Sets in the erg center region of the Cedar Mesa Sandstone reveal a wider range of climb angles, which were derived by Mountney (2006b, his Figure 12) trigonometrically from measurements of preserved set thicknesses and reconstructed original dune bedform wavelengths (the latter determined from the spacing between points where sets rise off supersurfaces which themselves define a paleohorizontal surface). The mean angle of climb of studied sets in the Cedar Mesa Sandstone is 1.54° (standard deviation = 0.75; n = 17 (Figure 4f).

Discussion

Several important empirical relationships describing relationships between the spatial arrangement of observed lithofacies and the geometry and style of distribution of larger-scale eolian architectural elements are identified from analysis of the field-derived data.

Relationship between preserved grainflow thickness, length and width

Where the pattern of outcrop has allowed, for every grainflow unit measured in the Navajo Sandstone (n = 517), the preserved thickness has been related to a corresponding grainflow length and width (Figures 5 & 6). In the Navajo Sandstone, measured grainflow widths exhibit a strong positive correlation with corresponding grainflow thickness (Figure 5; y = 0.0041x + 0.0035; R^2 = 0.86). The overall relationship between measured grainflow length and preserved grainflow thickness for sets in the Navajo Sandstone shows a positive correlation but with substantial scatter (Figure 6; y = 0.0019x + 0.0156; R^2 = 0.41). However, preserved grainflow thickness and length relationships from 25 *individual* sets are also depicted in Figure 6 and strong positive correlations between preserved thickness and length exist in almost every case. Significantly, however, data from different sets plot in distinct and, in many cases, non-overlapping fields on the graph. Together, these observations suggest that, although a simple overall general relationship between grainflow thickness and grainflow length exists, data from individual sets each preserve grainflows with their own geometry and this likely reflects the shape of the slipface that developed on the lee of the dune at the time of sedimentation.

Empirical relationships identified from outcrop data between grainflow thickness, length and width are important because they potentially allow the three-dimensional reconstruction of the expected geometry of grainflow sediment packages solely from a measurement of their thicknesses preserved in core. This is important for modeling lamina- and bed-scale heterogeneity and directional permeability in eolian reservoirs (Weber, 1982, 1987; Chandler et al., 1989; Krystinik, 1990).

Relationship between preserved set thickness, dune wavelength and angle-of-climb

In both the Cedar Mesa Sandstone and the Navajo Sandstone, dune-sets generated by the migration and climb of larger bedforms (as determined by reconstructed estimates of longer wavelengths) preserve thicker grainflow units, though considerable spread exists between the data (Figure 7a; Cedar Mesa Sandstone; y = 1E-05x + 0.0532; R^2 = 0.02; Navajo Sandstone; y = 6E-05x + 0.0148; R^2 = 0.38). Although the studied dune-sets from the Navajo Sandstone are indicative of original bedforms characterized by generally smaller wavelengths than those of the Cedar Mesa Sandstone, considerable overlap in original bedform wavelength exists. Of the preserved dune-sets for which estimates of reconstructed original bedform wavelengths are similar, examples from the Navajo Sandstone are characterized by distinctly thinner grainflow units than those from the Cedar Mesa Sandstone (Figure 7a). This could have arisen due to a number of reasons: different dune types, different slipface configurations, variations in dune-plinth shape, variations in dune height (a likely influence on slipface length) despite bedforms having similar wavelengths, and different grain-size distributions or grain-shape properties giving rise to different types of avalanches down the dune lee slopes. The overall correlation between preserved grainflow thickness and original bedform wavelength represents a possible method for making a first-order estimate of original bedform size from subsurface data since the former can be measured directly from core.

However, the spread of the data and the different trends in the data for the Navajo and Cedar Mesa sandstones demonstrate that it is essential to pick an appropriate analogue when making extrapolations regarding larger-scale architecture from core data.

For climbing eolian systems that accumulate a succession through progressive climb of bedforms over one another, preserved set thickness is a function of both bedform size (wavelength) and angle-of-climb (Figure 8; Rubin, 1987; Rubin & Carter, 2006). Despite preserved set thickness being only partly dependent on original dune wavelength, for the studied successions there exists a clear positive relationship between preserved set thickness and dune wavelength (Figure 7b – Cedar Mesa Sandstone - $R^2 = 0.61$; Navajo Sandstone - $R^2 = 0.78$). Note, however, that ignoring the outlier that represents the anomalously large bedform studied in the Cedar Mesa Sandstone reduces the R^2 value for the best-fit line for these data from 0.61 to 0.20.

The nature of the relationship between preserved set thickness and dune wavelength is similar for both the Cedar Mesa and Navajo sandstones, principally because sets from both systems in the areas studied are climbing at similar angles (the majority in the range 1 to 1.5°), which means that the effects of angle-of-climb are largely normalized. However, although sets in some other systems are known to climb at similar angles (e.g. Triassic Helsby Sandstone – 1 to 1.5°, Mountney & Thompson, 2002), others successions climb at lower angles (e.g. the transition zone between the Undifferentiated Cutler Group and the Cedar Mesa Sandstone at Indian Creek, SE Utah – 0.35°, Mountney & Jagger, 2004) or steeper angles (e.g. parts of the Etjo Sandstone, Namibia – up to 4°, Mountney & Howell, 2000, as well as examples from some very dry dune systems characterized by small dunes, which have not been addressed in this study). Thus, it is important to consider angle-of-climb when using preserved set thickness to reconstruct likely original bedform size.

Although a positive relationship has long been recognized whereby increased climb angles tend to preserve thicker sets (e.g. Mountney & Howell, 2000), such increased angles of climb do not necessarily arise from the accumulation of larger bedforms with longer wavelengths. Indeed, larger bedforms with longer wavelengths tend to undertake accumulation through climb at shallower angles, primarily because larger bedforms are likely to respond only slowly to changes in sand availability and will therefore tend to climb at only shallow angles, though they can preserve relatively thick sets by virtue of their long wavelength. Thus, preserved set thickness alone is not necessarily a reliable indicator of original bedform size.

Relationship between preserved set thickness and grainflow thickness

For each set for which a thickness has been measured, 15 to 25 grainflow thicknesses have also been measured; the relationship between preserved set thickness and grainflow thickness shows significant scatter (Figure 9; Cedar Mesa Sandstone, y = 102.09x - 0.9557, R^2 = 0.2137; Navajo Sandstone, y = 182.79x - 1.2566, R^2 = 0.5797). However, overall results demonstrate a weak positive correlation for data from both studied outcrop successions. Comparable ranges of preserved grainflow thicknesses measured from sets of known thickness were also demonstrated by Howell & Mountney (2001), whose results concluded that there was no apparent significant relationship between preserved set thickness and grainflow thickness for the Cretaceous Etjo Formation of Namibia. Plotting preserved set thicknesses against grainflow thicknesses does not necessarily reveal an obvious correlation for several reasons (Figure 10): (i) set thickness is a function of not only bedform size (wavelength), but also angle-of-climb and set-thickness data collected from multiple eolian successions or from different geographic locations or stratigraphic levels within the same succession will be partly dictated by bedforms that locally climbed at different angles (Figure 10a); (ii) values of set thicknesses determined from two-dimensional outcrops or from one-dimensional core do not necessarily represent the maximum thickness of a set since they might be clipping the edges of troughs that are significantly thicker in their central parts (Figure 10b); (iii) because preserved grainflow units thin and pinch-out laterally, two-dimensional outcrops and one-dimensional core might be clipping the ‘thin’ edges of grainflow units, thereby not recording their true maximum thickness (Figure 10c); (iv) sets might only preserve the basal-most toes of grainflow units, which typically thin and pinch-out in the lower parts of dune lee slopes as the angle of inclination of the slope decreases (Figure 10d) where packages of wind-ripple strata become dominant. Such situations most commonly arise when seasonally-reversing wind regimes encourage the development of a gently inclined dune plinth at the base of the lee slope (e.g. Rubin, 1987). For these reasons, when analyzing grainflow units in core data for the purpose of reconstructing likely bedform architecture, it is preferable to record data from the thickest sets that are likely most representative of a penetration through the centers of troughs. Within these, the thickest-preserved grainflow units will most closely reflect the maximum developed grainflow thickness, which might provide an indicator of lee slope length and therefore bedform height and overall size; thinner grainflow units will likely record examples where the well bore has intersected grainflows at points close to either their lateral or downslope margins.

The Cedar Mesa Sandstone offers the opportunity to examine this problem in more detail because the overall succession in both the erg center setting (e.g. Mile 75 of White Canyon) and in the erg margin setting (e.g. Squaw Butte) is divided into a number of separate eolian erg sequences each bounded both above and below by regionally extensive deflationary supersurfaces (Loope, 1985; Mountney & Jagger, 2004; Mountney 2006b). This partitioning into a series of stacked supersurface-bounded eolian sequences means that reliable estimates can be made of both the angle of climb of sets and of original dune wavelength. This provides the basis for a method with which to demonstrate how preserved set thickness is related to grainflow thickness.

Preserved set thicknesses plotted against grainflow thicknesses for a number of dune sequences in the erg center and lateral erg margin areas of the Cedar Mesa Sandstone are shown in Figure 11 ($y = 0.2614e^{99.347x}$, $R^2 = 0.6238$). The scatter in the data is less than that shown for the plot in Figure 9 for several reasons: (i) set thicknesses were determined from the centers of troughs (i.e. at their point of maximum thickness), which could be reliantly and consistently picked because of the exceptionally high-quality nature of the outcrop; (ii) for each set examined, 10 grainflows units were measured at their point of *maximum* thickness and the mean of these 10 values was recorded so as to negate the effects of thinning and pinching of grainflow units at their lateral and downslope margins.

Results from the eight individual eolian sequences examined and plotted on Figure 11 demonstrate that each exhibits a strong positive correlation between preserved set thickness and grainflow thickness *but* considerable scatter exists *between* each separate eolian sequence if the dataset is considered in its entirety. The origin of the scatter in these data arises partly because preserved set thickness is a function of both angle-of-climb and original bedform wavelength, which varied between each studied eolian sequence. Additionally, grainflow thickness is also known to vary as a function of slipface length, with thicker grainflows developing on longer slipfaces associated with larger bedforms (Kocurek & Dott, 1981). Thus, the strong positive correlation between preserved set thickness and grainflow thickness *within* each sequence indicates a direct relationship between grainflow thickness and bedform size (height), a relationship that is discussed in more detail in the next section.

Little overlap exists between the population of data describing reconstructed dune wavelength versus grainflow thickness from the Cedar Mesa and Navajo sandstones (Figure 7a). This demonstrates the importance of identifying and applying the most appropriate outcrop analogue when applying these types of data as a predictive tool with which to reconstruct likely bedform size from subsurface grainflow and set-thickness data recorded in core. Selection of an appropriate analogue should be based on the following: comparable preserved set thicknesses, comparable grainflow thickness distribution, proportion of facies which are comparable (grainflow, wind-ripple and grainfall), the arrangement of such facies, and the variability of foreset azimuth data. Overall, for sets thought to have been generated by dunes with similar wavelengths, the Navajo system has preserved significantly thinner grainflows than the Cedar Mesa system (Figure 7a), probably because the dunes of the two systems had markedly different morphologies with different slipface configurations.

Relationship between preserved grainflow thickness and original bedform size (dune height and wavelength)

A positive correlation has been demonstrated previously between dune slipface height and the thickness of grainflow units that are generated as a consequence of lee-slope avalanching down such slipfaces in modern, small-to-medium-sized dunes (Kocurek & Dott, 1981) and a similar relationship is noted for data collected as part of this study (Figure 12; Navajo Sandstone, $y = 1532.7x^{1.6006}$, $R^2 = 0.5965$; Kocurek

& Dott (1981) dataset, $y = 988.78x^{1.4796}$, $R^2 = 0.5555$). In their initial stages of development, sandflow avalanches thicken as an increasing volume of sand becomes entrained in the flow. For small and medium-sized dunes, grainflow deposits therefore become thicker with increasing slope length and, by implication, bedform height (Kocurek & Dott, 1981). Once fully developed, sandflow avalanches tend to attain an equilibrium thickness and individual preserved grainflow deposits rarely exceed 60 to 80 mm in thickness. Departures from the trend can arise for a number of reasons: (i) successive avalanches may be erosional at their base, such that previously emplaced avalanche deposits are partly reworked by later deposits, thereby reducing preserved grainflow thickness; (ii) deposits of individual grainflows tend to thin to a point of pinch-out at their downslope limit where they interfinger with packages of wind-ripple strata (e.g. Figure 1b), and it is these thinner grainflow deposits that have greater preservation potential in cases where bedform climbing at low angles allows for preservation of only the basal most parts of the original dune lee slope, or where grainflows do not extend to the base of the set (Figure 2b); (iii) the generally well sorted texture of eolian lee-slope deposits means that separate grainflow units might appear as a single apparently homogenous package of sand lacking any internal stratification and such deposits could be misinterpreted as a single anomalously thick avalanche deposit (e.g. “outliers” in Figure 7a and 9). Additionally, the effects of sediment compaction will influence comparisons between modern grainflow deposits and ancient preserved grainflow strata.

For many modern bedform types, dune height exhibits a positive correlation with bedform wavelength and spacing (e.g. Wilson, 1973; Lancaster, 1988; Figure 13; simple dunes, $y = 18.944x + 333.56$, $R^2 = 0.0885$; compound dunes, $y = 14.959x + 538.74$, $R^2 = 0.2854$; complex dunes, $y = 8.8474x + 268.74$, $R^2 = 0.3502$). It is therefore possible to demonstrate an indirect relationship between grainflow thicknesses preserved in ancient successions and original bedform height via this relationship between bedform wavelength and height (Figures 7a and 12). Importantly, this means that if grainflow thickness is known solely from subsurface core data, then a first-order estimate of both original bedform height and wavelength can tentatively be suggested. Furthermore, if both bedform wavelength and preserved set thickness are known, then a generalized estimate of the angle of climb of the succession can be made through a simple trigonometric relationship based on the approach outlined by Mountney & Thompson (2002). For this approach to be applied reasonably, care must be taken to determine which type of eolian bedform has been encountered in core, since mis-interpretation can result in errors of up to two orders of magnitude in reconstructed estimates of likely bedform spacing (Figure 13). Bedform type (simple, compound or complex) can potentially be deduced from a thick succession of core by ascribing different genetic significance to bounding surfaces of various types (e.g. interdune migration surfaces, superimposition surfaces, reactivation surfaces; see Brookfield, 1977, Rubin, 1987, and Rubin & Carter, 2006, for a summary of the technique).

The likely presence of an anomalously large bedform in the Cedar Mesa Sandstone at Mile 101 on Highway 95 (White Canyon) is supported by the relationships of Kocurek & Dott (1981), who suggest that original bedform size can be estimated based on proportions of grainfall strata to grainflow strata in preserved dune sets. Dune sets at Mile 101 preserve no grainfall strata and are composed almost entirely of grainflow strata (95%), with only minor intercalations of wind ripple strata (5%). The average grainflow thickness for this set at Mile 101 is 73 mm, 9mm greater than the average for other sets at this locality, again supporting the interpretation of a large bedform with an unusually high and long slipface.

Applied workflow for reconstruction of eolian architecture from core data

The series of empirical relationships identified as part of this study enable aspects of small-scale eolian stratigraphy observable in core to be related to larger-scale architectural elements; this potentially allows for the first-order reconstruction of the probable geometry and scale of aeolian bedforms responsible for giving rise preserved eolian accumulations directly from core data. Sedimentological attributes that can be measured directly from core (and in some cases wireline log) data include preserved set thickness, grainflow thickness, shape of dune toesets, rate of upward steepening of foresets within a set, and the distribution of primary lithofacies (grainflow, wind-ripple, and grainfall) within sets. Of these, this study has focused on the establishment of a series of empirical relationships based on measurements of preserved set thickness and grainflow thicknesses within the core sections.

For climbing eolian systems that have accumulated and preserved a succession through progressive climb of bedforms over one another, preserved set thickness is a function of both bedform size (wavelength) and the angle of system climb. Although preserved set thickness is only partly dependent on original bedform wavelength, there exists a positive linear relationship between preserved set thickness and reconstructed original bedform wavelength. Fundamental relationships exist between slipface height and thickness of grainflow packages preserved for small to medium dunes and these relationships established from this study of two ancient eolian successions compare closely to a similar relationship established previously for modern dunes (Kocurek & Dott, 1981). Preserved grainflow thicknesses observed in core can be used as a proxy (albeit with some reservations) to predict original bedform height, and therefore size (Figure 12), given that bedform height can be related to bedform wavelength for various types of dunes (Figure 13). If grainflow thickness is known, then an estimate of bedform wavelength can be made. If both original bedform wavelength and preserved set thickness are known, then the angle-of-climb of the succession can be determined using a simple trigonometric method in the absence of high-resolution seismic data. Although steeper angles of system climb preserve thicker sets for the accumulation of bedforms of a given wavelength, steeper angles of climb do not necessarily result from the migration and accumulation of larger dunes with longer wavelengths.

Conclusions

A suite of empirical relationships have been developed based on analysis of eolian outcrop data from parts of the Permian Cedar Mesa Sandstone and the Jurassic Navajo Sandstone in SE Utah. These relationships enable parameters measured directly from one-dimensional core to be related to larger scale eolian architectural elements observable in outcrop successions and underpin a simple method for reconstructing eolian geometry from one-dimensional subsurface datasets alone. However, care must exercised in the application of this technique: as with most statistical data derived from natural datasets, the spread of the data is, in many cases, considerable and significant; resulting in data distributions that yield best-fit trends with low R^2 values that are statistically weak. However, despite these shortcomings, relationships between measurements small- and larger-scale aspects of sedimentary architecture form the basis for the development of a predictive tool that can potentially be applied with care to subsurface datasets for elucidation of larger-scale sedimentary architecture and therefore for prediction of regional reservoir stratigraphic heterogeneity.

Acknowledgments

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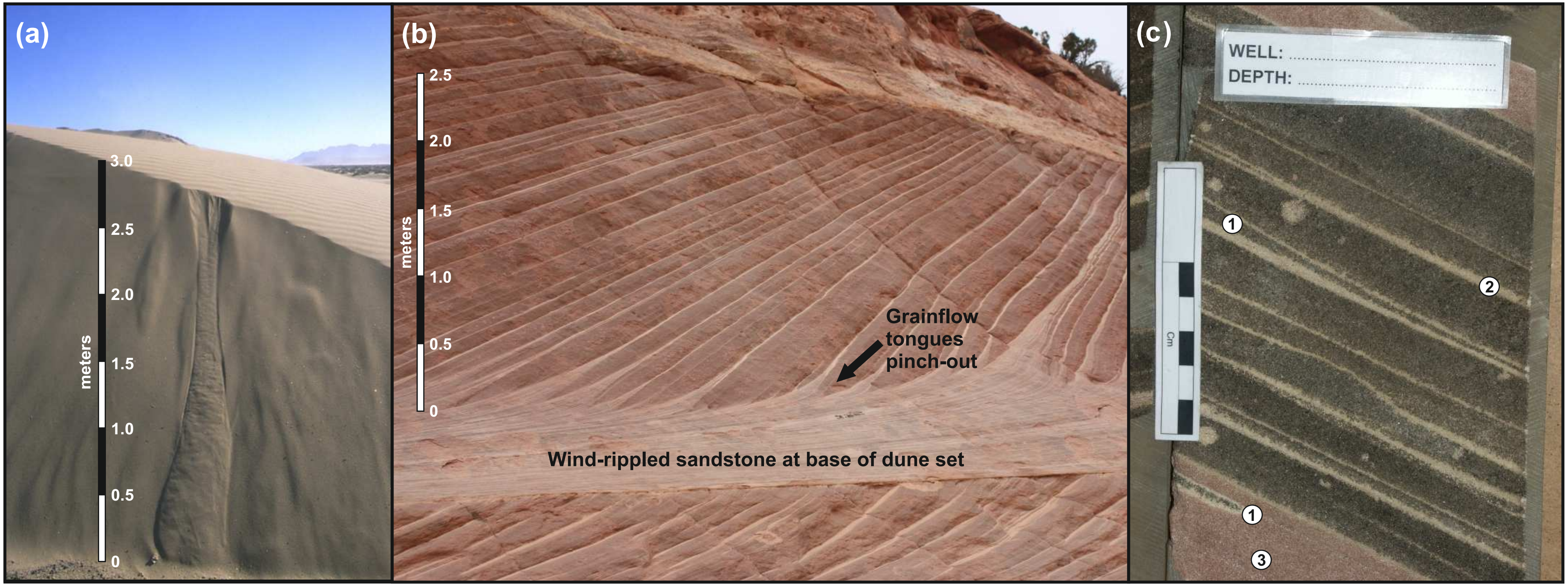
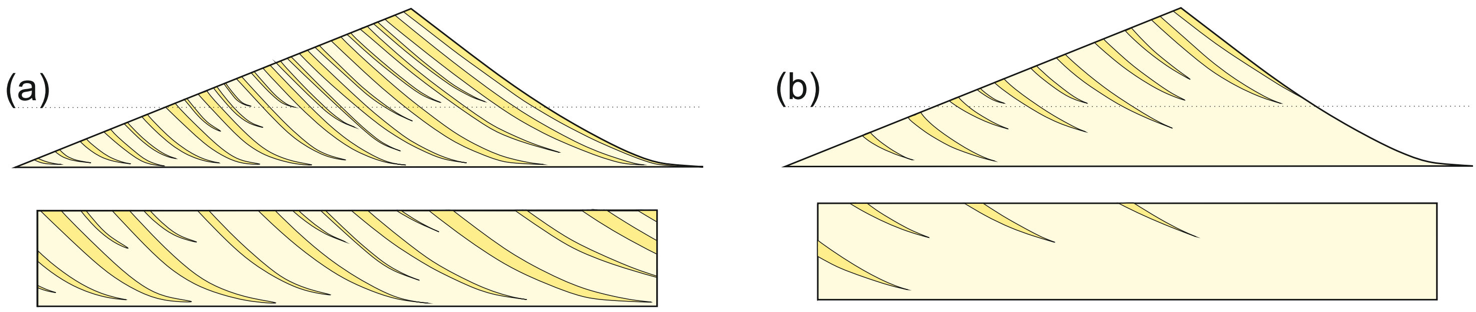
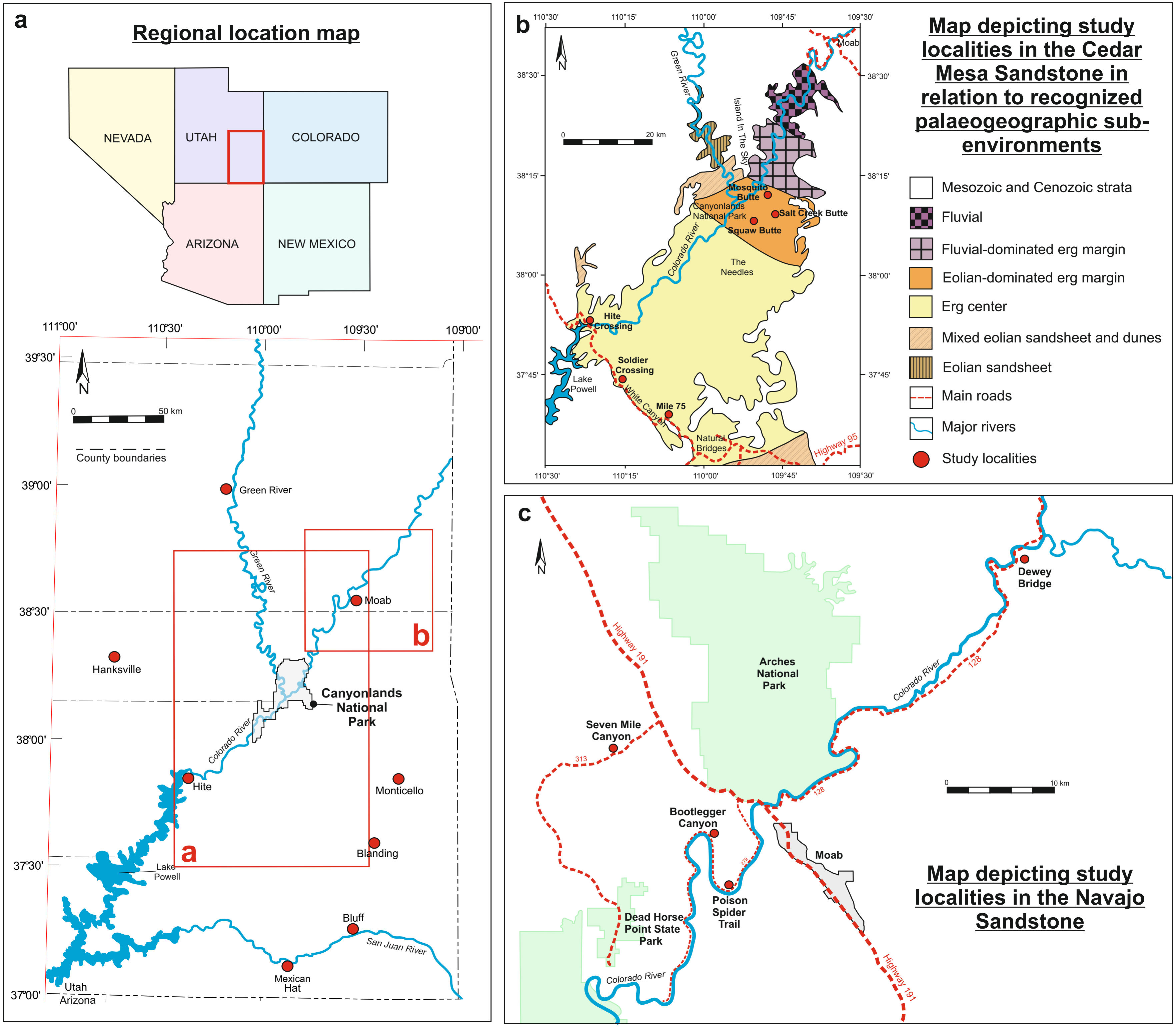
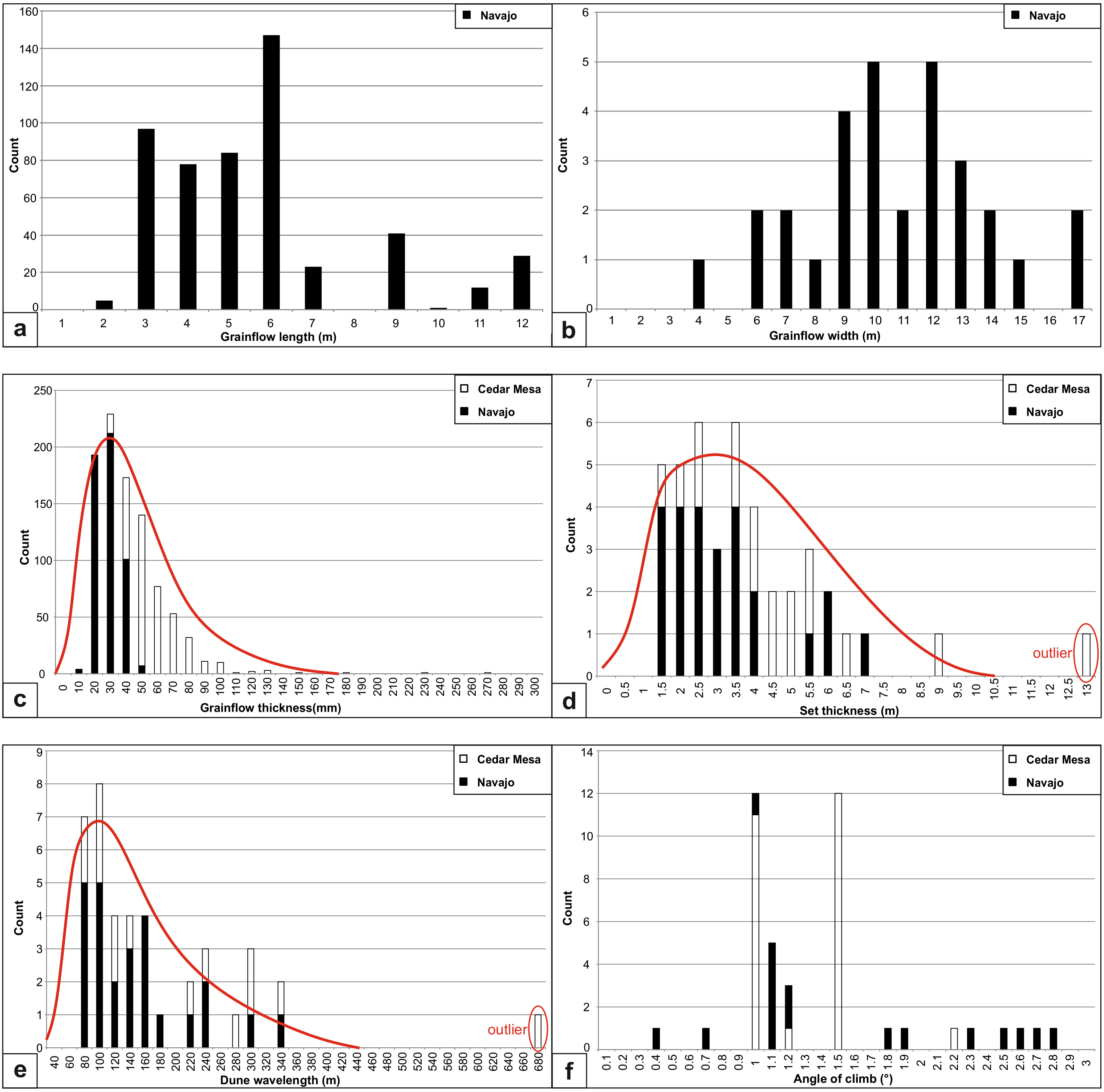
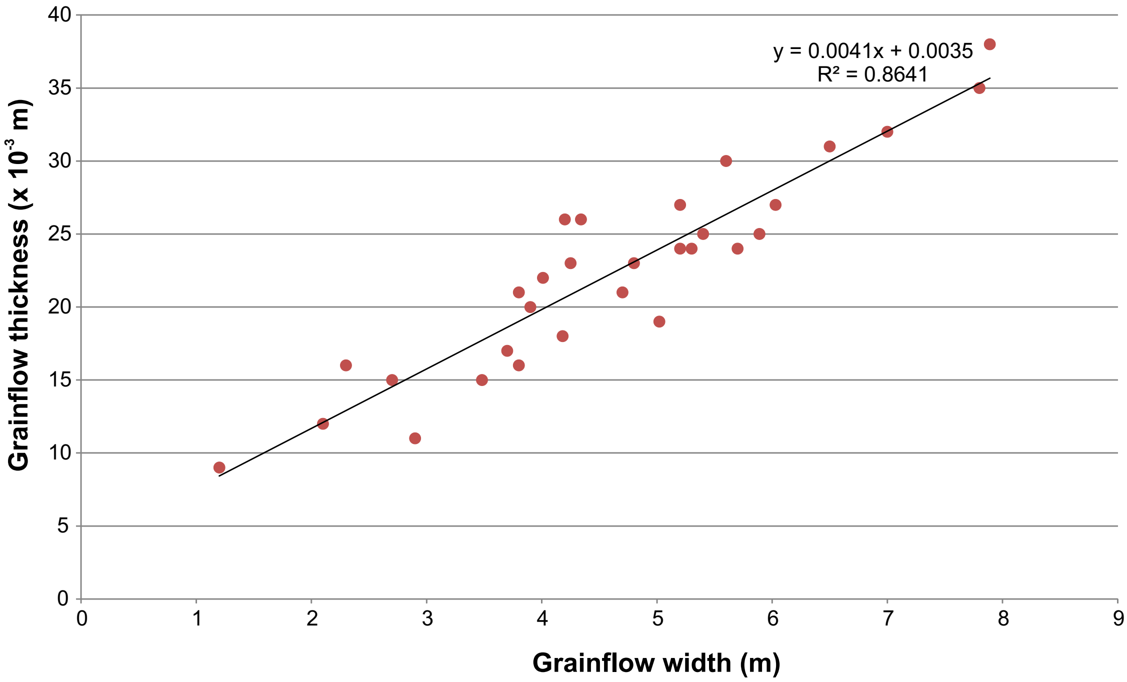

(a)
3.0
2.5
2.0
1.5
1.0
0.5
0
meters
(b)
2.5
2.0
1.5
1.0
0.5
0
meters
Grainflow tongues pinch-out
Wind-rippled sandstone at base of dune set
(c)
WELL:
DEPTH:
Cm
1
2
1
3


(a)
(b)

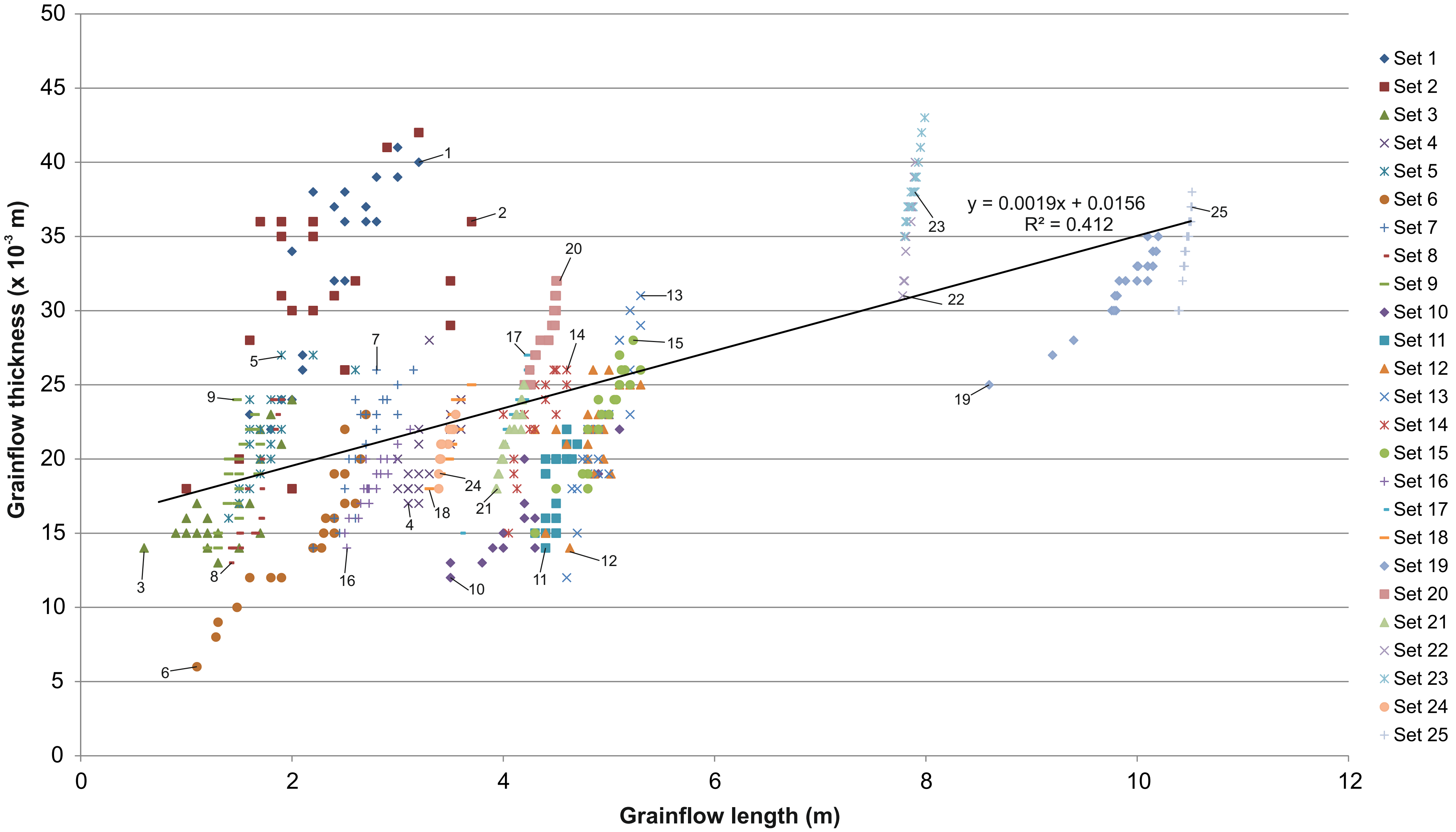


a
Regional location map
NEVADA
UTAH
COLORADO
ARIZONA
NEW MEXICO
County boundaries
50 km
Green River
Moab
Hanksville
Canyonlands National Park
Colorado River
Hite
Monticello
Blanding
Lake Powell
Bluff
San Juan River
Mexican Hat
Utah
Arizona
b
Map depicting study localities in the Cedar Mesa Sandstone in relation to recognized palaeogeographic sub-environments
Mesozoic and Cenozoic strata
Fluvial
Fluvial-dominated erg margin
Eolian-dominated erg margin
Erg center
Mixed eolian sandsheet and dunes
Eolian sandsheet
Main roads
Major rivers
Study localities
Island In The Sky
Mosquito Butte
Salt Creek Butte
Squaw Butte
The Needles
Hite Crossing
Soldier Crossing
White Canyon
Mile 75
Natural Bridges
Highway 95
20 km
c
Map depicting study localities in the Navajo Sandstone
Arches National Park
Highway 191
Seven Mile Canyon
Bootlegger Canyon
Poison Spider Trail
Dead Horse Point State Park
Dewey Bridge
10 km

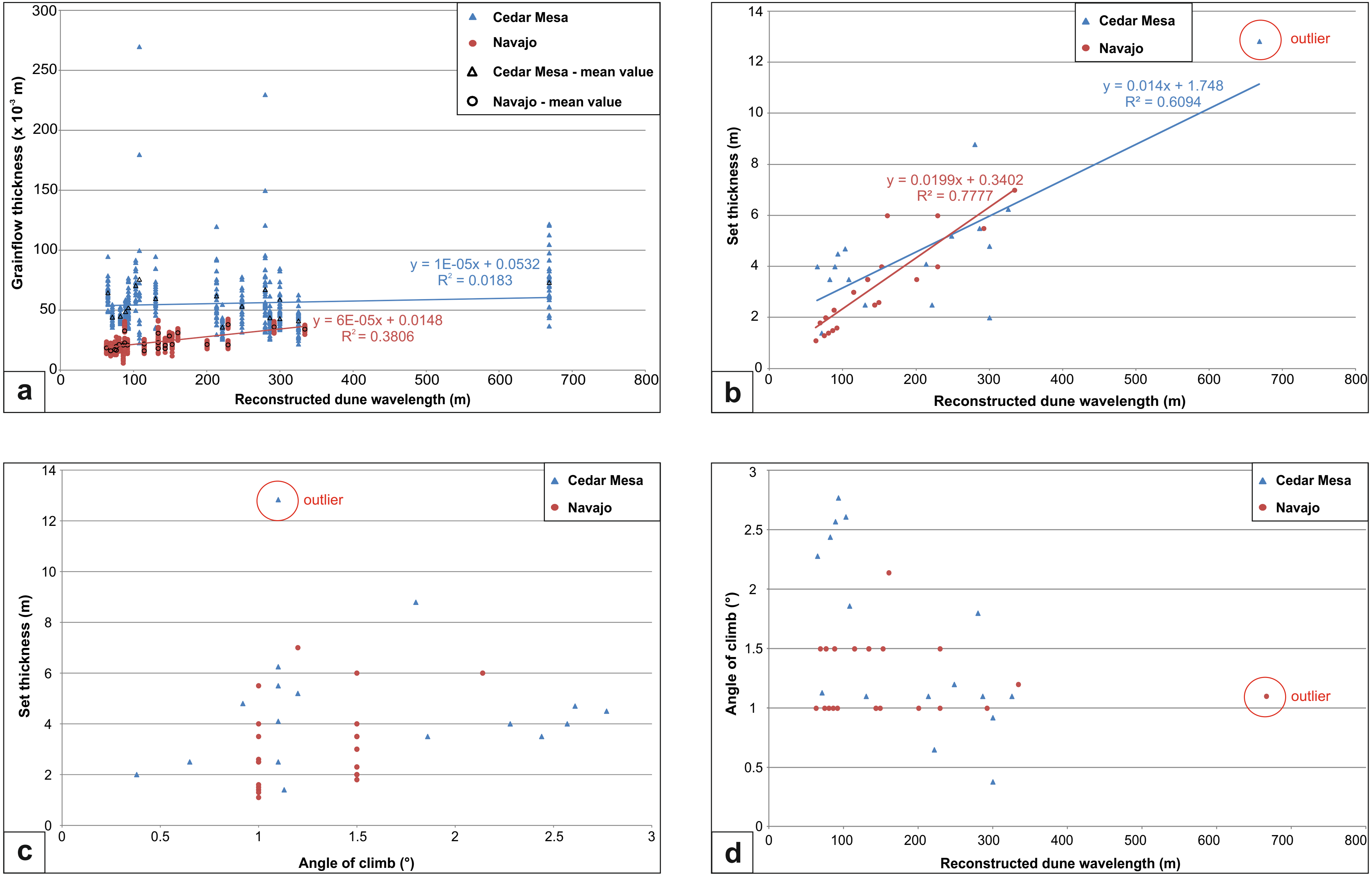

a
Navajo
Count
Grainflow length (m)
b
Navajo
Count
Grainflow width (m)
c
Cedar Mesa
Navajo
Count
Grainflow thickness(mm)
d
Cedar Mesa
Navajo
Count
Set thickness (m)
outlier
e
Cedar Mesa
Navajo
Count
Dune wavelength (m)
outlier
f
Cedar Mesa
Navajo
Count
Angle of climb (°)



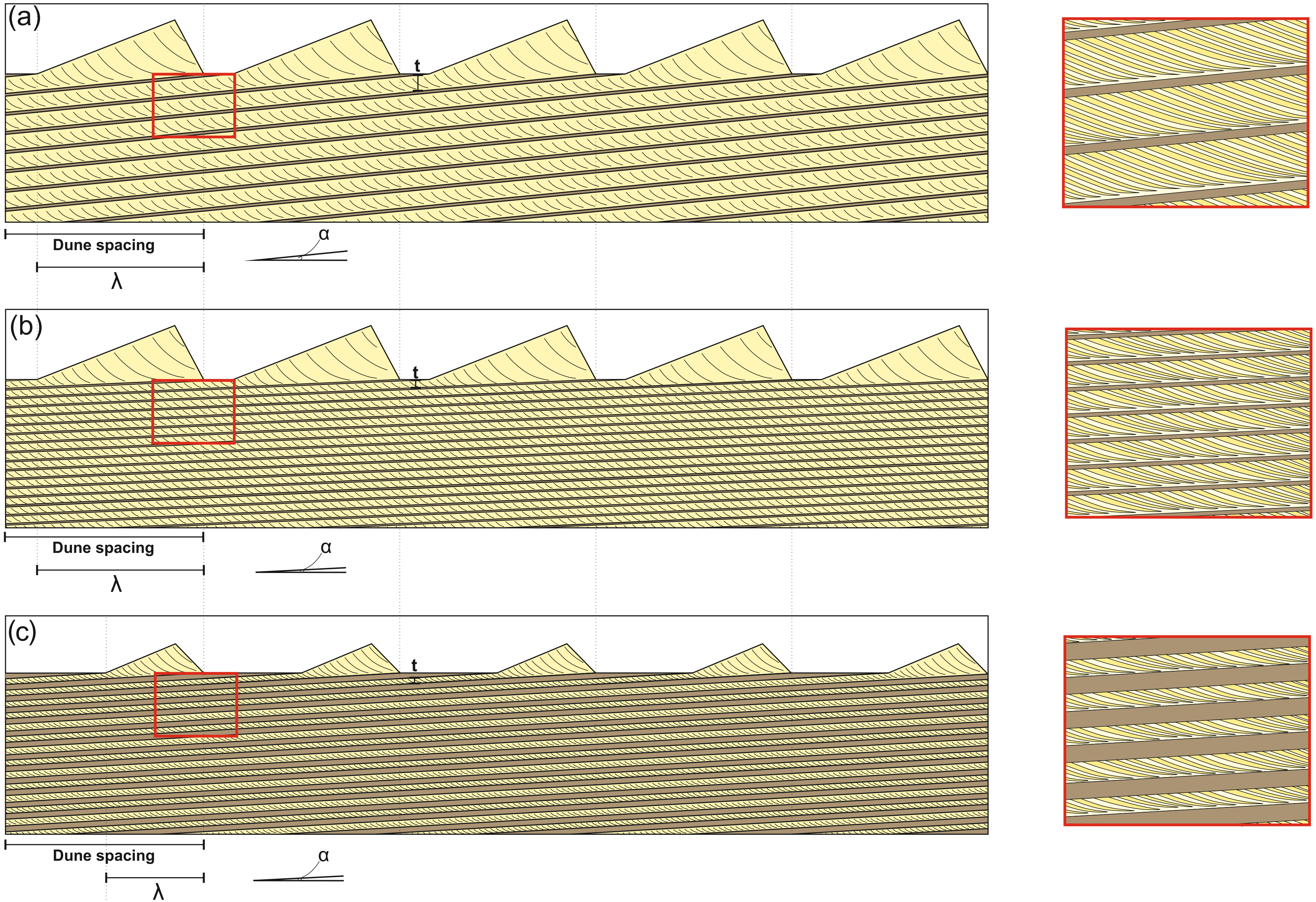
y = 0.0041x + 0.0035
R² = 0.8641
Grainflow thickness (x 10⁻³ m)
Grainflow width (m)
0
5
10
15
20
25
30
35
40
0
1
2
3
4
5
6
7
8
9



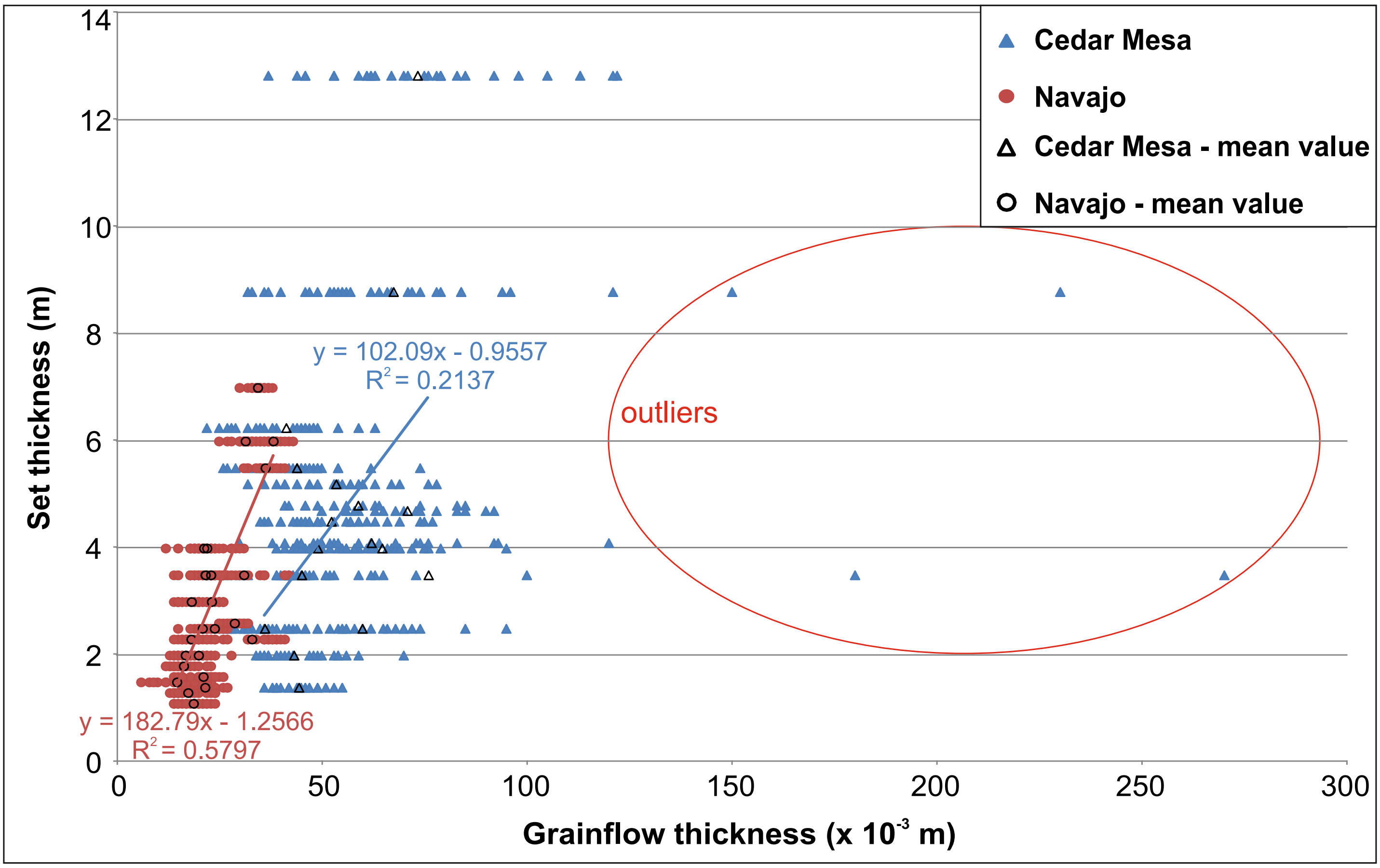
Grainflow thickness (x 10⁻³ m)
Grainflow length (m)
y = 0.0019x + 0.0156
R² = 0.412
Set 1
Set 2
Set 3
Set 4
Set 5
Set 6
Set 7
Set 8
Set 9
Set 10
Set 11
Set 12
Set 13
Set 14
Set 15
Set 16
Set 17
Set 18
Set 19
Set 20
Set 21
Set 22
Set 23
Set 24
Set 25



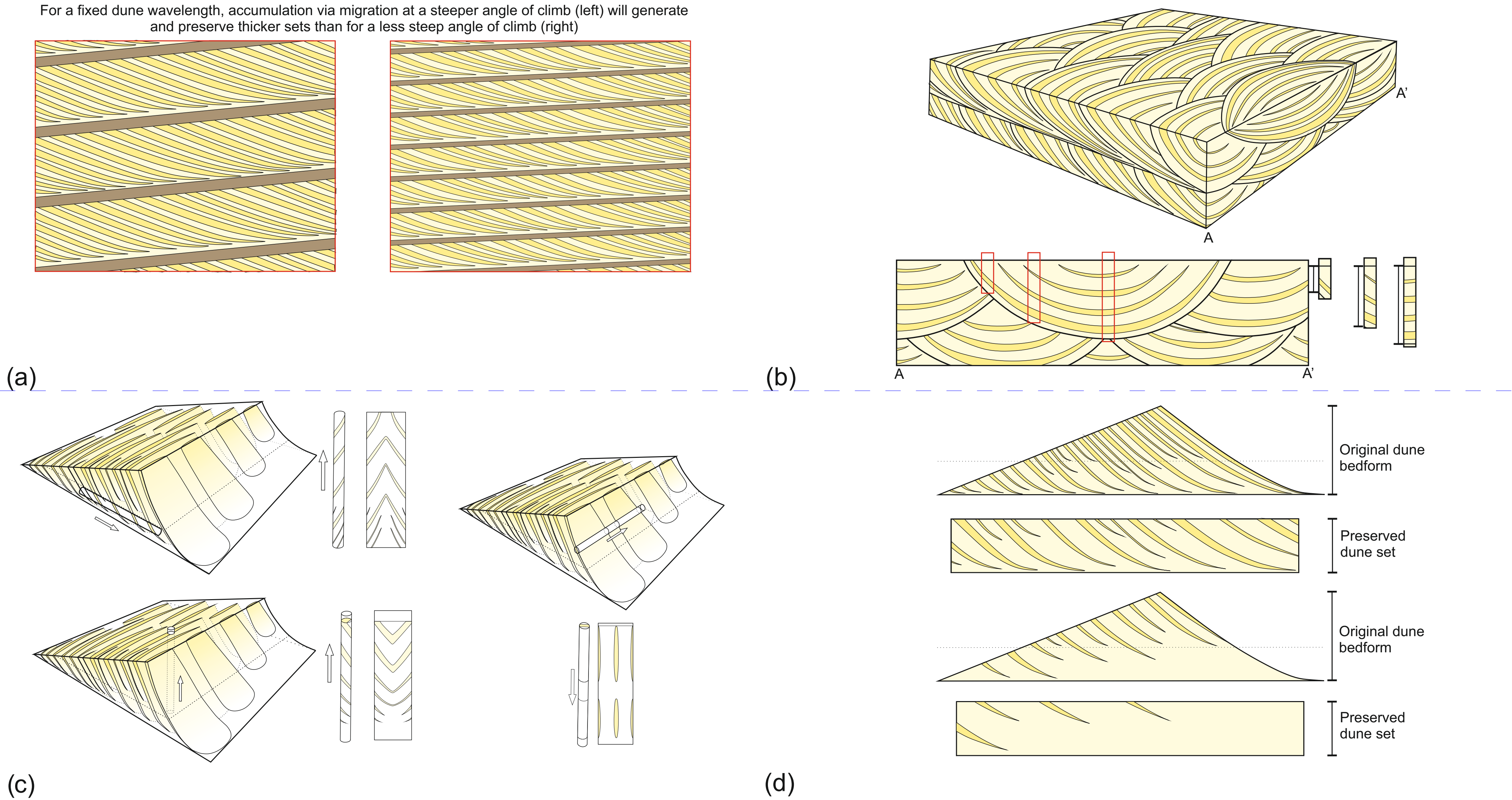
a
Grainflow thickness (x 10⁻³ m)
Reconstructed dune wavelength (m)
Cedar Mesa
Navajo
Cedar Mesa - mean value
Navajo - mean value
y = 1E-05x + 0.0532
R² = 0.0183
y = 6E-05x + 0.0148
R² = 0.3806
b
Set thickness (m)
Reconstructed dune wavelength (m)
outlier
y = 0.014x + 1.748
R² = 0.6094
y = 0.0199x + 0.3402
R² = 0.7777
c
Set thickness (m)
Angle of climb (°)
outlier
d
Angle of climb (°)
Reconstructed dune wavelength (m)
outlier

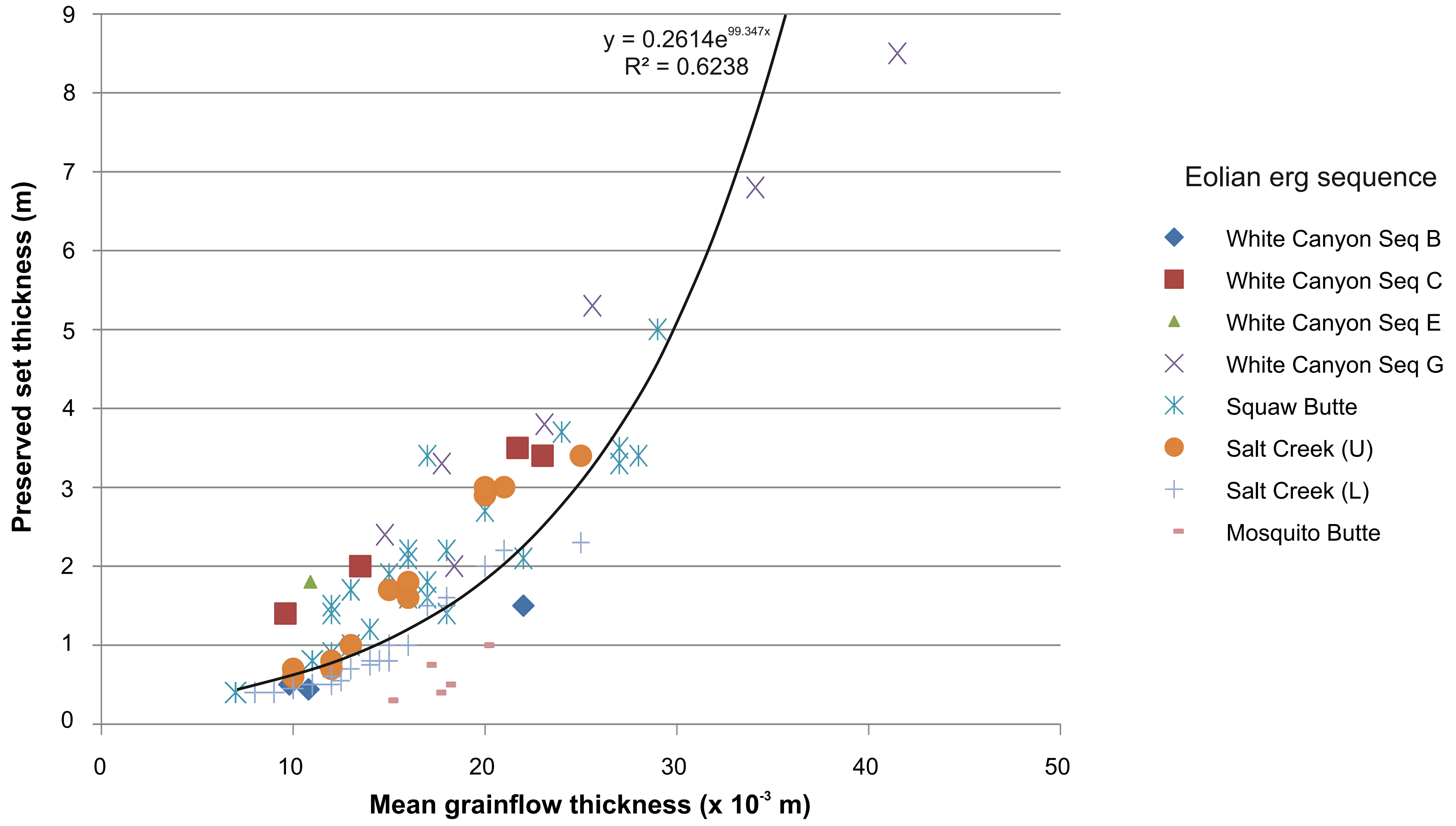


(a)
t
Dune spacing
λ
α
(b)
t
Dune spacing
λ
α
(c)
t
Dune spacing
λ
α

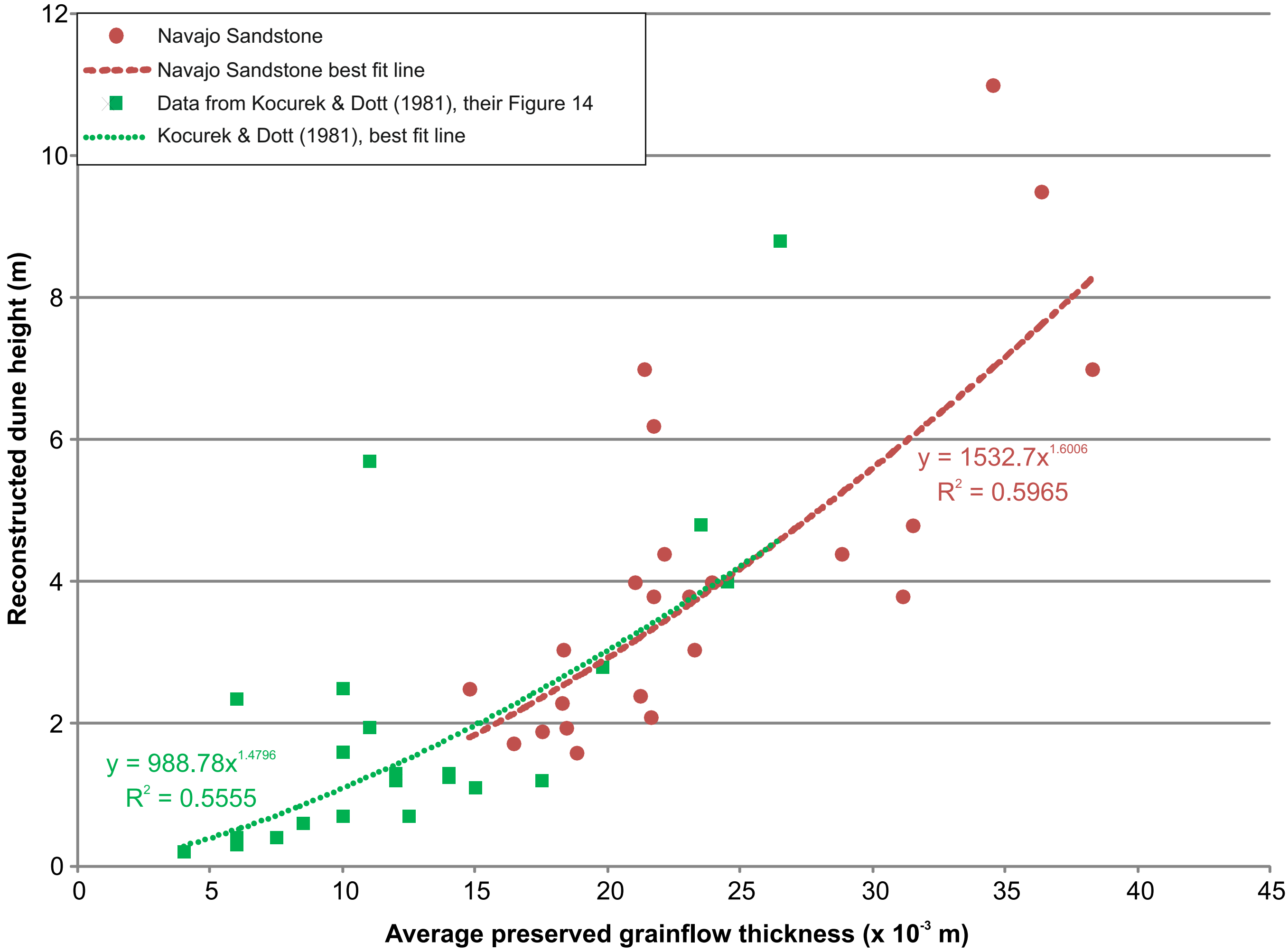


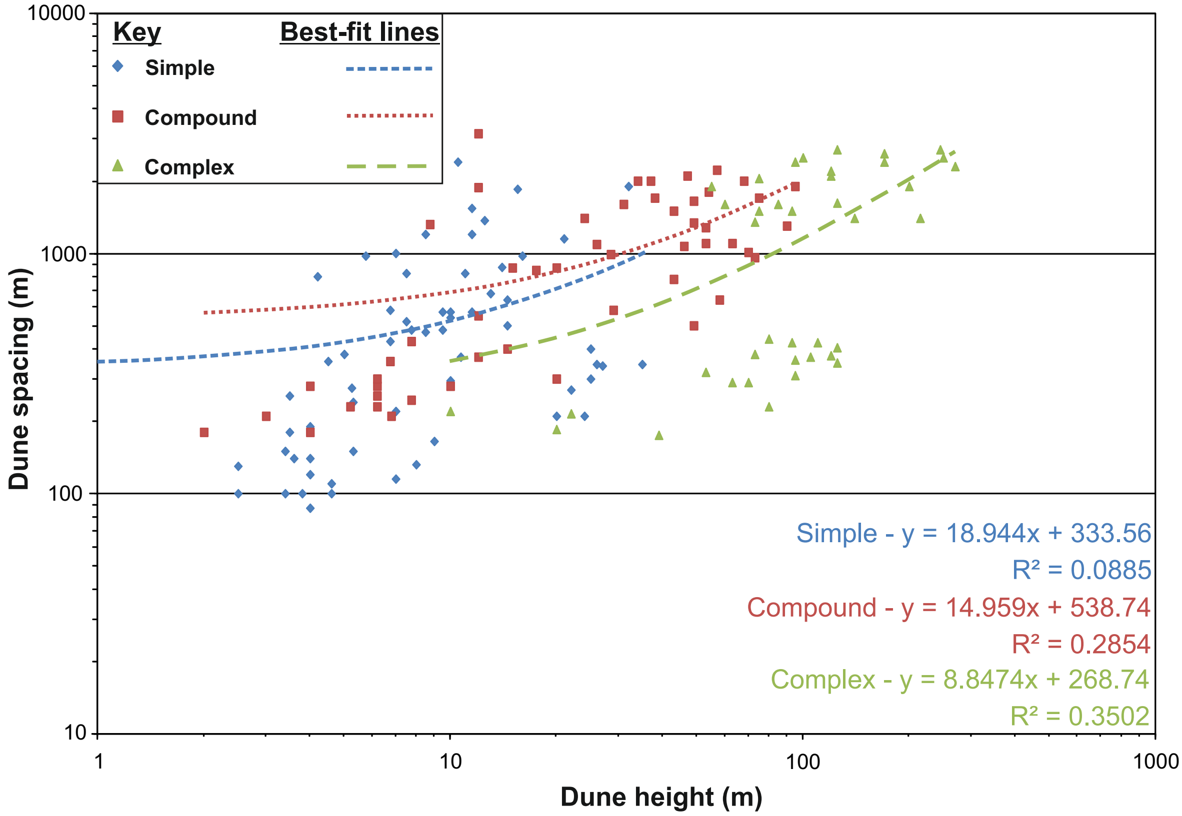
Cedar Mesa
Navajo
Cedar Mesa - mean value
Navajo - mean value
Set thickness (m)
Grainflow thickness (x 10^-3 m)
y = 102.09x - 0.9557
R² = 0.2137
y = 182.79x - 1.2566
R² = 0.5797
outliers


For a fixed dune wavelength, accumulation via migration at a steeper angle of climb (left) will generate and preserve thicker sets than for a less steep angle of climb (right)
(a)
A'
A
A
A'
(b)
(c)
Original dune bedform
Preserved dune set
Original dune bedform
Preserved dune set
(d)



y = 0.2614e^99.347x
R² = 0.6238
Preserved set thickness (m)
Mean grainflow thickness (x 10^-3 m)
0
1
2
3
4
5
6
7
8
9
0
10
20
30
40
50
Eolian erg sequence
White Canyon Seq B
White Canyon Seq C
White Canyon Seq E
White Canyon Seq G
Squaw Butte
Salt Creek (U)
Salt Creek (L)
Mosquito Butte


Navajo Sandstone
Navajo Sandstone best fit line
Data from Kocurek & Dott (1981), their Figure 14
Kocurek & Dott (1981), best fit line
y = 1532.7x^1.6006
R^2 = 0.5965
y = 988.78x^1.4796
R^2 = 0.5555
Reconstructed dune height (m)
Average preserved grainflow thickness (x 10^-3 m)
0
2
4
6
8
10
12
0
5
10
15
20
25
30
35
40
45



Key
Best-fit lines
Simple
Compound
Complex
Dune spacing (m)
Dune height (m)
10000
1000
100
10
1
10
100
1000
Simple - y = 18.944x + 333.56
R² = 0.0885
Compound - y = 14.959x + 538.74
R² = 0.2854
Complex - y = 8.8474x + 268.74
R² = 0.3502