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

3

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7 **Introduction**

8 Exploration and asset appraisal teams working in hydrocarbon companies typically  
9 have access to a varied set of data derived from core and well-log investigations  
10 relating to the sedimentology of deposits that make up potential subsurface reservoir  
11 intervals. However, at the sub-seismic scale, such datasets are almost exclusively  
12 one-dimensional in form, meaning that determination of sedimentary system type  
13 and elucidation of the three-dimensional geometry of the various architectural  
14 elements present in a reservoir volume, and their reciprocal relationships to one  
15 another, are usually highly subjective, resulting in potentially ambiguous  
16 interpretations and the postulation of equivocal depositional models (Kocurek 1988;  
17 Schenk, 1990; North & Prosser, 1993; North & Boering, 1999). This is especially true  
18 for eolian reservoir intervals where the ability to reliably correlate between  
19 neighboring wells – even those spaced only a few hundred meters apart, such as  
20 deviated sidetracks – is severely hindered by the absence of beds or bounding  
21 surfaces that can demonstrably be shown to serve as reliable markers for correlation  
22 purposes (Mountney, 2006a). In many cases, the inability to even establish the  
23 presence of features regarded to be reliable indicators of paleo-horizontal in

24 preserved eolian reservoir successions is highly problematic (Kocurek, 1988, 1991).  
25 This presents difficulties when estimating volumetric sand content and regional  
26 porosity-permeability distributions for eolian reservoirs, where the geometries of the  
27 various dune, interdune and extradune elements present within the overall three-  
28 dimensional rock volume are poorly constrained in the subsurface (e.g. Nagtegaal,  
29 1979; Heward, 1991).

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

47 Eolian dunes of different morphological type exhibit varying yet predictable  
48 configurations of primary depositional facies (principally packages of grainflow, wind-

49 ripple and grainfall strata) and associations of such facies (Hunter, 1977a, b, 1981;  
50 Kocurek & Dott, 1981). The distribution of associations of these facies tends to vary  
51 predictably over the surface of individual modern eolian bedforms as a function of  
52 the various eolian processes that operate on the flank, lee-slope, stoss-slope and  
53 brink areas of bedforms (Hunter, 1977a), meaning that primary lithological  
54 characteristics such as grain-size distribution, grain packing, and styles of small-  
55 scale lamination are also predictable (Livingstone, 1987).

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

69 Importantly, accumulation of sets of eolian strata via the climbing of bedforms over  
70 one another means that typically only the lowermost flanks of migrating bedforms  
71 undergo accumulation and preservation into the long-term rock record, whereas the  
72 upper parts of bedforms (in most cases the upper 90% or more of a bedform) are  
73 truncated by the advance of the following bedform in the train (Rubin & Carter,

74 2006), with the majority of the original dune sediment being reworked (Figure 2).  
75 Thus, the proportion and distribution of primary lithofacies preserved in successions  
76 in the ancient record does not necessarily reflect the proportion and distribution of  
77 primary lithofacies present in modern bedforms. Care must therefore be exercised  
78 when using modern bedforms as analogues with which to make predictions about  
79 likely facies distributions in reservoir successions. Methods for the accurate  
80 prediction and characterization of zones of good reservoir quality in subsurface  
81 eolian successions require a clear understanding of the geometry of the various  
82 preserved architectural elements and the distribution of packages of facies  
83 associated within these elements.

84 Architectural elements (i.e. three-dimensional sediment bodies with specific internal  
85 facies characteristics) form the building blocks of eolian reservoir successions and,  
86 in most examples, both the elements themselves and the lithofacies of which they  
87 are composed internally exhibit a strong preferred directional heterogeneity due to  
88 the inherent preferred orientation of layering of laminations and beds of facies, often  
89 in a complex nested manner (Weber, 1987; Chandler et al., 1989; Krystinik, 1990).  
90 Understanding the detailed arrangement of the style of heterogeneity present in  
91 these elements is crucial for reservoir prediction as this exerts a primary control on  
92 porosity and permeability structure within eolian reservoirs and therefore dictates  
93 production flow rates and patterns within complex eolian reservoir bodies  
94 (Nagtegaal, 1979; Heward, 1991; Ellis, 1993; Stanistreet & Stollhofen, 2002; Garden  
95 et al., 2005; Bloomfield et al., 2006). In most eolian hydrocarbon plays, it is  
96 particularly important to target those intervals within a reservoir that contain a high  
97 proportion of grainflow laminae – the deposits of avalanching down dune lee slopes  
98 – as these tend to form packages of well-sorted, loosely-packed sandstone with

99 permeabilities that are typically one or more orders of magnitude greater than those  
100 in packages of grainfall and wind-ripple strata that dominate in other eolian elements  
101 (Chandler et al., 1989; Prosser & Maskall, 1993; Howell & Mountney, 2001).

## 102 **Background**

103 Since the late 1970s, considerable eolian sedimentological research has focused on  
104 large scale stratigraphic relationships and the development of sequence stratigraphic  
105 models with which to account for the origin of the eolian record in terms of external  
106 controls on sedimentation (e.g. Brookfield, 1977; Kocurek, 1988; Kocurek &  
107 Havholm, 1993; Mountney, 2012). As a result of this emphasis, a wide variety of data  
108 have been published relating to large-scale stratigraphic architectures preserved in a  
109 number of ancient eolian successions (e.g. Glennie & Provan, 1990; Herries, 1993;  
110 Mountney & Thompson, 2002; Mountney & Jagger, 2004; Taggart et al., 2010).  
111 However, there remain relatively few studies that have investigated the sedimentary  
112 style of small-scale dune elements and the arrangement of facies present within  
113 preserved eolian sets originating from the migration of different types of eolian  
114 bedforms (Ellwood et al., 1975; Hunter, 1977a, b; Kocurek & Dott, 1981; Fryberger &  
115 Schenk, 1988). Although some explanation has been offered to account for how  
116 such types of small-scale stratification impact on reservoir quality (Lindquist, 1988;  
117 Chandler et al., 1989; Prosser & Maskall, 1993; Cox, 1994; Howell & Mountney,  
118 2001; Stanistreet & Stollhofen, 2002; Garden et al., 2005; Bloomfield et al., 2006), an  
119 effective method to relate deposits seen in one-dimensional core to larger-scale  
120 architectural elements has yet to be fully developed.

121 Prediction of facies variability in three dimensions is a key requirement for  
122 quantitative reservoir characterization (e.g. Sweet et al., 1996; Fischer et al., 2007)

123 because it enables reliable predictions to be made of the characteristics of a  
124 subsurface eolian reservoir bodies such as the extent, type and pattern of  
125 distribution of heterogeneities away from the points of data control provided by  
126 subsurface wells (Pryor, 1973). For the majority of eolian reservoirs, production  
127 behavior and characteristics are primarily influenced and controlled by original  
128 sediment fabric (grain size distribution), though secondary alteration of sediment  
129 fabric by diagenesis is also important (e.g. Mou & Brenner, 1982). A method to  
130 enable the prediction of the spatial occurrence of the original depositional processes  
131 that occurred on dunes and in interdunes, and the resultant distribution of lithofacies  
132 in preserved eolian architectural elements is therefore essential (Lewis & Couples,  
133 1993).

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

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

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

173 which is an indicator of the periodicity with which the original bedforms undertook  
174 changes in lee-slope steepness, asymmetry, or migration direction (Rubin, 1987;  
175 Fryberger, 1993).

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

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

198 construction of reservoir models for the prediction of porosity-permeability  
199 distributions and likely flow properties.

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

## 209 **Data and Methods**

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

222 Primary measurements of eolian bedset architectures were made at each study  
223 locality to determine three-dimensional relationships present in the successions of  
224 eolian dune sets. Aspects of eolian architecture measured included: (i) maximum  
225 preserved set thicknesses for 42 individual trough cross-bedded sets exposed in  
226 orientations both parallel and perpendicular to eolian transport direction (itself  
227 determined through analysis of dip-azimuth data relating to grainflow deposits  
228 representative of accumulation on the slipface of the original bedforms) – care was  
229 taken to account for set-thickness variations arising from the curved nature of trough  
230 cross-bedded sets; (ii) geometries of packages of grainflow strata representative of  
231 individual lee-slope sand avalanches, including thickness (932 readings in total),  
232 width (30 readings in total) and length (517 readings in total); (iii) measurements of  
233 bedform wavelength (42 readings in total) determined in directions parallel to eolian  
234 paleo-transport mostly by the measurement of the spacing between the points at  
235 which successive interdune migration surfaces climb off basal supersurfaces that are  
236 themselves inferred to represent paleohorizontal surfaces (see Mounney & Howell,  
237 2000 and Mounney, 2006b for details of the methodology); (iv) measurements of  
238 angles of set climb (42 readings in total), determined trigonometrically in directions  
239 parallel to eolian paleo-transport (again determined through analysis of dip-azimuth  
240 data relating to grainflow deposits representative of accumulation on the slipface of  
241 the original bedforms) by evaluating the rate of rise of interdune migration surfaces  
242 relative to underlying supersurfaces (see Mounney, 2006b for methodology); (v)  
243 measurements of the rate of upward steepening of eolian dune toset deposits with  
244 increasing height above the base of sets (36 readings in total).

## 245 **Results**

## 246 Grainflow Geometry

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

## 261 Preserved Set Thickness

262 Preserved set thicknesses have been measured from the central axes of troughs  
263 (i.e. at the location of the thickest development of the set). The mean thicknesses of  
264 simple preserved sets (*sensu* McKee, 1979) of strata bounded by interdune  
265 migration bounding surfaces in the Navajo Sandstone and Cedar Mesa Sandstone  
266 are 3.10 m (standard deviation = 1.60; n = 25), and 4.71 m (standard deviation =  
267 2.72; n = 17), respectively (Figure 4d). For the Cedar Mesa Sandstone, measured  
268 set thicknesses are representative of the succession overall, though considerable  
269 variability exists in some locations. For the Navajo Formation, which is exposed over

270 large areas of Utah, Arizona and Colorado, preserved set thicknesses vary  
271 considerably and the sets measured as part of this study from parts of the  
272 succession exposed around the town of Moab, Utah, are not necessarily  
273 representative of the formation overall. Indeed, significantly thicker compound sets  
274 are known from other parts of this formation (see, for example, Herries, 1993 and  
275 Rubin, 1987), though these have not been examined for this study.

#### 276 Bedform Wavelength Reconstruction

277 Original dune wavelengths were mostly determined via direct measurement. In  
278 directions parallel to eolian paleo-transport, the spacing between the points at which  
279 successive interdune migration surfaces climb off basal supersurfaces that are  
280 themselves inferred to represent paleohorizontal surfaces is a measure of bedform  
281 spacing, where bedform spacing is defined as the bedform wavelength plus the  
282 additional component of width of any adjoining interdune flat. Additional calculations  
283 of original dune wavelengths were derived trigonometrically from estimates of set  
284 thicknesses and angles of climb: see Mountney & Howell (2000) for details of the  
285 method. The mean reconstructed dune bedform wavelengths in directions parallel to  
286 inferred eolian bedform migration direction for studied parts of the Navajo Sandstone  
287 and Cedar Mesa Sandstone are 138.26 m (standard deviation = 70.75; n = 25), and  
288 202.42 m (standard deviation = 159.19; n = 15), respectively (Figure 4e).

289 Based on relationships observed from Navajo Sandstone, where sets are seen to  
290 rise (climb) off supersurfaces, reconstructed dune bedforms are estimated to have  
291 had original wavelengths ranging from 80 to 340 m. The erg center region of the  
292 Cedar Mesa Sandstone exhibits a wider range of reconstructed dune wavelength  
293 values (65 m to 668 m). Overall, these data fall within the ranges determined

294 previously for eolian dunes of the Cedar Mesa Sandstone in the White Canyon  
295 region of SE Utah (Mountney, 2006b). However, one exception is Set 1 from Mile  
296 101 of Highway 95 (a 12.8 m-thick set climbing at an angle of 1.1°), which is  
297 estimated to represent the preserved deposit of a bedform that had an anomalously  
298 large wavelength of 668 m, considerably greater than values determined for other  
299 bedforms in the succession.

### 300 Angle of Climb

301 The Navajo Sandstone exhibits a narrow range of observed angles of climb, with the  
302 majority of sets climbing up through the stratigraphy in a downwind direction at  
303 angles between 1 to 1.5°. The mean angle of climb of studied sets in the Navajo  
304 Sandstone is 1.29° (standard deviation = 0.30; n = 25). Sets in the erg center region  
305 of the Cedar Mesa Sandstone reveal a wider range of climb angles, which were  
306 derived by Mountney (2006b, his Figure 12) trigonometrically from measurements of  
307 preserved set thicknesses and reconstructed original dune bedform wavelengths  
308 (the latter determined from the spacing between points where sets rise off  
309 supersurfaces which themselves define a paleohorizontal surface). The mean angle  
310 of climb of studied sets in the Cedar Mesa Sandstone is 1.54° (standard deviation =  
311 0.75; n = 17 (Figure 4f).

### 312 **Discussion**

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

317 Relationship between preserved grainflow thickness, length and width

318 Where the pattern of outcrop has allowed, for every grainflow unit measured in the  
319 Navajo Sandstone ( $n = 517$ ), the preserved thickness has been related to a  
320 corresponding grainflow length and width (Figures 5 & 6). In the Navajo Sandstone,  
321 measured grainflow widths exhibit a strong positive correlation with corresponding  
322 grainflow thickness (Figure 5;  $y = 0.0041x + 0.0035$ ;  $R^2 = 0.86$ ). The overall  
323 relationship between measured grainflow length and preserved grainflow thickness  
324 for sets in the Navajo Sandstone shows a positive correlation but with substantial  
325 scatter (Figure 6;  $y = 0.0019x + 0.0156$ ;  $R^2 = 0.41$ ). However, preserved grainflow  
326 thickness and length relationships from 25 *individual* sets are also depicted in Figure  
327 6 and strong positive correlations between preserved thickness and length exist in  
328 almost every case. Significantly, however, data from different sets plot in distinct  
329 and, in many cases, non-overlapping fields on the graph. Together, these  
330 observations suggest that, although a simple overall general relationship between  
331 grainflow thickness and grainflow length exists, data from individual sets each  
332 preserve grainflows with their own geometry and this likely reflects the shape of the  
333 slipface that developed on the lee of the dune at the time of sedimentation.

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

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

342 In both the Cedar Mesa Sandstone and the Navajo Sandstone, dune-sets generated  
343 by the migration and climb of larger bedforms (as determined by reconstructed  
344 estimates of longer wavelengths) preserve thicker grainflow units, though  
345 considerable spread exists between the data (Figure 7a; Cedar Mesa Sandstone;  $y =$   
346  $1E-05x + 0.0532$ ;  $R^2 = 0.02$ ; Navajo Sandstone;  $y = 6E-05x + 0.0148$ ;  $R^2 = 0.38$ ).  
347 Although the studied dune-sets from the Navajo Sandstone are indicative of original  
348 bedforms characterized by generally smaller wavelengths than those of the Cedar  
349 Mesa Sandstone, considerable overlap in original bedform wavelength exists. Of the  
350 preserved dune-sets for which estimates of reconstructed original bedform  
351 wavelengths are similar, examples from the Navajo Sandstone are characterized by  
352 distinctly thinner grainflow units than those from the Cedar Mesa Sandstone (Figure  
353 7a). This could have arisen due to a number of reasons: different dune types,  
354 different slipface configurations, variations in dune-plinth shape, variations in dune  
355 height (a likely influence on slipface length) despite bedforms having similar  
356 wavelengths, and different grain-size distributions or grain-shape properties giving  
357 rise to different types of avalanches down the dune lee slopes. The overall  
358 correlation between preserved grainflow thickness and original bedform wavelength  
359 represents a possible method for making a first-order estimate of original bedform  
360 size from subsurface data since the former can be measured directly from core.

361 However, the spread of the data and the different trends in the data for the Navajo  
362 and Cedar Mesa sandstones demonstrate that it is essential to pick an appropriate

363 analogue when making extrapolations regarding larger-scale architecture from core  
364 data.

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

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

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

#### 396 Relationship between preserved set thickness and grainflow thickness

397 For each set for which a thickness has been measured, 15 to 25 grainflow  
398 thicknesses have also been measured; the relationship between preserved set  
399 thickness and grainflow thickness shows significant scatter (Figure 9; Cedar Mesa  
400 Sandstone,  $y = 102.09x - 0.9557$ ,  $R^2 = 0.2137$ ; Navajo Sandstone,  $y = 182.79x -$   
401  $1.2566$ ,  $R^2 = 0.5797$ ). However, overall results demonstrate a weak positive  
402 correlation for data from both studied outcrop successions. Comparable ranges of  
403 preserved grainflow thicknesses measured from sets of known thickness were also  
404 demonstrated by Howell & Mountney (2001), whose results concluded that there was  
405 no apparent significant relationship between preserved set thickness and grainflow  
406 thickness for the Cretaceous Etjo Formation of Namibia. Plotting preserved set  
407 thicknesses against grainflow thicknesses does not necessarily reveal an obvious  
408 correlation for several reasons (Figure 10): (i) set thickness is a function of not only  
409 bedform size (wavelength), but also angle-of-climb and set-thickness data collected  
410 from multiple eolian successions or from different geographic locations or

411 stratigraphic levels within the same succession will be partly dictated by bedforms  
412 that locally climbed at different angles (Figure 10a); (ii) values of set thicknesses  
413 determined from two-dimensional outcrops or from one-dimensional core do not  
414 necessarily represent the maximum thickness of a set since they might be clipping  
415 the edges of troughs that are significantly thicker in their central parts (Figure 10b);  
416 (iii) because preserved grainflow units thin and pinch-out laterally, two-dimensional  
417 outcrops and one-dimensional core might be clipping the 'thin' edges of grainflow  
418 units, thereby not recording their true maximum thickness (Figure 10c); (iv) sets  
419 might only preserve the basal-most toes of grainflow units, which typically thin and  
420 pinch-out in the lower parts of dune lee slopes as the angle of inclination of the slope  
421 decreases (Figure 10d) where packages of wind-ripple strata become dominant.  
422 Such situations most commonly arise when seasonally-reversing wind regimes  
423 encourage the development of a gently inclined dune plinth at the base of the lee  
424 slope (e.g. Rubin, 1987). For these reasons, when analyzing grainflow units in core  
425 data for the purpose of reconstructing likely bedform architecture, it is preferable to  
426 record data from the thickest sets that are likely most representative of a penetration  
427 through the centers of troughs. Within these, the thickest-preserved grainflow units  
428 will most closely reflect the maximum developed grainflow thickness, which might  
429 provide an indicator of lee slope length and therefore bedform height and overall  
430 size; thinner grainflow units will likely record examples where the well bore has  
431 intersected grainflows at points close to either their lateral or downslope margins.

432 The Cedar Mesa Sandstone offers the opportunity to examine this problem in more  
433 detail because the overall succession in both the erg center setting (e.g. Mile 75 of  
434 White Canyon) and in the erg margin setting (e.g. Squaw Butte) is divided into a  
435 number of separate eolian erg sequences each bounded both above and below by

436 regionally extensive deflationary supersurfaces (Loope, 1985; Mountney & Jagger,  
437 2004; Mountney 2006b). This partitioning into a series of stacked supersurface-  
438 bounded eolian sequences means that reliable estimates can be made of both the  
439 angle of climb of sets and of original dune wavelength. This provides the basis for a  
440 method with which to demonstrate how preserved set thickness is related to  
441 grainflow thickness.

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

452 Results from the eight individual eolian sequences examined and plotted on Figure  
453 11 demonstrate that each exhibits a strong positive correlation between preserved  
454 set thickness and grainflow thickness *but* considerable scatter exists *between* each  
455 separate eolian sequence if the dataset is considered in its entirety. The origin of the  
456 scatter in these data arises partly because preserved set thickness is a function of  
457 both angle-of-climb and original bedform wavelength, which varied between each  
458 studied eolian sequence. Additionally, grainflow thickness is also known to vary as a  
459 function of slipface length, with thicker grainflows developing on longer slipfaces  
460 associated with larger bedforms (Kocurek & Dott, 1981). Thus, the strong positive

461 correlation between preserved set thickness and grainflow thickness *within* each  
462 sequence indicates a direct relationship between grainflow thickness and bedform  
463 size (height), a relationship that is discussed in more detail in the next section.

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

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

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

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

506 For many modern bedform types, dune height exhibits a positive correlation with  
507 bedform wavelength and spacing (e.g. Wilson, 1973; Lancaster, 1988; Figure 13;  
508 simple dunes,  $y = 18.944x + 333.56$ ,  $R^2 = 0.0885$ ; compound dunes,  $y = 14.959x +$   
509  $538.74$ ,  $R^2 = 0.2854$ ; complex dunes,  $y = 8.8474x + 268.74$ ,  $R^2 = 0.3502$ ). It is

510 therefore possible to demonstrate an indirect relationship between grainflow  
511 thicknesses preserved in ancient successions and original bedform height via this  
512 relationship between bedform wavelength and height (Figures 7a and 12).  
513 Importantly, this means that if grainflow thickness is known solely from subsurface  
514 core data, then a first-order estimate of both original bedform height and wavelength  
515 can tentatively be suggested. Furthermore, if both bedform wavelength and  
516 preserved set thickness are known, then a generalized estimate of the angle of climb  
517 of the succession can be made through a simple trigonometric relationship based on  
518 the approach outlined by Mountney & Thompson (2002). For this approach to be  
519 applied reasonably, care must be taken to determine which type of eolian bedform  
520 has been encountered in core, since mis-interpretation can result in errors of up to  
521 two orders of magnitude in reconstructed estimates of likely bedform spacing (Figure  
522 13). Bedform type (simple, compound or complex) can potentially be deduced from a  
523 thick succession of core by ascribing different genetic significance to bounding  
524 surfaces of various types (e.g. interdune migration surfaces, superimposition  
525 surfaces, reactivation surfaces; see Brookfield, 1977, Rubin, 1987, and Rubin &  
526 Carter, 2006, for a summary of the technique).

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

534 the average for other sets at this locality, again supporting the interpretation of a  
535 large bedform with an unusually high and long slipface.

#### 536 Applied workflow for reconstruction of eolian architecture from core data

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

548 For climbing eolian systems that have accumulated and preserved a succession  
549 through progressive climb of bedforms over one another, preserved set thickness is  
550 a function of both bedform size (wavelength) and the angle of system climb.  
551 Although preserved set thickness is only partly dependent on original bedform  
552 wavelength, there exists a positive linear relationship between preserved set  
553 thickness and reconstructed original bedform wavelength. Fundamental relationships  
554 exist between slipface height and thickness of grainflow packages preserved for  
555 small to medium dunes and these relationships established from this study of two  
556 ancient eolian successions compare closely to a similar relationship established  
557 previously for modern dunes (Kocurek & Dott, 1981). Preserved grainflow

558 thicknesses observed in core can be used as a proxy (albeit with some reservations)  
559 to predict original bedform height, and therefore size (Figure 12), given that bedform  
560 height can be related to bedform wavelength for various types of dunes (Figure 13).  
561 If grainflow thickness is known, then an estimate of bedform wavelength can be  
562 made. If both original bedform wavelength and preserved set thickness are known,  
563 then the angle-of-climb of the succession can be determined using a simple  
564 trigonometric method in the absence of high-resolution seismic data. Although  
565 steeper angles of system climb preserve thicker sets for the accumulation of  
566 bedforms of a given wavelength, steeper angles of climb do not necessarily result  
567 from the migration and accumulation of larger dunes with longer wavelengths.

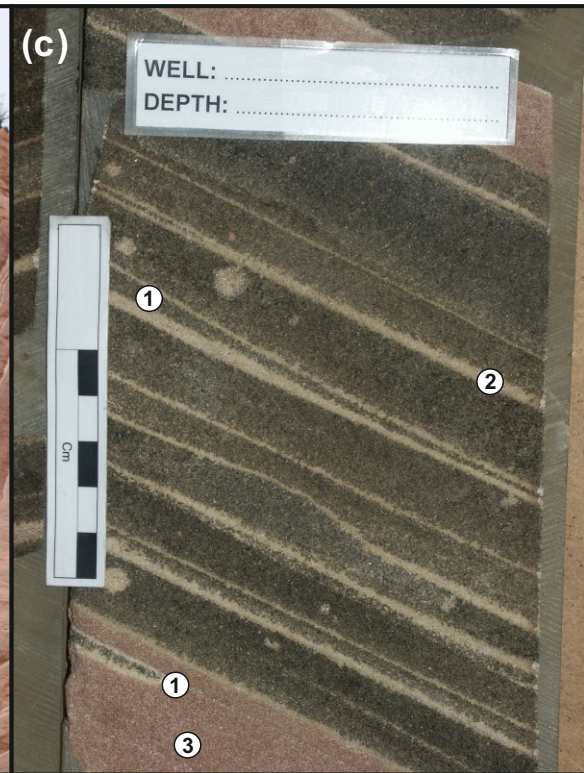
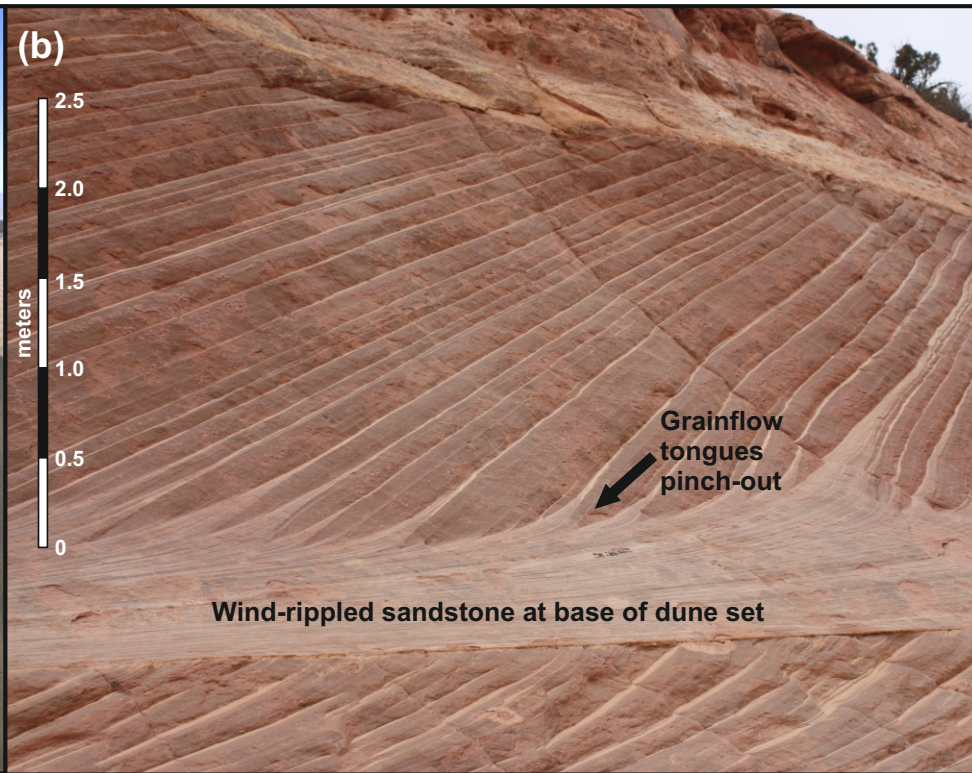
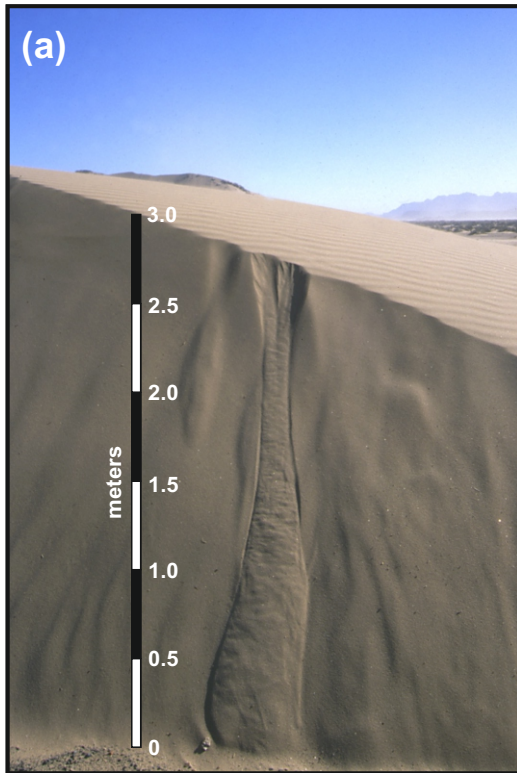
## 568 **Conclusions**

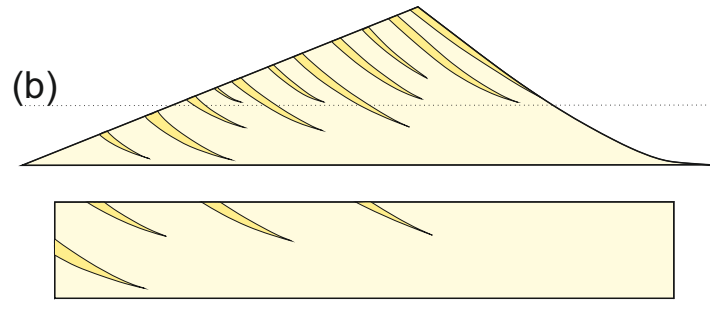
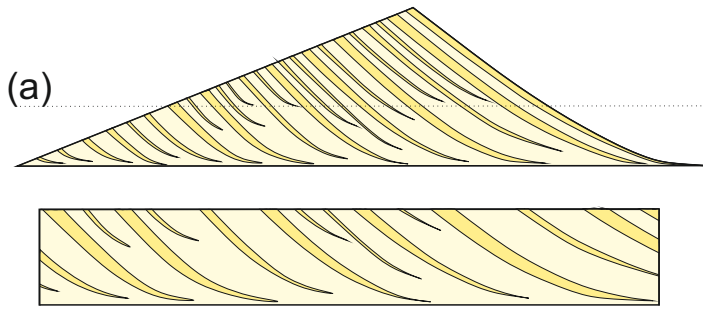
569 A suite of empirical relationships have been developed based on analysis of eolian  
570 outcrop data from parts of the Permian Cedar Mesa Sandstone and the Jurassic  
571 Navajo Sandstone in SE Utah. These relationships enable parameters measured  
572 directly from one-dimensional core to be related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

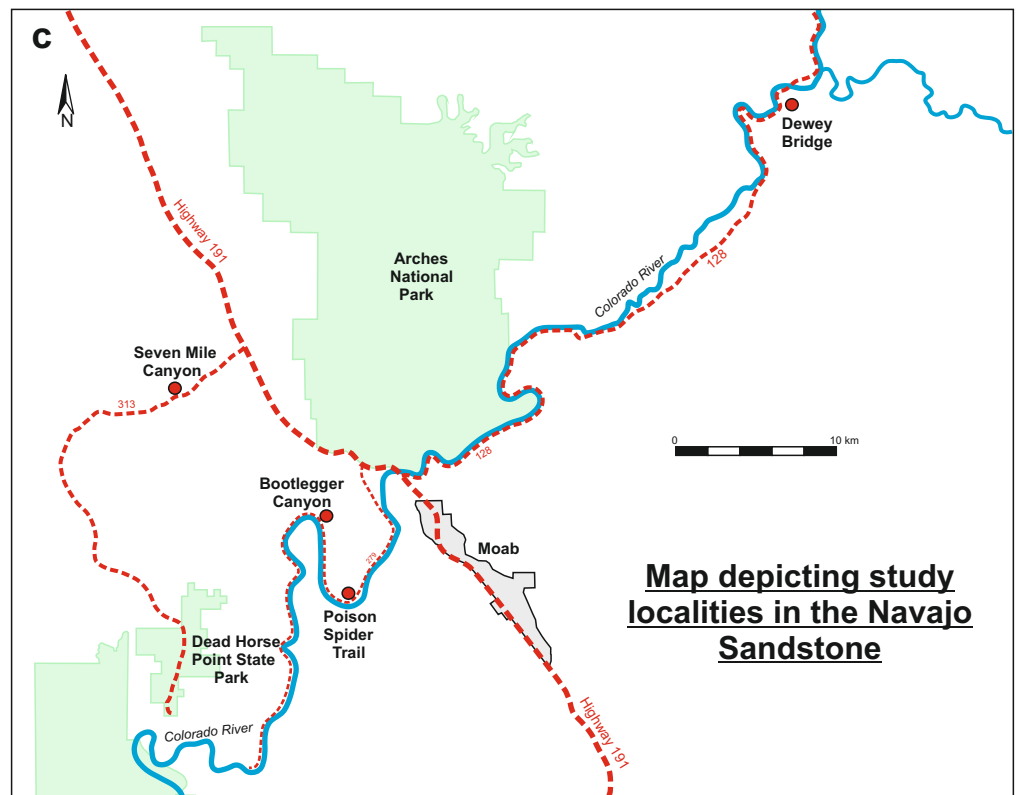
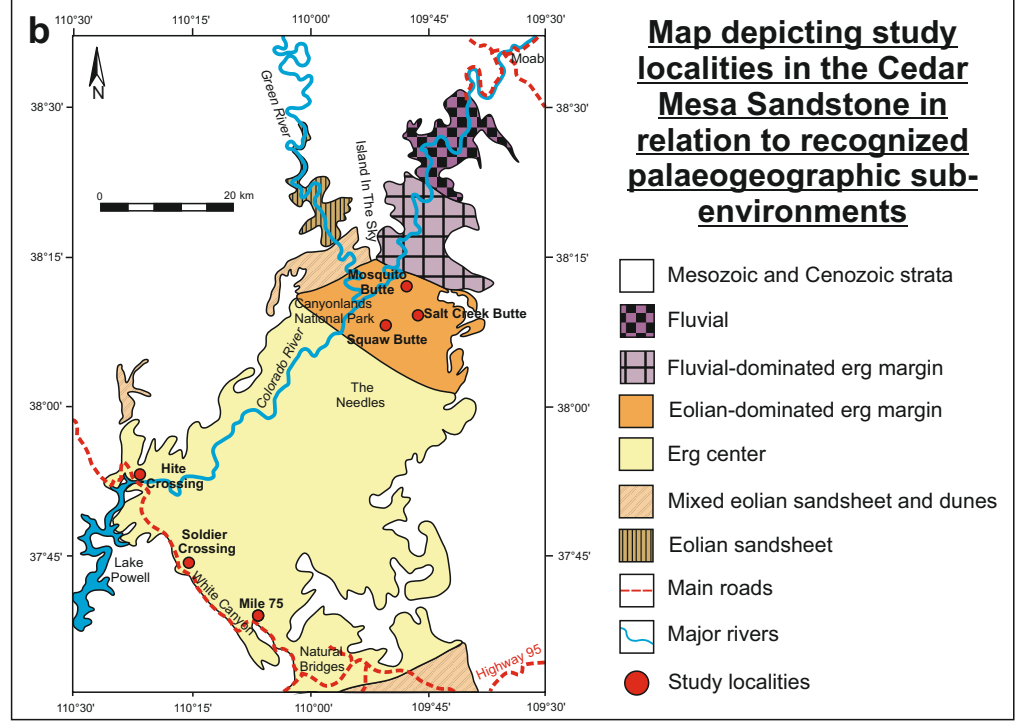
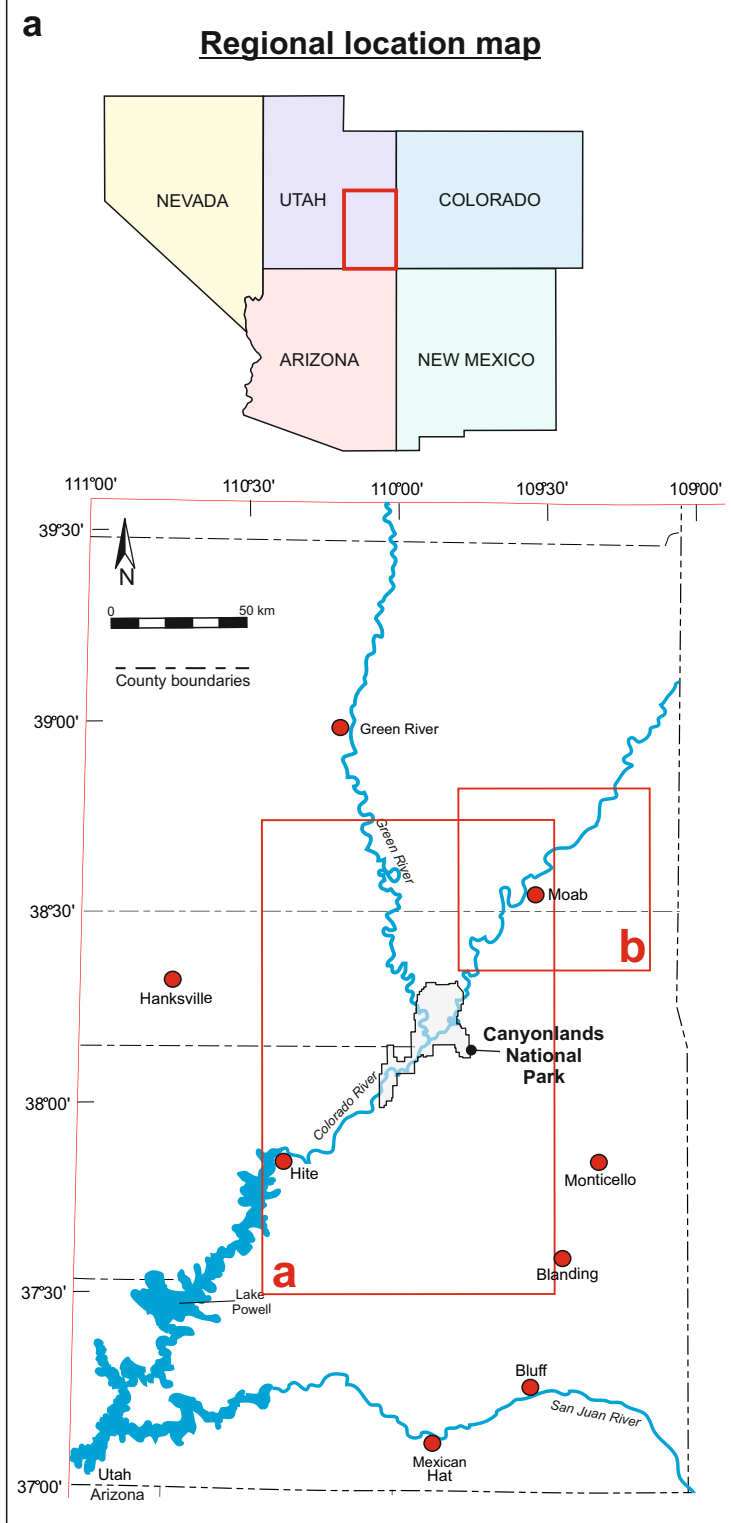
582 larger-scale sedimentary architecture and therefore for prediction of regional  
583 reservoir stratigraphic heterogeneity.

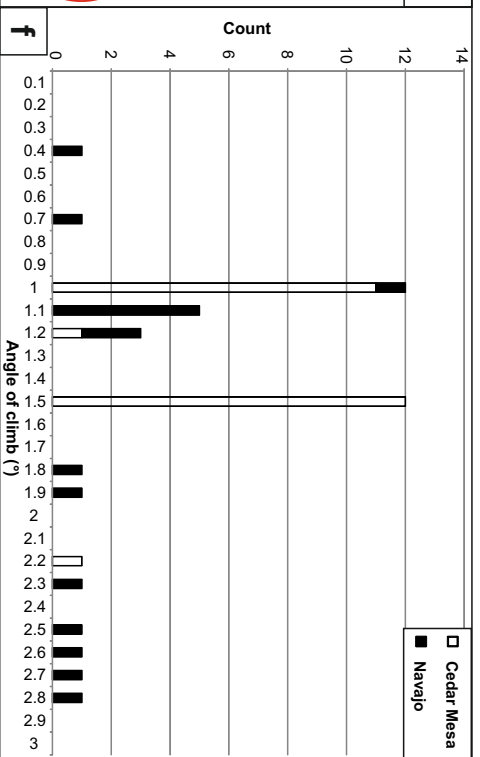
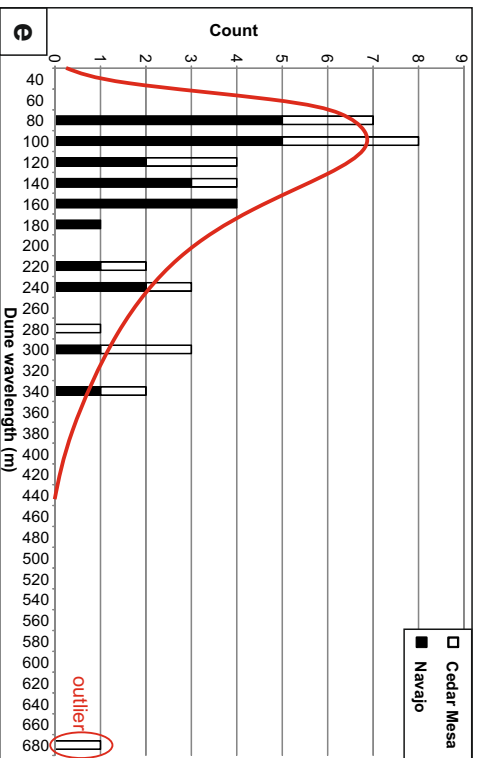
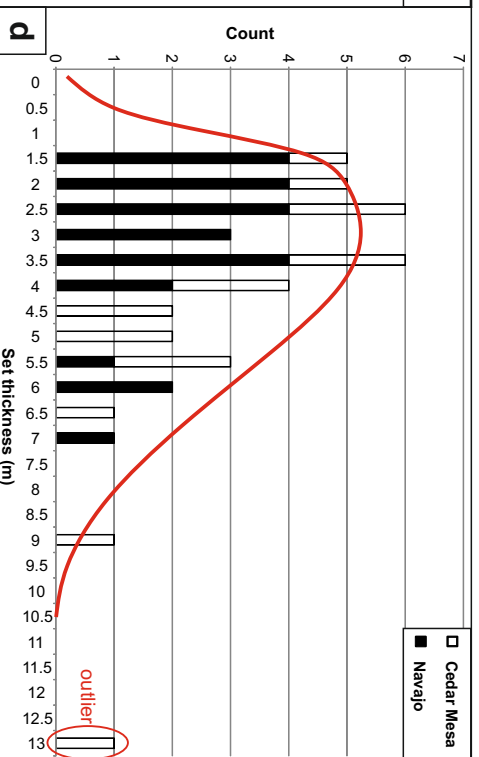
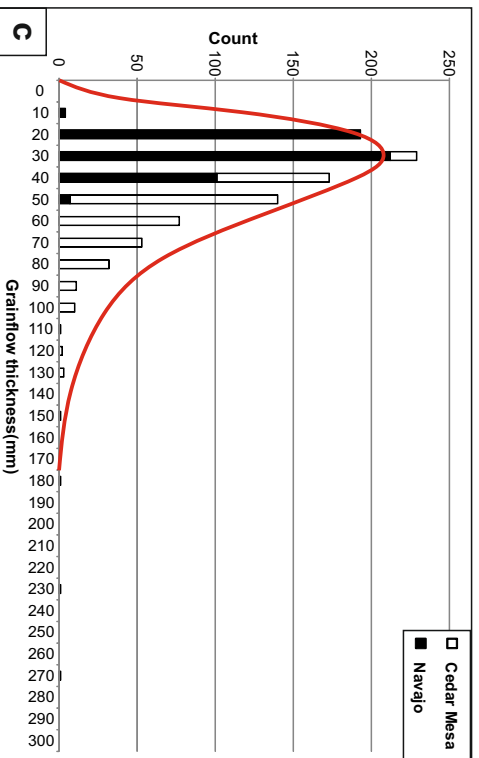
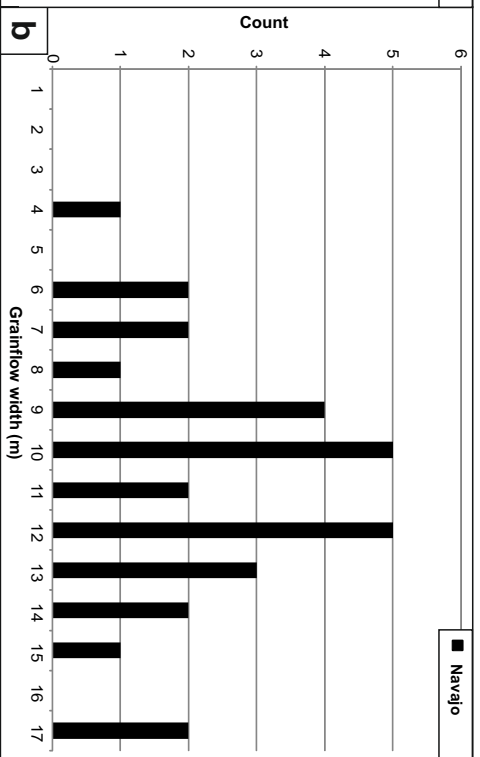
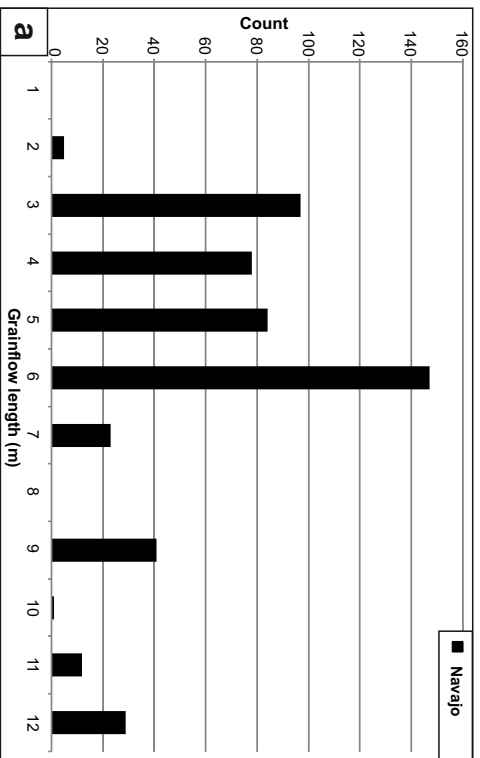
#### 584 **Acknowledgments**

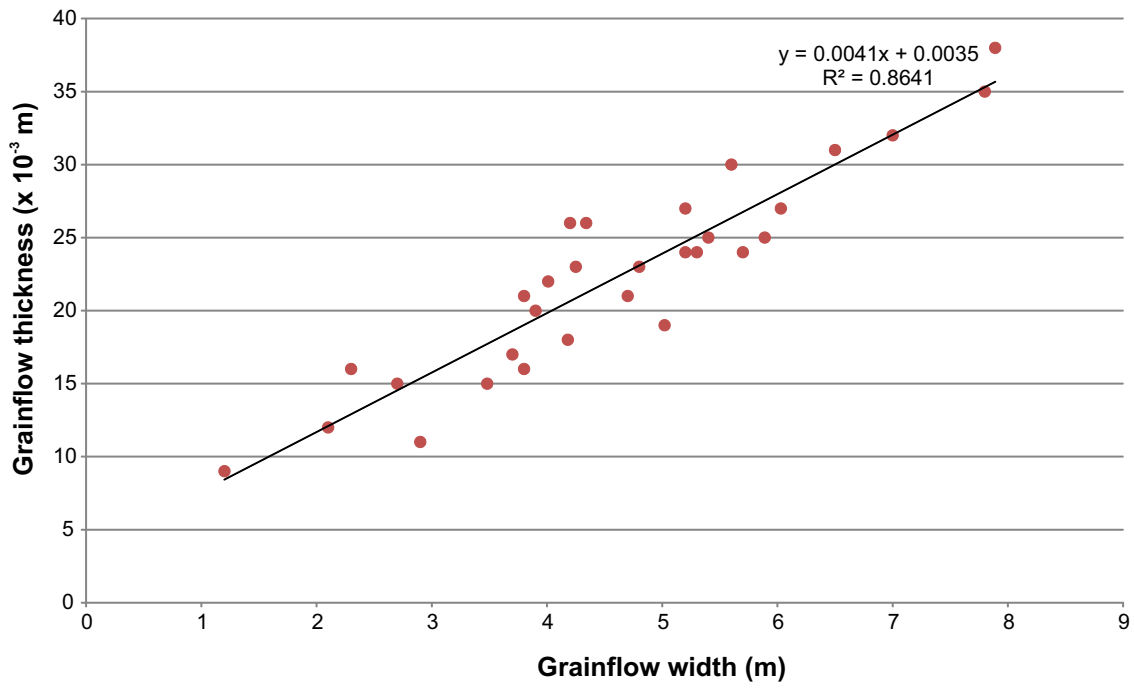
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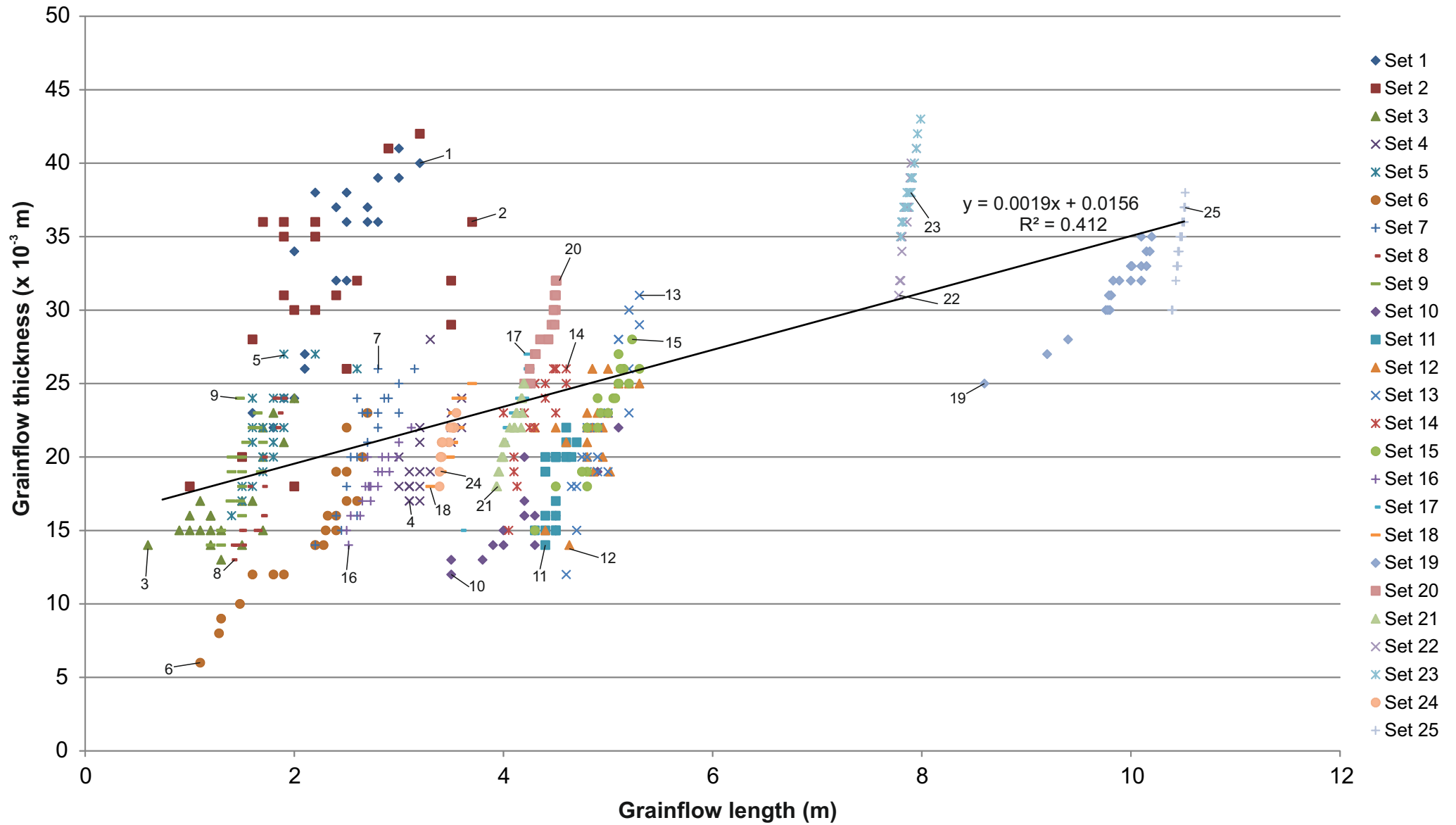


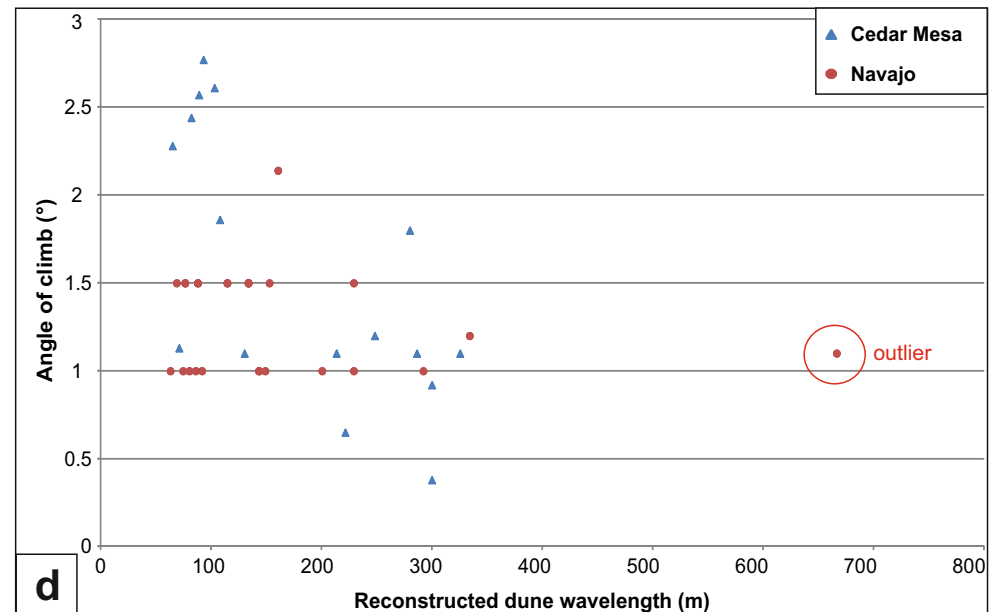
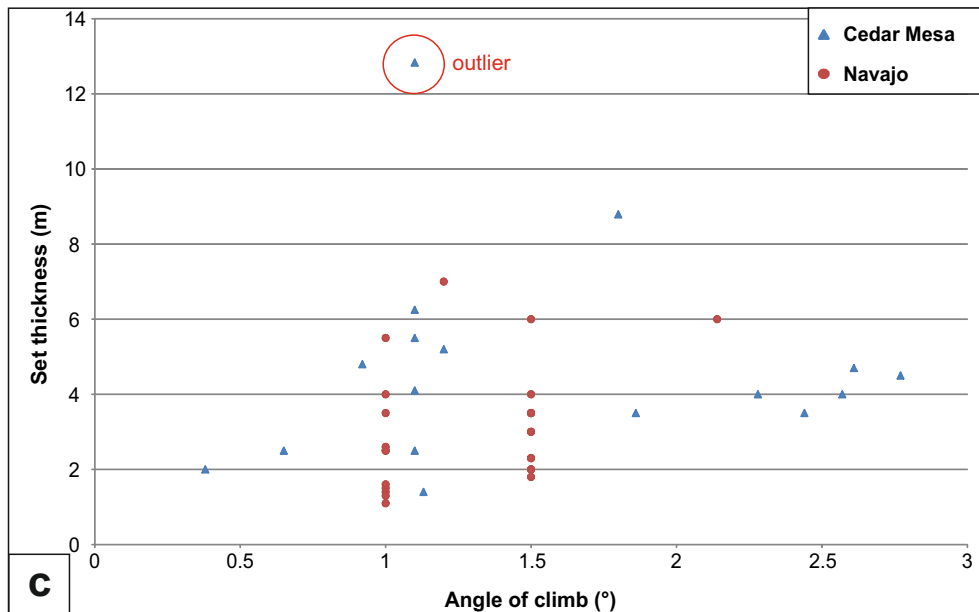
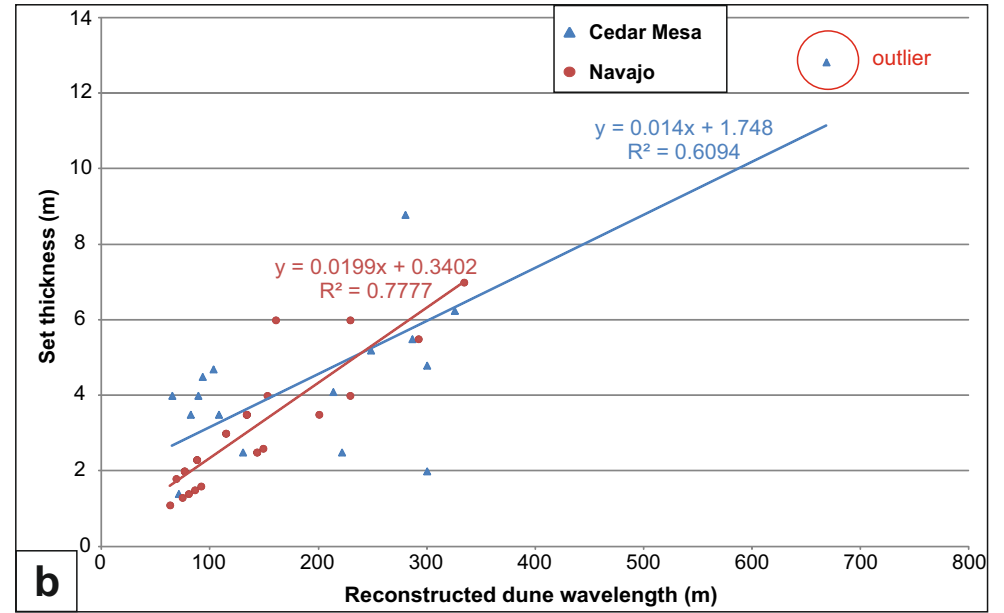
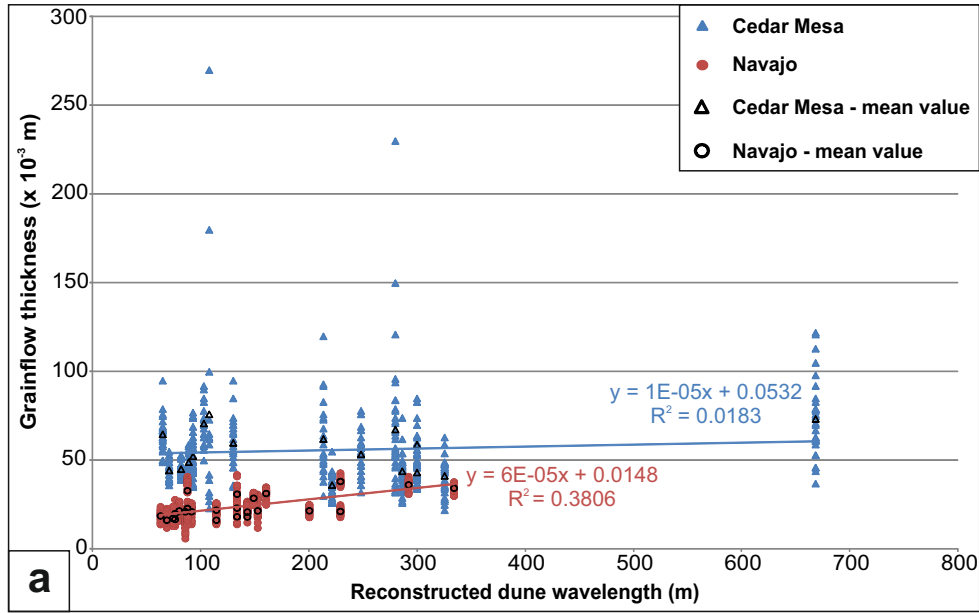


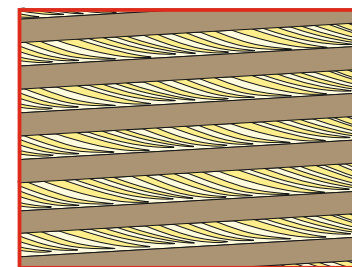
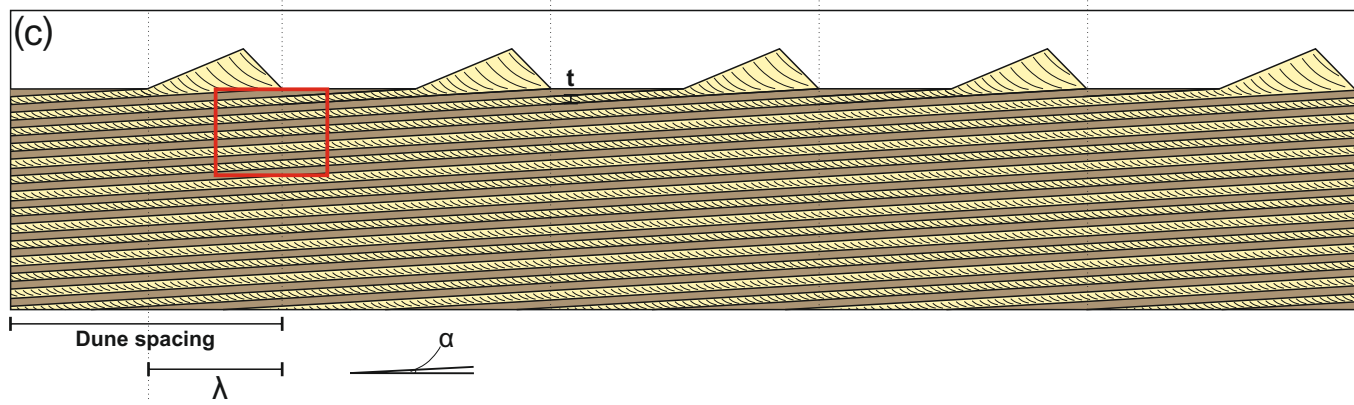
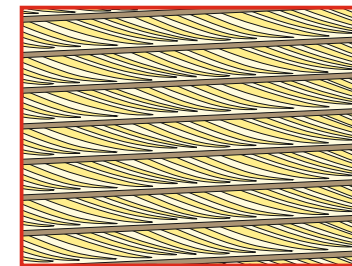
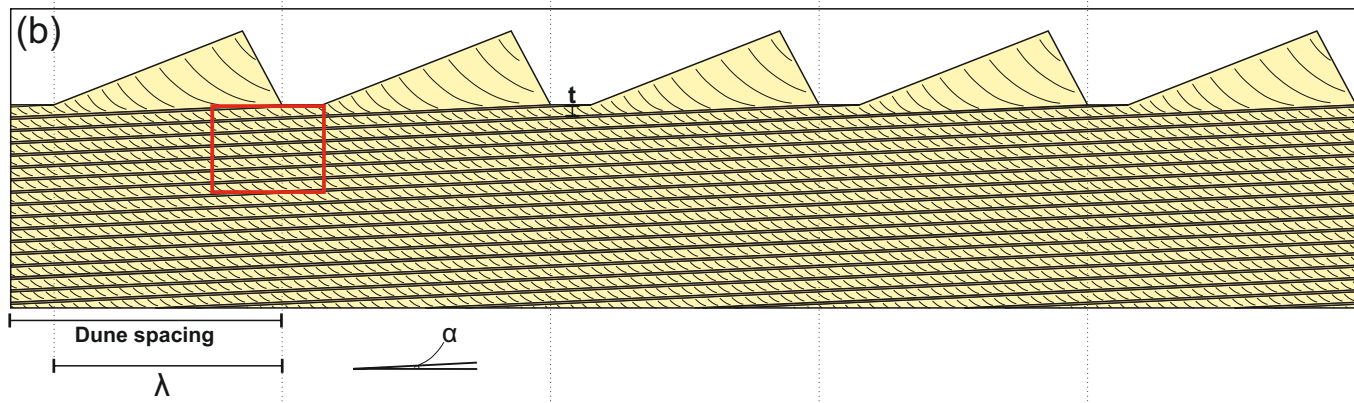
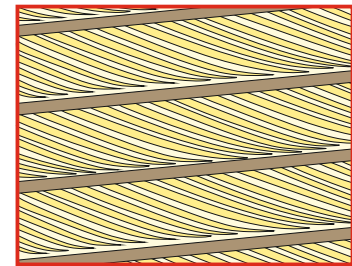
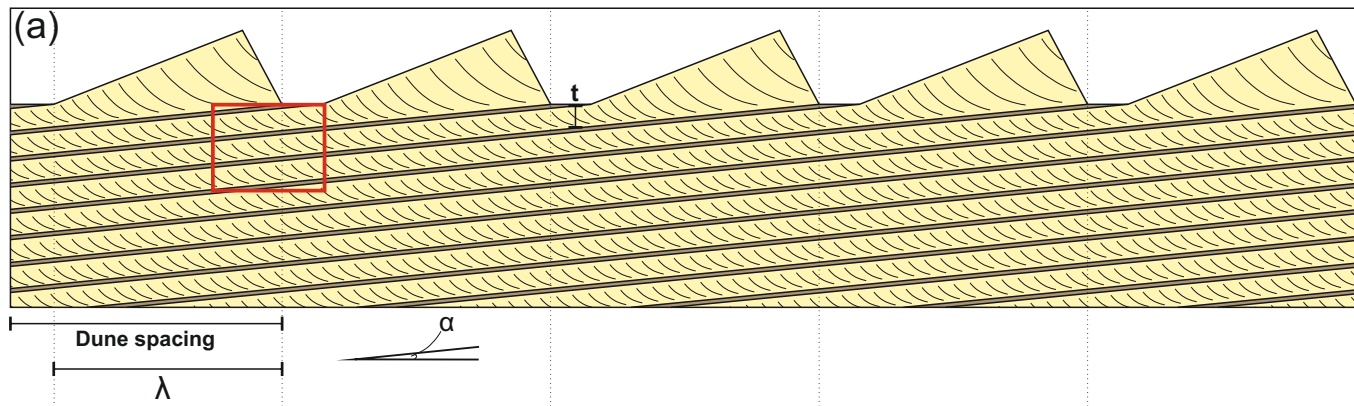


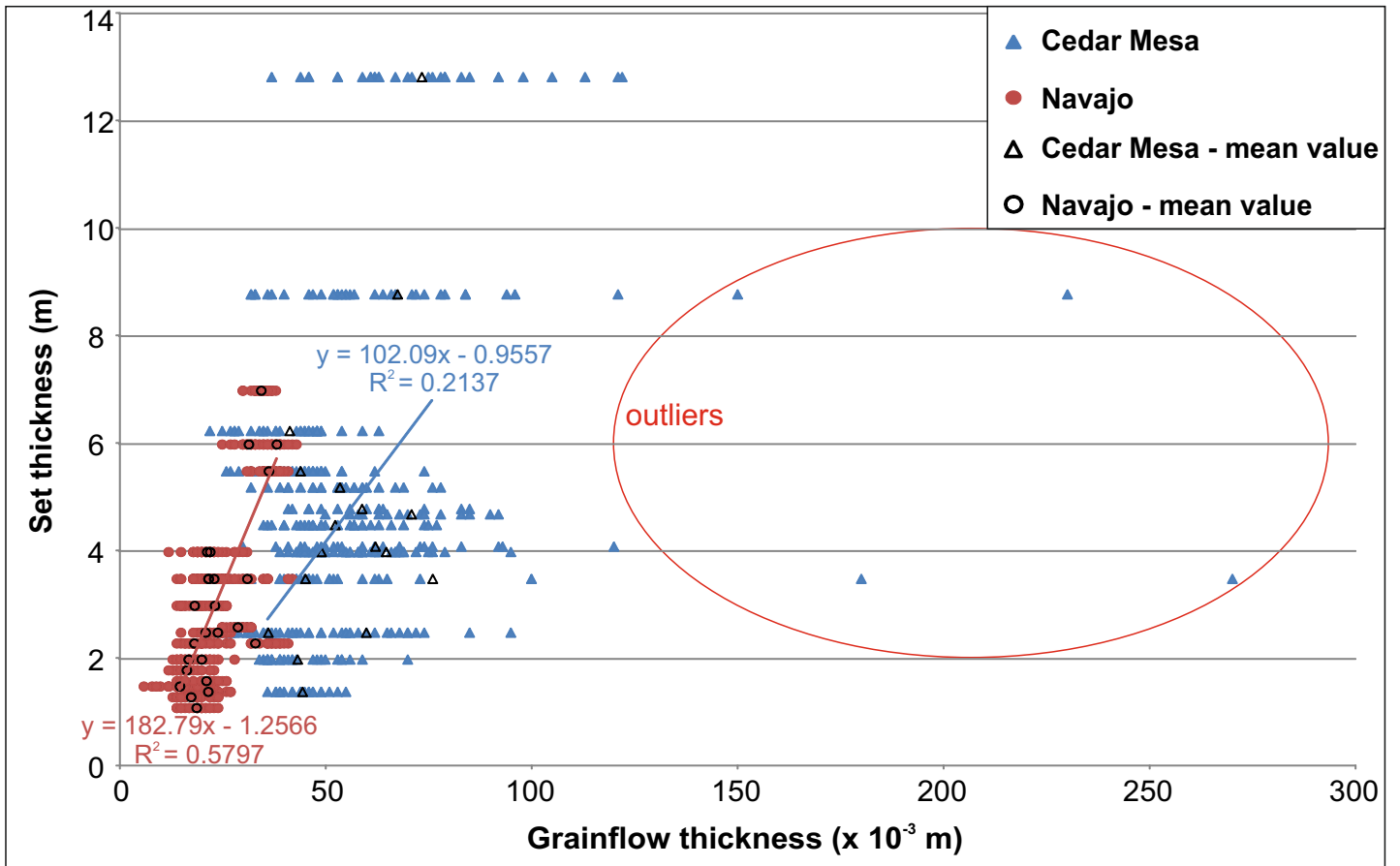




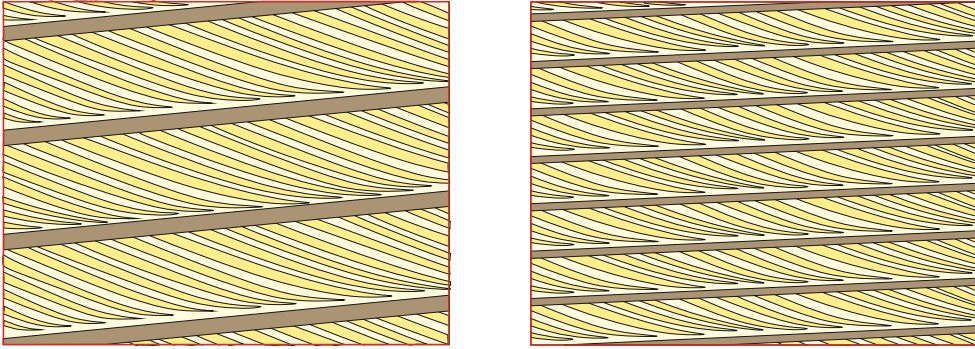




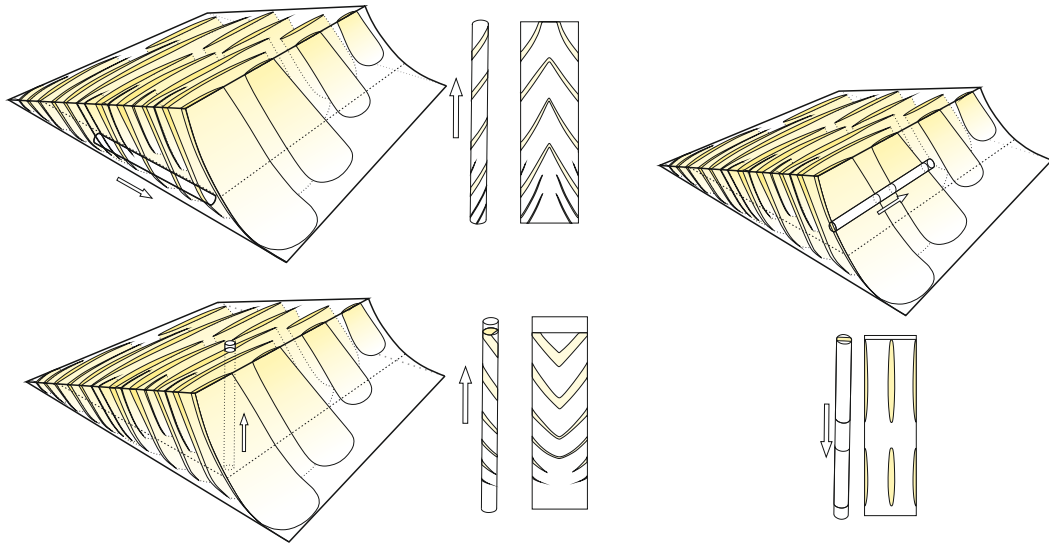




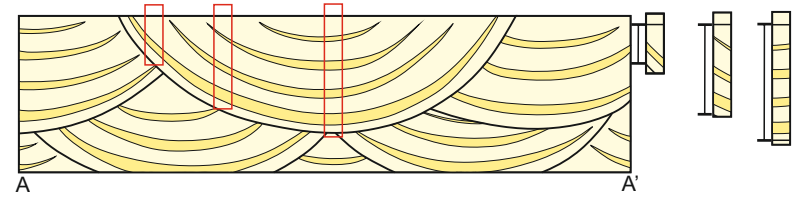
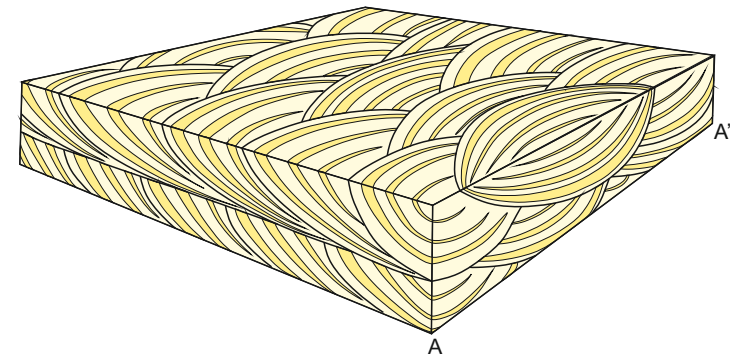
For a fixed dune wavelength, accumulation via migration at a steeper angle of climb (left) will generate and preserve thicker sets than for a less steep angle of climb (right)



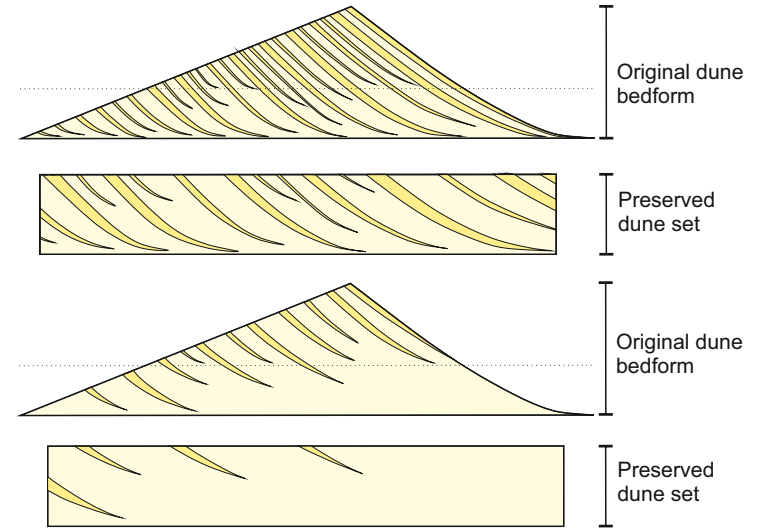
(a)



(c)



(b)



(d)

