1   **itle: Effective flow properties of heterolithic, cross-bedded**
2   **tidal sandstones: Part 1. Surface-based modeling**

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21

Abstract

23 Tidal heterolithic sandstones are often characterized by millimeter- to centimeter-scale

24 intercalations of mudstone and sandstone. Consequently, their effective flow properties are

25 poorly predicted by (1) data that do not sample a representative volume, or (2) models that

26 fail to capture the complex three-dimensional architecture of sandstone and mudstone

27   layers. We present a modelling approach in which surfaces are used to represent all

28   geologic heterogeneities that control the spatial distribution of reservoir rock properties

29   ("surface-based modeling"). The workflow uses template surfaces to represent

30   heterogeneities classified by geometry rather than length-scale. The topology of the

31   template surfaces is described mathematically by a small number of geometric input

32   parameters and models are constructed stochastically. The methodology has been applied

33   to generate generic, 3D mini-models (9 m^3 volume) of cross-bedded heterolithic sandstones

34   representing trough and tabular cross-bedding with differing proportions of sandstone and

35   mudstone, using conditioning data from two outcrop analogs from a tide-dominated deltaic

36   deposit. The mini-models capture the cross-stratified architectures observed in outcrop and

37   are suitable for flow simulation, allowing computation of effective permeability values for

38   use in larger-scale models. We show that mudstone drapes in cross-bedded heterolithic

39   sandstones significantly reduce effective permeability and also impart permeability

40   anisotropy in the horizontal as well as vertical flow directions. The workflow can be used

41   with subsurface data, supplemented by outcrop analog observations, to generate effective

42   permeability values to be derived for use in larger-scale reservoir models. The methodology

43   could be applied to the characterization and modeling of heterogeneities in other types of

44   sandstone reservoirs.

45

Introduction

47   Heterolithic sandstones are commonly generated by tidal processes in shallow marine

48   environments, such as deltaic and estuarine depositional systems. In these tidally-influenced

49   environments, the main current direction varies depending on the relative strength of tidal

50   currents over daily to twice-daily cyclical time periods, and the interaction of tidal currents

51   with waves and river currents (e.g. Dalrymple and Choi, 2007). Sand is transported as

52   bedload by strong currents to form ripples and dunes during periods of rising (flood) and

53   falling (ebb) tide, and mudstone drapes are deposited during intervening slack-water

54   periods. Depending on the flow regime, the mudstone drapes are more or less continuous

55   over the sandy bedforms (Reineck and Wunderlich, 1968; Reineck and Singh, 1980; Nio and

56   Yang, 1991). This results in interstratified, millimeter- to centimeter-thick sandstone and

57   mudstone layers that are deposited over multiple tidal cycles, and form the fine-scale

58   heterogeneities that are characteristic of heterolithic tidal sandstone reservoirs. The

59   distribution of mudstones and sandstones is delimited by a hierarchy of stratigraphic

60   surfaces including (in order of increasing length scale): (1) lamina boundaries and

61   reactivation surfaces that record incremental migration of bedforms, (2) the erosional bases

62   of beds and bedsets, (3) boundaries between facies and facies associations, and (4)

63   sequence stratigraphic surfaces. These four levels of stratigraphic surfaces define the multi-

64   scale architecture and connectivity of mudstone and sandstone layers which, in turn, exerts

65   a key control on the flow of gas, oil and water during field production (Weber, 1986; Jackson

66   *et al.*, 2003, 2005; Ringrose *et al.*, 2005; Nordahl *et al.*, 2005, 2006; Nordahl and Ringrose,

67   2008).

68   The presence of these multi-scale heterogeneities in heterolithic tidal sandstone

69   reservoirs ensures that the characterization of effective reservoir properties such as

70   permeability, relative permeability, and capillary pressure, is a recurring problem (e.g.

71   Martinius *et al.*, 2005). Effective reservoir properties are typically derived from subsurface

72   well data such as wireline logs and well tests, combined with laboratory measurements on

73   cores and core plugs. Laboratory-derived reservoir properties are measured at a length scale

74   that is small (of the order centimeters for a typical core plug) compared to the dimensions of

75   grid cells in reservoir simulation models (of the order tens to hundreds of meters in plan-

76   view, and 10's cm to meters in the vertical direction). In the case of tidal heterolithic

77   sandstones, lateral and vertical variations in the continuity and connectivity of sandstone

78   and mudstone laminae (e.g. meters to tens of meters) are not sampled by either subsurface

79   well data or laboratory measurements. However, effective reservoir properties in

80   heterolithic units are highly dependent on the volume sampled (Norris and Lewis, 1991;

81   Jackson *et al.*, 2003, 2005; Nordahl and Ringrose, 2008). Consequently, effective reservoir

82   properties derived solely from subsurface and laboratory data in such heterolithic units are

83   not representative of reservoir behavior; instead, models are required that capture the

84   continuity and connectivity of sandstone and mudstone laminae at the appropriate length-

85   scale.

86   Two different methodologies have been used to create such models, which both use

87   stratigraphic surfaces to reproduce multi-scale heterogeneities. The first approach mimics

88   depositional processes by generating and translating bedforms with a particular geometry

89   according to user-defined inputs such as current velocity and sediment accumulation rate

90   through time (e.g. Rubin, 1987; Wen *et al.*, 1998; Rubin and Carter, 2005). Cross-

91   stratification is defined by the preserved remnants of the bedform-bounding surfaces, while

92   lithologies are distributed according to the local current velocities during deposition. This

93   process-based methodology has been used to generate highly realistic models of near-

94   wellbore regions (with dimensions of the order 0.3 x 0.3 x 2 m) (Nordahl *et al.*, 2005;

95   Ringrose *et al.*, 2005). However, process-based methodologies suffer from two problems.

96   First, the models cannot be conditioned directly to data available from outcrop or subsurface

97   measurements. Second, the required input parameters describing ancient depositional

98   properties, such as variations in current velocity and sediment availability, are highly

99   uncertain and have to be selected so as to produce a model that matches the preserved rock

100   architecture observed in core or outcrop; this is a complex and non-unique inversion

101   problem that is difficult to solve.

102   The second approach uses geometric and lithologic data from the subsurface in

103   conjunction with outcrop analogs to directly condition reservoir models (e.g. White and

104   Barton, 1999; Willis and White, 2000; White *et al.*, 2004; Jackson *et al.*, 2009; Sech *et al.*,

105   2009). Jackson *et al.* (2005) generated 3D models of rock samples (with dimensions of order

106   0.5 x 0.5 x 0.3 m) from heterolithic tidal sandstones observed at outcrop using serial 2D

107   sectioning, scanning and surface reconstruction techniques. Their methodology yields

108   models that are directly conditioned to observed geologic data, but its application relies on

109   selection of an appropriate analog (or analogs) for the reservoir facies to be characterized.

110   Furthermore, such a method is time-consuming, difficult to replicate, and leads to the

111   creation of deterministic models that do not capture uncertainty in sandbody proportions,

112   geometry and connectivity.

113   In this study, a surface-based modeling workflow is presented, which is then used to

114   produce stochastic models of heterolithic, cross-bedded tidal sandstones conditioned to

115   outcrop or subsurface data. A cross-bedding template surface is used in order to define and

116   populate a rock volume. The 3D morphology of the template surface is defined by purely

117   geometric input parameters that, in the case documented herein, were defined using

118   measurements from an outcrop analog (the Eocene Dir Abu Lifa Member, Western Desert,

119   Egypt; Bown and Kraus, 1988; Legler *et al.*, 2013). The models incorporate three of the four

120   hierarchical levels of heterogeneity for heterolithic tidal sandstone reservoirs described

121 above: (1) lamina boundaries and reactivation surfaces, (2) erosional bases of beds and

122 bedsets, and (3) boundaries between facies and facies associations. The paper has four

123 objectives. First, we present the new surface-based modeling workflow. Second, we identify

124 the geometric input parameters required for the modeling process and extract a range of

125 values for these parameters from statistical analysis of the outcrop analog dataset. Third, we

126 describe two generic models that reproduce: (1) trough cross-bedding dominated by muddy

127 toesets and with a relatively low sandstone content (89%), and (2) tabular cross-bedding

128 dominated by sandy foresets and with a higher sandstone content (94%). Finally, we use

129 flow-simulation to calculate the effective permeability of the models in order to

130 demonstrate the effectiveness of the surface-based modeling workflow and its application

131 to build models suitable for flow simulation. In a companion paper (Massart *et al.*, 2016, this

132 issue), the surface-based methodology has been used to create a set of mini-models in order

133 to investigate the range of effective permeability in heterolithic cross-bedded tidal

134 sandstone facies.

135

Methodology

Model-construction methodology

138   The stratigraphic surfaces that define sedimentary structures within tidal sandstone

139 reservoirs can be categorized by their 3D geometries, irrespective of length scale: (1) planar

140 surfaces (parallel bedding; erosional or conformable facies contacts), (2) concave-upward

141 surfaces (sigmoidal bedding or cross bedding structures; channelized erosional contacts), or

142 (3) wavy surfaces (wavy-bedding, lenticular-bedding and flaser-bedding structures; irregular

143 erosional contacts). The surface-based methodology uses these scale-independent

144   stratigraphic surface geometries by modeling rock volumes within which surfaces share a

145   common geometric template. This methodology comprises the following three steps (Figure

146   1).

147   (1) The volume of rock to be modeled is subdivided into "elemental volumes" delimited

148   by a basal and a top surface. In each elemental volume, the heterogeneities are associated

149   with stratigraphic surfaces that have the same 3D geometry. The elemental volumes have

150   uniform shapes, but their dimensions can be varied. The model volume is filled with

151   elemental volumes until an appropriate 3D density is reached, in an approach analogous to

152   object-based modeling (e.g. Haldorsen and Damsleth, 1990). Rules of superposition and

153   erosion are applied to the elemental volumes to mimic their chronostratigraphic ordering.

154   For example, if the elemental volumes represent erosionally-based sediment bodies, then

155   each elemental volume is eroded by the basal surfaces of "younger" elemental volumes.

156   (2) Each elemental volume contains only one type of stratigraphic surface, the geometry

157   of which is defined by a "template surface". The 3D geometry of the template surface is

158   defined mathematically. Each elemental volume is then filled with numerous stratigraphic

159   surfaces derived from the single template surface, following rules introduced by the user to

160   define, for example, the vertical and horizontal surface spacing. The vertical and lateral

161   extent of the surfaces within each elemental volume is controlled by the vertical and lateral

162   extent of the elemental volume.

163   (3) Once every elemental volume has been filled with template surfaces, a facies code is

164   assigned to the geologic domains defined by the surfaces, or to the surfaces themselves. The

165   facies codes constrain the modeling of fine-scale petrophysical properties such as porosity

166   and permeability.

167   (4) The surface-based model is then gridded for flow simulation. The grid is constructed

168   around the stratigraphic surfaces, in order to retain the geometries defined by the surfaces

169   and minimize the number of active grid cells required for flow simulation (Jackson *et al.*,

170   2005, 2009, 2013, 2015; Sech *et al.*, 2009). The resulting models are geometrically accurate

171   and computationally efficient, although the complex grid architectures may introduce

172   numerical artefacts in conventional reservoir simulators (described in more details in

173   Massart *et al.*, 2016; see also Graham *et al.*, 2015).

174

175   ***Application to heterolithic, cross-bedded tidal sandstones***

176   The three-step methodology described above is applied herein to the modeling of

177   heterolithic, cross-bedded tidal sandstones (Figure 1). Cross-bedded sandstones are

178   common in a wide range of depositional environments, including those influenced by tides

179   (e.g. Harms *et al.*, 1982; Rubin, 1987; Ashley, 1990). Cross-beds result from the migration of

180   dunes (or megaripples *sensu* Allen, 1968, or sand waves *sensu* Allen, 1980) in response to a

181   unidirectional current. Dunes develop straight crests (2D dunes) under low current

182   velocities, and sinuous or discontinuous crests (3D dunes) under higher current velocities

183   (Dalrymple *et al.*, 1978; Allen, 1980; Elliott and Gardiner, 1981; Middleton and Southard,

184   1984). Any dip-section (parallel to the main current direction) gives the same geometry for

185   tabular (or planar) cross-beds resulting from the migration of 2D dunes, whereas trough

186   cross-beds resulting from the migration of 3D dunes have a more variable dip-section

187   geometry. Each migrating dune is preserved as a cross-bed set with an erosional base, whose

188   geometry and extent reflect the morphology and trajectory of the scoured area in front of

189   the migrating dune. In the case of 2D dunes, the unidirectional current is dispersed along a

190   large area downstream of the dune crest, such that an extensive planar erosion surface of

191   low scour capacity is formed (Harms *et al.* 1982). In the case of 3D dunes, the current is

192   focused downstream of the migrating dune into scour pits, which migrate to produce a

193   curved, concave-upwards erosion surface (Dalrymple *et al.*, 1978; Harms *et al.*, 1982). Cross-

194   beds produced by dune migration are commonly stacked into larger sediment bodies of

195   characteristic internal architecture. For example, the deposits of larger bedforms, such as

196   bars, accumulate via the accretion of cross-beds that record the migration of smaller,

197   superposed bedforms, such as dunes and ripples, across the bar surface. Tidal bars migrate

198   laterally into adjacent channels due to changes in tidal flow patterns or interactions with

199   other processes (e.g. variations in wave climate or fluvial discharge). Consequently, tidal bar

200   deposits can be comprised entirely of stacked cross-bed sets, corresponding to the

201   preserved remnants of repeated dune migration (Allen, 1980; Dalrymple, 1984; Ashley,

202   1990).

203

204   *Modeling of elemental volumes*

205   A volume of 9 m^3 (3 x 3 x 1 m) of cross-bedded sandstone is considered in this study; in a

206   companion paper (Massart *et al.*, 2016), we demonstrate that this volume comfortably

207   exceeds the minimum volume (the representative elementary volume or REV) required to

208   calculate representative values of effective permeability in these dune scale cross-bedded

209   heterolithic units. At this length scale, the elemental volumes comprise tabular and trough

210   cross-bed sets, representing the preserved parts of 2D and 3D dunes in a tidal bar

211   succession, respectively. In each cross-bed set, the key heterogeneities captured are

212   mudstone drapes along foreset-toeset surfaces and each set corresponds to an elemental

213 volume. The model volume of 9 m^3 here samples approximately 6 cross-bed sets and 600

214 foreset-toeset surfaces, based on outcrop-analog data presented in a later section.

215   Cross-bed set boundaries correspond to the preserved remnants of the erosional surface

216 developed downcurrent of migrating 2D- or 3D-dunes (Figure 2 A). Observations of modern

217 tidal dunes show that this erosional surface has a curved, elliptical shape in the strike

218 direction (orthogonal to the main paleocurrent direction, Figure 2 B). As the dunes migrate,

219 the resulting erosional surface is a downstream-amalgamated composite of the elliptical

220 strike-sections that record the successive positions of the deepest part of the scour pool in

221 front of the dune (Figure 2 B). In order to mimic the 3D geometry of this composite erosional

222 surface, the corresponding elemental volumes have been modeled here as ellipsoids (Figures

223 3, 4). The model volume is thus subdivided into ellipsoidal elemental volumes that

224 correspond to cross-bet sets, with tops that are truncated by the basal surfaces of overlying

225 elemental volumes (Figure 1 B). The elemental volumes are modeled stochastically using the

226 input parameters summarized in Table 1. For each parameter, the modeling algorithm can

227 use a single value, or a distribution characterized by a mean value and a standard deviation.

228

229 ***Modeling template surfaces within elemental volumes***

230   Each ellipsoidal elemental volume representing a cross-bed set contains multiple foreset-

231 toeset template surfaces of uniform geometry. The spacing of foresets and toesets, and their

232 associated mudstone drapes, is typically rhythmic, reflecting a hierarchy of periodic cycles in

233 tidal current velocity (e.g. Nio and Yang, 1991). The shortest tidal cycle is semi-diurnal (c. 12

234 hour period), and is characterized by the alternation of flood and ebb current stages,

235 separated by slack-water periods when the current velocity is zero. During slack-water

236   periods, mud particles and clay aggregates (flocs) are deposited to form mudstone drapes

237   over sandy bedforms (Allen, 1981; Dalrymple *et al.*, 2003). In an idealized semi-diurnal tidal

238   cycle, both the ebb and flood tides are recorded by deposition of a sand lamina on the lee

239   face (foreset) of a dune (Visser, 1980). Slack-water periods are recorded by mudstone drapes

240   that separate the foreset-toeset sandstone laminae representing the ebb-tidal and flood-

241   tidal currents. The tide is typically asymmetric, such that the ebb-tidal or flood-tidal currents

242   are either of unequal velocity or are physically separated around the bar form (Visser, 1980).

243   The dominant tide is represented by thicker foreset-toeset sandstone laminae and the

244   subordinate tide by either thinner laminae or erosion (reactivation) surfaces.

245   An idealized, fully preserved semi-diurnal tidal cycle is thus represented by two

246   sandstone laminae and two mudstone drapes ("paired mudstone drapes" or "mud couplet";

247   Visser, 1980) that constitute one tidal bundle (Boersma, 1969). Longer tidal cycles, which are

248   commonly preserved as rhythmic variations in the thickness of sandstone laminae and

249   mudstone drapes within cross-bed sets, are diurnal (c. 24 hour period) and spring-neap

250   (c. 14 day period) cycles. Superposition of the different tidal cycles, combined with other

251   sediment transport processes, leads to preservation of sandy foresets and muddy toesets. A

252   vertical profile through dune toeset deposits typically exhibits rhythmic alternation of

253   millimeter- to centimeter-thick, wavy-bedded mudstone and sandstone laminae (Reineck

254   and Singh, 1967). The transition between the foreset and toeset of each lamina in a cross-

255   bed set is marked by a gradual reduced downcurrent curvature. The resulting foreset-toeset

256   geometry may be referred to as "shovel" shaped (Van den Berg *et al.*, 2007). In a dip-section,

257   the shape of the foreset part is therefore approximated by a parabolic curve, and that of the

258   toeset part is approximated by a straight line:

$$\begin{cases} \text{Foreset:if } x > 0, z(x) = Ax^2 \\ \text{Toeset:if } x < 0, z(x) = 0 \end{cases}$$ (1)

260 where x is the dip-direction coordinate, and z is the vertical coordinate, relative to the

261 junction point O between the flat toeset part and the concave-upward foreset part (which is

262 defined to be the origin, $x = 0$, $z = 0$). The whole toeset-foreset surface is then rotated by an

263 angle α, which corresponds to the dip angle of the toeset. Equation (1) becomes:

$$\begin{cases} \text{Foreset: if } x > 0, z(x) = \dfrac{\cos\alpha - 2xA\cos\alpha\sin\alpha - \sqrt{\cos^2\alpha - 4Ax\sin\alpha}}{2A\sin^2\alpha} \\ \text{Toeset:if } x < 0, z(x) = x\tan\alpha \end{cases}$$ (2)

265 Notice that both equations have the same derivative $z'(x = 0) = \tan\alpha$ at the junction point

266 O, so that the curve is continuous from the toeset part to the foreset part of the surface.

267 In a strike section with coordinate y, the foreset and toeset geometry reflects the

268 erosional scour at the base of the migrating dune, so that the resulting cross-section in the

269 strike direction corresponds to trough or tabular cross-beds. Successive foreset-toeset

270 surfaces are parallel to each other, and parallel to the erosional base of the cross-bed set

271 (i.e. elemental volume). Consequently, equation (2) is generalized for any *(x,y)* direction:

$$\begin{cases} \text{Foreset:if } x > 0, z(x,y) = \left[\dfrac{\cos\alpha - 2xA\cos\alpha\sin\alpha - \sqrt{\cos^2\alpha - 4Ax\sin\alpha}}{2A\sin^2\alpha}\right] + \left[\sum_1^i T_{Ti} + B(x,y)\right] \\ \text{Toeset:if } x < 0, z(x,y) = \left[x\tan\alpha\right] + \left[\sum_1^i T_{Ti} + B(x,y)\right] \end{cases}$$ (3)

273 where *B(x,y)* describes the 3D ellipsoidal shape of the basal surface of the cross-bed set (i.e.

274 elemental volume):

$$B(x,y) = (H_E/2)\sqrt{1 - \frac{x^2}{(L_E/2)^2} - \frac{y^2}{(W_E/2)^2}}$$

275

(4)

276

277 The term $\sum_1^i T_{Ti}$ corresponds to the cumulative toeset thickness, with T_T corresponding to

278 the individual toeset thickness. Every cross-section of one foreset-toeset surface in the strike

279 direction is an ellipse parallel to the erosional base of the cross-bed set. In particular, for

280 $x = 0$, the strike cross-section curve links all junction points O of any given foreset-toeset

281 surface, creating a junction line Oy, simplifying equations (3) and (4) to yield:

$$z(x = 0, y) = \sum_1^i T_{Ti} + (H_E/2)\sqrt{1 - \frac{y^2}{(W_E/2)^2}}$$

282

(5)

283 In order to populate the ellipsoidal elemental volumes with foreset-toeset template

284 surfaces, the input parameters summarized in Table 1 are required (Figures 1 C, 5). Toeset

285 thicknesses T_T (Figure 5) are generally too small to be routinely measured directly from cores

286 and outcrop analogs with high accuracy (< 1 cm). Therefore we calculate T_T indirectly from

287 two other parameters: the dip angle of the toesets α and the angle of dune climb δ (Figure

288 5). The dip angle α corresponds to the angle of rotation applied to the parabolic curve

289 representing the foreset-toeset template surface. T_T is then given by:

$$T_T = F_T \sin(\alpha + \delta)$$

290

(6)

291

Modeling of mudstone drapes along foreset-toeset surfaces

293 If the succeeding flood-tide or ebb-tide is sufficiently strong, then mudstone drapes can

294 be partially or entirely eroded, such that only one mudstone drape and one reactivation

295   surface may be preserved during one flood-and-ebb tidal cycle (de Mowbray and Visser,

296   1984). Thus, the foreset-toeset surfaces modeled in the previous step may not be entirely

297   covered by mudstone. The extent and continuity of mudstone drapes is defined using a

298   function to describe the mudstone frequency in the dip direction along the stratigraphic

299   surfaces, relative to a well-defined position on the surfaces. Mudstone drapes are modeled

300   as elliptical patches of mudstone that are placed stochastically on each surface. Where they

301   overlap, new patches erode older patches, so the patches coalesce to produce drapes with

302   complex geometries. The length and aspect ratio of each elliptical patch is also modeled

303   stochastically. Patches are placed on the stratigraphic surfaces until a user-specified

304   proportion of their area is reached, following the methodology of Jackson and Muggeridge

305   (2000). The mudstone frequency function denotes the probability that a patch will be placed

306   at a certain location along each surface. The foreset part of each surface is modelled first;

307   the mudstone drape coverage is then calculated at the transition between foreset and

308   toeset parts (line Δ in Figure 5), and this calculated value is then used as the target

309   mudstone drape coverage for the toeset parts, in order to ensure mudstone drape coverage

310   continuity between the foreset and toeset parts. Consequently, toeset and foreset parts of

311   each surface can have different mudstone drape coverage, allowing us to capture the muddy

312   toesets typically observed in outcrop. The distribution of mudstone drapes along each

313   surface is controlled by the chosen mudstone frequency function f, which is determined here

314   from outcrop analog data. The following equation has been used to define f:

$$f\left(\frac{x - x_O}{x_F - x_O}\right) = \frac{M}{1 + e^{\left(N\left(\frac{x - x_O}{x_F - x_O}\right) + O\right)}}$$

315   (7)

316   where x_O corresponds to the coordinate of the junction point O between foreset and toeset

317   sections, x_F corresponds to the coordinate of the point F marking the preserved top of the

318   foreset, and M, N and O are constants that are chosen to fit data extracted from the outcrop

319   analog. Such data could also be extracted from process-based models.

320   Mudstone drape thickness is user defined in the models and, at present, is assumed to be

321   constant for each drape. As mudstones are modeled as barriers to flow, their thickness has

322   no impact on their flow properties; however, drape thickness does affect the total volume of

323   the model that is occupied by mudstone. Here we have assumed a mud drape thickness of

324   3.5 mm, which is a typical mean value encountered in heterolithic cross-bedded tidal

325   sandstones (Terwindt, 1971; Nio and Yang, 1991; Martinius and Van den Berg, 2011).

326   Measurements of mudstone drape thickness could be taken from core datasets for

327   application to a specific reservoir, or from a suitable outcrop analog. The input parameters

328   required for modeling mudstone drapes are summarized in Table 1 (Figure 1 D).

329

330   ***Outcrop analog data analysis to define model input parameters***

331   The input parameters required to construct the models of heterolithic, cross-bedded

332   tidal sandstones were collected from an exceptionally well-exposed outcrop analog (see

333   below), which enabled the 3D geometry of the elemental volumes, template surfaces and

334   mudstone distribution to be evaluated quantitatively.

335   The studied outcrop analog forms part of the Eocene Dir Abu Lifa Member, located in the

336   Western Desert of Egypt (Figure 6). The Dir Abu Lifa Member was deposited in a shallow-

337   marine environment protected from wave energy, resulting in a predominance of tidal

338   processes (Abdel-Fattah *et al.*, 2010; Legler *et al.*, 2013). The lower part of the Dir Abu Lifa

339   Member consists largely of tidal bar and channel deposits that are stacked laterally and

340   vertically (Legler *et al.*, 2013). The lower parts of tidal bar deposits typically comprise

341   heterolithic, cross-bedded sandstones.

342   The lower Dir Abu Lifa Member is exposed in a continuous escarpment over 20 km long,

343   which is cut by multiple canyons that provide some three dimensional control (e.g. Legler

344   *et al.*, 2013). The datasets used in this study are taken from two locations, labelled Gecko

345   Nose and Butterfly Canyon in Figure 6. Gecko Nose is a small promontory which is defined by

346   two cliff faces that trend approximately WNW-ESE and SSW-NNE, nearly perpendicular to

347   each other (Figures 6, 7). The promontory exposes stacked trough and tabular cross-bedded

348   sandstones, interpreted as the deposits of tidal bars in a channel belt (the "yellow channel"

349   in the Gebel Sagha area of Legler *et al.*, 2013). The WNW-ESE-oriented cliff face (N110-N290)

350   is 17 m long, and the SSW-NNE-oriented cliff face (N030-N210) is 12 m long. Paleocurrent

351   measurements from the cross-beds are oriented towards N230, indicating that the WNW-

352   ESE- and SSW-NNE-oriented cliff faces provide close to strike and dip sections, respectively.

353   The slight deviation from the mean dip direction indicated by the paleocurrent data does not

354   significantly impact the geometry of the modeled cross-bed sets.

355   Butterfly Canyon contains a larger promontory than Gecko Nose, defined by two cliff

356   faces that trend approximately N-S and W-E. The Butterfly Canyon outcrop also exposes

357   stacked trough and tabular cross-bedded sandstones deposited in bars occupying an isolated

358   channel in a tidal flat environment (the Wadi Ghorab area of Legler *et al.*, 2013).

359   Paleocurrent measurements from the cross-beds are oriented towards N196, indicating that

360   the W-E- and N-S-oriented cliff faces again provide close to strike and dip sections,

361   respectively. Tidal bar deposits exposed at Butterfly Canyon are sandier than those at Gecko

362 Nose, and the two deposits are considered to be end-members of the same heterolithic,

363 cross-bedded tidal sandstone facies.

364 High-resolution photographs and precise sketches were collected from the cliff faces of

365 both localities, in order to capture the dimensions and geometries of cross-bed sets.

366 Photographs were collected using no-distortion lenses. Each cross-bed set in the Gecko Nose

367 outcrop has been reconstructed from the high-resolution photographs and scaled using the

368 sketches. The boundaries of the cross-bed sets and their constituent foreset-toeset surfaces

369 have been traced on the reconstructed pictures, enabling quantitative, statistically

370 representative datasets to be compiled for the various input parameters of the modeling

371 methodology described above. All values are summarized in Table 1.

372 To define the dimensions of ellipsoidal elemental volumes (L_E, W_E and H_E) we used data

373 from the Gecko Nose outcrop. W_E and H_E were determined from 12 trough cross-bed set

374 boundaries (identified in Figure 8 A) from the strike-oriented face, using the method

375 presented in Figure 4. The dataset was limited to cross-bed sets with sufficient exposure to

376 allow a best fit elliptical curve, with dimensions corresponding to W_E and H_E, to be fitted to

377 their erosional basal surfaces (Figure 4 C). L_E was estimated from cross-bed sets exposed on

378 the dip-oriented face. ,The basal boundaries of all trough cross-bed sets in the dip-oriented

379 face were continuous and nearly planar over the 12 m extent of the face, suggesting

380 $L_E \gg W_E$. No pinch-outs were observed. The elemental volume density D, was determined

381 from the total of 90 trough cross-bed sets observed at the Gecko Nose location within a

382 volume of 12 x 17 x 3 m, such that D is equal to 0.15 elemental volumes per m^3. The

383 dimensions of the preserved parts of the ellipsoidal elemental volumes (L_A, W_A and H_A) were

384 determined using data from both outcrops. W_A and H_A were determined from the strike-

385   oriented face of Gecko Nose (Figure 8 B). Values of both W_A and H_A define log-normal

386   distributions (Figure 9). All of the cross-bed sets observed in the dip-oriented face of Gecko

387   Nose are laterally continuous, in which case $L_A > 12$ m. At Butterfly Canyon, L_A is observed in

388   one cross-bed set to equal 25 m, which is the value used thereafter.

389   In order to determine the degree of curvature A, the 90 foreset-toeset surfaces

390   contained in three well-preserved trough cross-bed sets in the Gecko Nose outcrop

391   (numbered 34, 50 and 52 in Figure 8 A) have been extracted from photomontages. The three

392   cross-bed sets show clear, dip-oriented cross-sections of the foreset-toeset surfaces. The

393   foreset-toeset surfaces are rotated in our analysis so that their toesets are horizontal. For

394   each foreset-toeset surface, the junction point O is identified. All the foreset curves are then

395   translated to the same origin and a best-fit parabolic curve is fitted to the data (Figure 10).

396   To determine the foreset thickness F_T, the sandstone laminae thicknesses comprised

397   between the 544 foreset-toeset surfaces contained in 12 studied cross-bed sets (identified in

398   Figure 8 A) have been measured after extraction of the surfaces from photomontages. A log-

399   normal distribution of F_T values is observed (Figure 11). The dip angle of the toesets α has

400   been measured on photopanoramas of the NNE-SSW-oriented (oblique dip-oriented) face of

401   Gecko Nose. The angle of dune climb δ has been determined by generating a best-fit line

402   through the foreset-to-toeset junction points O of laminae in each of the studied cross-bed

403   sets.

404   To define the mudstone frequency function f, the positions of mudstone drapes along

405   the same 90 foreset-toeset surfaces of the three cross-bed sets used to determine the

406   parameter A (numbered 34, 50 and 52 in Figure 8 A) have been extracted from

407   photomontages. From this dataset, a frequency distribution of mudstone drape presence

408   relative to position along the foreset has been determined using equation (7) to define a

409   best-fit curve (Figure 12).

410

411   **Results**

412   ***Models constructed from outcrop analog data***

413   The 3D models of heterolithic, cross-bedded tidal sandstones are based on those

414   observed at the Gecko Nose and the Butterfly Canyon localities. Generic models have been

415   generated using input parameters derived from both localities (Figures 13 and 14; Table 1).

416   The models are stochastically generated using the data reported in the previous section,

417   except for the elemental volumes, whose coordinates inside the model are extracted directly

418   from photomontages of the two outcrop localities so that the traces of the elemental

419   volumes in cross-sections of the model accurately reproduced the cross-bed set boundaries

420   of the outcrop sections. Both models are 9 m^3 in volume (3 x 3 x 1 m), and contain four

421   partially preserved ellipsoidal elemental volumes in the case of the Butterfly Canyon model

422   and six partially preserved ellipsoidal elemental volumes in the case of the Gecko Nose

423   model. The model volumes are approximately five orders of magnitude larger than the

424   volume of a typical core plug (c. 20 cm^3). Around 500 foreset-toeset surfaces are populated

425   in in the Gecko Nose model, whereas only 170 of the same surfaces are present in the

426   Butterfly Canyon model (parameter N_{CB} in Table 1). Note that the two outcrop localities

427   both display examples of tabular and trough cross bedding. However, the Gecko Nose

428   model shown here contains only trough cross-beds, and the Butterfly Canyon model

429   contains only tabular cross-beds, reflecting the specific parts of the outcrops modelled. The

430   mudstone drape coverage that was chosen for both models is equal to 25% along the foreset

431 parts and 57% along the toeset parts of the foreset-toeset surfaces; the foreset drape

432 coverage was extracted from outcrop data, while the toeset drape coverage is given by the

433 fraction at the foreset-toeset junction resulting from the chosen mudstone frequency

434 function (Figure 12), as outlined in the methodology.

435 A comparison between the outcrop cliff faces of Gecko Nose and Butterfly Canyon, and

436 the corresponding generic models is presented in Figure 15. The models honor the geometry

437 of the cross-bed set boundaries, in both strike and dip directions, which validates the choice

438 of having cross-bed sets represented as ellipsoidal elemental volumes (Figures 2, 3 and 4).

439 The input average foreset thickness F_T is respected as observed at the outcrop locations,

440 with F_T being smaller for the Gecko Nose model than for the Butterfly Canyon model. The

441 Gecko Nose model is relatively mudstone-rich (sandstone volume fraction $V_S/V_T = 0.89$), as it

442 comprises trough cross-beds containing a relatively high proportion of toesets and thin

443 foresets (foreset thickness $F_T = 5.85$ cm and foreset to toeset volume ratio $R_{F/T} = 6.5 : 1$,

444 Table 1) due to the high dune climb angle of $\delta = 5°$. The Butterfly Canyon model is

445 comparatively mudstone-poor (sandstone volume fraction $V_S/V_T = 0.94$), as it comprises

446 tabular cross-beds dominated by thicker foresets (foreset thickness $F_T = 10.0$ cm and foreset

447 to toeset volume ratio $R_{F/T} = 24 : 1$, Table 1), with a low dune climb angle $\delta = 0°$.

448 The distribution of mudstone drapes along the cross-bedding surfaces closely matches

449 the distribution observed at outcrop. Both in the models and at outcrop, some mudstone

450 drapes appear continuous along the entire cross-bedding surface, from the toeset part to

451 the top of the foreset at the top boundary of the cross-bed set. In most cases, the mudstone

452 drapes in the models are discontinuous over the entire length of the cross-bedding surfaces

453 in dip-oriented cross-sections, but the discontinuities are limited in the strike direction,

454 which is again a close match to outcrop observations. Discontinuities of the mudstone

455 drapes in the models are mostly located at the top of the foreset part of the cross-bedding

456 surfaces, following the trend of the input mudstone drape frequency function defined from

457 statistical analysis of outcrop data (Figure 12).

458

459 *Calculation of effective permeability*

460 The method to calculate effective permeability is presented in the companion paper

461 (Massart *et al.*, 2016) and we report only the results here for the two models shown in

462 Figures 13 and 14. We report the effective permeability as a normalized value, expressed as

463 a fraction of the sandstone permeability:

464 $$k_e^n = \frac{k_e}{k_{sand}}$$ (8)

465 The results reported in this way are independent of the value of sandstone permeability

466 used in the models; moreover, the normalized effective permeability can be rescaled to any

467 value of sandstone permeability obtained from core or mini-permeameter measurements.

468 The effective permeability of the model volume has been extracted in three orthogonal

469 directions: the horizontal effective permeability down depositional dip k_d, the horizontal

470 effective permeability along depositional strike k_s, and the vertical effective permeability k_v.

471 The mean value for horizontal permeability k_h is defined as the arithmetic average between

472 k_s and k_d such as $k_h = (k_d + k_s)/2$ (Jackson *et al.*, 2003). The results for each model are

473 summarized in Table 2. Despite the relatively low fraction of mudstone in the models, the

474 presence of the mudstone drapes significantly reduces both horizontal and vertical

475 permeabilities, and introduces permeability anisotropy in the horizontal as well as the

476   vertical directions : $k_s \neq k_d$ and $k_v \ll k_h$. For the trough-cross bedded model of Gecko Nose,

477   the dip-oriented horizontal permeability (k_d^n = 47.5%) is only 65% of the strike-oriented

478   horizontal permeability (k_s^n = 72.8%), as the flow must cross a larger number of mudstone-

479   draped foresets when flowing down depositional dip as opposed to along depositional strike.

480   The k_v/k_h ratio is reduced to only 0.040, reflecting that vertical flow must also cross

481   numerous mudstone-draped foresets. The horizontal permeability anisotropy of the tabular

482   cross-bedded Butterfly Canyon model is less pronounced than in the trough-cross-bedded

483   Gecko Nose model, reflecting the lower mudstone fraction and greater strike-oriented

484   continuity of foreset-toeset sandstone laminae in the former model: the dip-oriented

485   horizontal permeability (k_d^n = 70.0%) is 78% of the strike-oriented horizontal permeability

486   (k_s^n = 90.0%). Despite the lower overall mudstone fraction, the k_v/k_h of the tabular cross-

487   bedded Butterfly Canyon model is one order of magnitude smaller (at 0.003) than the value

488   of the trough cross-bedded model. Mudstone drapes are approximately three times more

489   numerous in the trough cross-bedded model ($N_{CB} \approx 500$) than in the tabular cross-bedded

490   model ($N_{CB} \approx 170$); they are more densely spaced and laterally continuous in the toesets of

491   the trough cross-bedded model because of the high values of the toeset dip angle α.

492   Moreover, the sandstone volume fraction in the toesets of the tabular cross-bedded model

493   is 0.26, which is less than half of the sandstone volume fraction in the toesets of the trough

494   cross-bedded model, despite the common value of mudstone drape coverage of 57% in both

495   models. The smaller value of k_v/k_h ratio in the tabular cross-bedded model arises from the

496   closer spacing of mudstone-draped toesets, higher density of toeset surfaces, and

497   consequent lower sandstone volume fraction in the toeset parts of cross-bed sets.

498   For the two models studied, the normalized effective permeability values can be rescaled

499   to any measured sandstone permeability to yield estimates of effective permeability suitable

500 for use in larger-scale reservoir models (Figure 16). For example, if the measured

501 permeability of the sandstone was 500 md, then the trough-cross bedded (Gecko Nose)

502 model yields permeability values of k_d = 238 md, k_s = 364 md and k_v = 12 md, while the

503 tabular cross-bedded (Butterfly Canyon) model yields permeability values of k_d = 350 md,

504 k_s = 450 md and k_v = 10 md. If the permeability of the sandstone was lower at 100 md,

505 effective permeabilities are proportionately reduced as well, yielding k_d = 48 md, k_s = 73 md

506 and k_v = 3 md for the trough cross-bedded model, and k_d = 70 md, k_s = 90 md and k_v = 2 md

507 for the tabular cross-bedded model. Effective permeability values from a broader range of

508 model geometries and mudstone fractions are reported in the companion paper (Massart

509 *et al.*, 2016).

510 The modeling workflow reported here can be applied to create appropriate models for

511 the calculation of effective permeability values depending on the geometric characteristics

512 of the heterogeneity surfaces of any tidal cross-bedded heterolithic sandstone observed at

513 outcrop location or in subsurface. The required input parameters and methods for

514 measuring each of them are summarized in Figure 1. The main orientation of cross-bed sets

515 (i.e. the paleocurrent) and its standard deviation can be deduced from dipmeter logs. The

516 style of cross-bedding is easily recognizable from the trace of the cross-bedding plane

517 around the core or from borehole image logs. The tracing of the cross-bedding plane on well

518 imagery can be considered for more precision, as core observations are typically only

519 possible on one half of the core. The foreset thickness F_T can be measured on core from a

520 representative number of occurrences, even if the typical width of a core (8 − 20 cm)

521 prevents observation of a complete spring-neap cycle that displays cyclical variation of

522 foreset thickness. The foreset to toeset ratio $R_{F/T}$ can be appraised in a similar way from core

523 observations, but with similar limitations on the degree to which core data can represent

524 variation in the parameter. For both parameters, an outcrop analog(s) can provide a more

525 complete dataset. As dune climb angle δ has typically small values, the ratio $R_{F/T}$ remains

526 relatively uniform in the cross-bed set (Figures 3, 5). However, no lateral variation in $R_{F/T}$ can

527 be deduced from core observations. Finally, the toeset dip angle α can be observed in core if

528 toeset areas are sampled. All input parameters can be otherwise derived from statistical

529 analysis of appropriate outcrop analogs, in a similar way to the analysis presented herein

530 using the Dir Abu Lifa Member as an outcrop analog, with the important proviso that the

531 degree of analogy between subsurface and outcrop cases must be established with due care.

532

533 **Conclusions**

534 This study presents a novel reservoir modeling methodology that accurately and

535 efficiently reproduces the geometry and connectivity of sandstone and mudstone layers in

536 heterolithic, cross-bedded tidal sandstones by stochastically modeling stratigraphic surfaces

537 and associated heterogeneity. The model input parameters are geometric and can be

538 derived from subsurface cores and/or outcrop analog observations. The application of the

539 modeling methodology is demonstrated via the construction of models that represent

540 heterogeneity in significantly larger volumes (9 m^3) than those sampled by core plugs

541 (c. 20 cm^3), using input parameters derived from analysis of an outcrop analog. Quantitative

542 outcrop-analog data are collated and used to constrain the geometry and spatial distribution

543 of the small-scale heterogeneity surfaces (i.e. cross-bed set boundaries, cross-bedding

544 foreset-toeset surfaces, and mudstone drapes). The resulting models are a close visual

545 match to the outcrop data, such that the complex mudstone and sandstone connectivity of

546 the heterolithic tidal deposits is accurately reproduced. The surface-based methodology is

547   not dependent on length scale, but on the geometric configuration and hierarchical

548   arrangement of geologic surfaces. The methodology can, therefore, be applied to a much

549   wider range of reservoir types in which the heterogeneity style can be characterized by the

550   3D shape and distribution of geologic surfaces.

551

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762

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764   Department of Earth Science and Engineering, Imperial College, UK. He obtained a B.Sc. and

765   Ph.D. from the University of Manchester. His research interests are in the

766   tectonostratigraphic evolution of rifts and the application of 3D seismic data to

767   understanding the formation and filling of sedimentary basins.

768

Figure captions

Figure 1: Three-step methodology for constructing models of heterolithic, cross-bedded tidal sandstones. A) Subdivision of the model volume into elemental volumes, in which heterogeneities have the same length scale and geometry. In the cross-bedded sandstones modeled here, the elemental volumes are cross-bed sets represented by ellipsoids with erosional bases. Ellipsoid boundaries are represented by bold black lines. B) Each ellipsoid (i.e. cross-bed set) is populated with template surfaces that represent foreset-toeset lamina boundaries. Foreset-toeset template surfaces are represented by thin black lines. C) Each foreset-toeset template surface is then lined by mudstone drapes of variable continuity, using a mudstone frequency function, to produce D) the final model. Mudstone drapes are represented by bold gray lines. For each step, the required input parameters are listed on the right of the figure. Some parameters can be extracted from subsurface core data (*) or dipmeter logs (†), whereas others must be taken from sedimentologic analogs.

Figure 2: A) Modern 3D dune in an inter-tidal flat environment, the Wash Estuary, United Kingdom. B) Interpretation of the erosion surface resulting from migration of a dune and associated scour pool as the lower part of an ellipsoid of dimensions L_E (length, in blue), W_E (width, in red), and H_E (height, in green) relative to the horizontal reference plane Γ. Dotted lines correspond to parts of the ellipsoid beneath the dune in its present position. The yellow crescent corresponds to the dune foreset, and the gray truncated ellipse to the rippled dune toeset. The bold black line corresponds to the dip cross-section of one foreset-toeset surface.

793 **Figure 3:** A) Ancient trough cross-bed set viewed in cross-section oriented approximately

794 along depositional dip (parallel to the paleocurrent direction), Dir Abu Lifa Member, Gecko

795 Nose location (NNE-SSW-oriented cliff face shown with dotted line in Figures 6, 7), Western

796 Desert, Egypt. The cross-bed set contains tidal bundles separated by double mudstone

797 drapes in the sandy foresets, and wavy-bedded muddy toesets. B) Interpretation of the

798 cross-bed set as the lower part of an ellipsoidal elemental volume. The purple line shows the

799 erosional base of the cross-bed set, and the green line shows the top surface of the

800 preserved cross-bed set (i.e. the erosional base of an overlying cross-bed set). The thin

801 dotted line is the boundary between foresets and toesets within the cross-bed set marking

802 the angle of climb of the dune δ. The bold black line corresponds to an interpreted foreset-

803 toeset template surface in dip cross-section. C) The corresponding best fit ellipsoidal

804 elemental volume is traced in 3D (see Figure 2 for colors).

805

806 **Figure 4:** A) Ancient trough cross-bed set viewed in cross-section oriented approximately

807 along depositional strike (perpendicular to the paleocurrent direction which corresponds to

808 dip direction , here out of the page), Dir Abu Lifa Member, Gecko Nose location (WNW-ESE-

809 oriented cliff face shown with bold line in Figures 6, 7; see also Figure 8 A), Western Desert,

810 Egypt. B) Interpretation of the cross-bed set as the lower part of an ellipsoidal elemental

811 volume. The purple line shows the erosional base of the cross-bed set, and the green line

812 shows the top surface of the preserved cross-bed set. The dotted arrows indicate the

813 preserved width W_A and height H_A of the cross-bed set. The bold black line corresponds to an

814 interpreted foreset-toeset template surface in strike cross-section. C) The erosional base of

815 the cross-bed set has been extracted from the photomontage and a best fit elliptical curve

816 (in red) has been defined in order to obtain the width W_E and the height H_E of the elemental

817 volume.

818

819 **Figure 5:** Detail of transition between foreset and toeset along template surfaces within an

820 elemental volume. Input parameters required to describe the geometry of the foreset-toeset

821 surfaces include foreset thickness F_T, toeset thickness T_T, the angle of climb of the dune δ,

822 and the dip angle of the toeset α. The dotted line Δ corresponds to the limit between sandy

823 foresets (light gray) and muddy toesets (dark gray), and links the junction points O of each

824 foreset-toeset surface. The reference line Γ corresponds to the median plane of the

825 ellipsoidal elemental volume that contains the foreset-toeset surfaces (blue ellipse in Figure

826 2). Once F_T is set, T_T is calculated using angles α and δ (Equation (6)).

827

828 **Figure 6:** A. Map of Egypt highlighting the position of the Eocene Dir Abu Lifa outcrop belt

829 (black rectangle, south west of Cairo) B. Map of the main outcrop belt of the Dir Abu Lifa

830 Member, highlighting the Gecko Nose and Butterfly Canyon localities. C. Close-up of the

831 Gecko Nose outcrop, with the two studied cliff faces shown with bold lines, the continuous

832 line corresponding to the WNW-ESE oriented section, and the dotted line to the NNE-SSW

833 oriented cross-section (Figure 7).

834

835 **Figure 7:** Photograph of the two nearly perpendicular cliff faces at Gecko Nose (Figure 6).

836 Paleocurrents in heterolithic, trough and tabular cross-bedded sandstones are oriented

837 towards N196 (inset rose diagram), such that the WNW-ESE-oriented (bold line) and NNE-

838 SSW-oriented cliff faces (dotted line) approximate strike and dip sections, respectively. A

839 person is present in front of the outcrop for scale.

840

841   **Figure 8:** A) Photomontage of the WNW-ESE-oriented face of Gecko Nose (bold line face in

842   Figure 7), oblique to depositional strike. The 12 numbered trough cross-bed sets were

843   chosen to define best fit elliptical curves (cf. Figure 4). B) Interpretation of the

844   photomontage. Trough (gray) and tabular (yellow) cross-beds are numbered sequentially

845   and interpreted to be stacked vertically within a tidal bar deposit. Note that the numbering

846   starts at 10, as nine underlying cross-bed sets are exposed on the adjacent SSW-NNE-

847   oriented face (dotted line face in Figure 7).

848

849   **Figure 9:** Distribution of A) the preserved height H_A and B) preserved apparent width W_A of

850   49 trough cross-bed sets exposed on the WNW-ESE-oriented face of Gecko Nose (bold line

851   face in Figure 7; Figure 8 B), oblique to depositional strike. A log-normal distribution of the

852   form LogN(μ,σ^2) is interpreted, with parameters μ: mean value; σ: standard deviation. p

853   corresponds to the Kolmogorov-Smirnov test criterion: a value of 1 corresponds to a perfect

854   fit of the data with a log-normal distribution. For the height H_A in A), μ = 0.3 cm and σ =

855   0.4 cm with p = 0.82; for the width W_A in B), μ = 3.1 cm and σ = 1.4 cm with p = 0.98.

856

857   **Figure 10:** Point clouds defining the 90 foreset-toeset surfaces traced from three cross-bed

858   sets of the WNW-ESE-oriented face of Gecko Nose (numbered 34, 50 and 52 in Figure 8 A).

859   The surfaces are translated so that their foreset-to-toeset junction points (labelled O in

860   Figure 5) are superimposed, and a best-fit line for a foreset-toeset template surface is

861   determined (bold line). This line is described by equation (5) with the curvature parameter A

862   = 5.5 x 10^{-3}, and the resulting line has a very strong correlation to the data (R^2 = 0.98).

863

864   **Figure 11:** Distribution of foreset thickness F_T for the 544 foreset-toeset surfaces of 12

865   studied cross-bed sets (Figure 8 A). A log-normal distribution of the form $LogN(\mu,\sigma^2)$ is

866   interpreted with parameters μ, mean value = 5.9 cm; σ, standard deviation = 2.0 cm.

867

868   **Figure 12:** Point cloud defining the coverage of mudstone drapes along 90 foreset-toeset

869   surfaces traced from three cross-bed sets (numbered 34, 50 and 52 in Figure 8 A). A best-fit

870   line for mudstone drape coverage along a foreset-toeset surface is determined (bold line).

871   This line is described by equation (4) with parameters M = -1.004, N = -4.316, and O = 1.610,

872   and it correlates very strongly to the data (R^2 = 0.99).

873

874   **Figure 13:** A) 3D view of the generic trough cross-bedding model, generated with input

875   parameters extracted from the Gecko Nose outcrop and summarized in Table 1. Only

876   mudstone drapes are displayed here and sandstone is removed from the model. The model

877   displays a mudstone drape coverage of 25% along the foreset parts, and a coverage of 57 %

878   along the toeset parts of the foreset-toeset surfaces. The trough aspect of the cross-bedding

879   appears in the strike direction. Warm colors indicate increasing height of mudstone drapes

880   above the cross-bed base, for each cross-bed set. B) Orthogonal sections through the same

881   model with mudstone and sandstone layers colored in black and yellow respectively. The

882   layers of mudstone have a constant thickness of 3.5 mm in the whole model. C) Dip-oriented

883   cross-section of the model presented in part A representing the cross-bedding surfaces. D)

884   The same dip-oriented cross-section but with the 25% mudstone drape coverage of foresets

885   and 57% mudstone drape coverage of toesets.

886

887 **Figure 14:** A) 3D view of the generic tabular cross-bedding model, generated with input

888 parameters extracted from the Butterfly canyon outcrop and summarized in Table 1. Only

889 mudstone drapes are displayed here and sandstone is removed from the model. The model

890 displays a mudstone drape coverage of 25% along the foreset parts, and a coverage of 57 %

891 along the toeset parts of the foreset-toeset surfaces. B) Orthogonal sections through the

892 model. The layers of mudstone have a constant thickness of 3.5 mm in the whole model.

893 C) Dip-oriented cross-section of the model presented in part A representing the cross-

894 bedding surfaces. D) The same dip-oriented cross-section but with the 25% mudstone drape

895 coverage of foresets and 57% mudstone drape coverage of toesets. Same color schemes

896 than in Figure 13.

897

898 **Figure 15:** Comparison between outcrop photographs (top row), and corresponding cross-

899 sections of the surface-based models showing foreset-toeset surfaces (central row) and

900 mudstone drapes along these surfaces (bottom row). Column A) shows dip-oriented sections

901 from the Butterfly Canyon outcrop and model. Column B) shows strike-oriented sections

902 from the Gecko Nose outcrop and model (red rectangle in Figure 8 A).

903

904 **Figure 16:** Determination of effective permeability from the flow simulation results of the

905 two outcrop models (Figures 13, 14). If the studied heterolithic sandstone features trough

906 cross-bedding with muddy toeset regions, the Gecko Nose model should be used for

907 reference; if the studied heterolithic sandstone features tabular cross-bedding with a

908 predominance of sandy foreset regions, the Butterfly Canyon model should be used. The two

909 examples of effective permeability derivation presented in the text are featured with

910   straight vertical lines: k_{sand} = 500 md and k_{sand} = 100 md. The resulting effective permeability

911   k_e can be read at the intersection of these straight lines with the different curves.

912

913   **Table captions**

914

915   **Table 1:** Input parameters for the Gecko Nose and Butterfly Canyon models (Figures 13, 14).

916

917   **Table 2:** Results for the Gecko Nose and Butterfly Canyon models (Figures 13, 14) after single

918   phase flow simulation. All measurements are dimensionless.

919 **Table 1:**

| Input parameter	Symbol	Unit	Trough cross-bedded model (Gecko Nose)	Tabular cross-bedded model (Butterfly Canyon)	Definition
Volume of the model	V_T	m^3	9	9	
Elemental volume length	L_E	m	20	20	Trough cross-beds are modelled as highly elongate, oblate ellipsoids with $L_E \gg W_E > H_E$. Tabular cross-beds are modelled as oblate ellipsoids with $W_E \geq L_E > H_E$, which yields laterally continuous sheets at the model scale (geometrical mean value $E[W_E]$ ± standard deviation $\sigma[W_E]$).
Elemental volume width	W_E	m	4.85 ± 1.67	20	
Elemental volume height	H_E	m	1.35 ± 0.55	1.35 ± 0.55	
Preserved length of elemental volume	L_A	m	80% of L_E	100% of L_E	These parameters define the preserved aspect of the ellipsoidal elemental volumes in the model, after erosion at the base of overlying elemental volumes (geometrical mean value $E[W_A]$ ± standard deviation $\sigma[W_A]$).
Preserved width of elemental volume	W_A	m	50% of W_E	100% of W_E	
Preserved height of elemental volume	H_A	m	30% of H_E	40% of H_E	
Elemental volume density	D	m^{-3}	6 elemental volumes in 9 m^3	4 elemental volumes in 9 m^3	Number of ellipsoidal elemental volumes present per unit volume of the model.
Elemental volume orientation	ϑ	°	0	0	The azimuthal orientation angle ϑ of the ellipsoidal elemental volumes corresponds to the paleocurrent direction indicated by the foreset-toeset surfaces within a cross-bed set.
Number of cross-bedding surfaces	N_{CB}	-	≈500	≈170	
Parabolic curvature of foreset-toeset template surfaces	A	-	5.5 x 10^{-3}	5.5 x 10^{-3}	Characteristic coefficient of the square term for a parabolic curve, $z(x) = Ax^2$ as equation (1)

Foreset thickness	F_T	cm	5.85 ± 3.88	10 ± 3.88	Distance between two consecutive foreset-toeset surfaces, measured between their junction points O and O' (Figure 5).
Toeset dip angle	α	°	8	1	Angle between the straight toeset surface and the median reference plane of the ellipsoidal elementary volume Γ (Figure 5)
Angle of dune climb	δ	°	5	0	Angle between the median reference plane Γ and the boundary surface Δ which separates the foreset and the toeset parts in an elementary volume (Figure 5)
Foreset to toeset volume ratio	$R_{F/T}$	-	6.5 : 1	24 : 1	Ratio of the volume occupied by foreset by the volume occupied by toeset in the model
Mudstone frequency function	$f(M,N,O)$	-	Function f of Figure 12	Function f of Figure 12	Defined in 2D, along the azimuth of the ellipsoidal elemental volume (i.e. dip direction), according to the distance from the top of the foreset to the junction point O with the toeset. M = -1.004, N = -4.316, and O = 1.610 in equation (7)
Mudstone drape coverage	M_C	-	Foreset 25% Toeset 57%	Foreset 25% Toeset 57%	Mudstone patches are added along the foreset-toeset template surfaces until a specific proportion M_C of their area is covered. $$M_C = A_M / A_F$$
Total area of the preserved foreset-toeset surface	A_F	cm²	-	-	
Area of the foreset-toeset surface covered by mudstone	A_M	cm²	-	-	
Mudstone patch length	MP_L	cm	[0 – 20] Uniform distribution	[0 – 100] Uniform distribution	After the dimension of the major axis of the elliptical patch MP_L is defined, the dimension of the minor axis MP_W is randomly set as a fraction of MP_L
Mudstone patch width	MP_W	cm	[0 – 20] Uniform distribution Smaller than MP_L	[0 – 20] Uniform distribution Smaller than MP_L	

920 **Table 2:**

Measured parameter	Symbol	Trough cross-bedded model (Gecko Nose)	Tabular cross-bedded model (Butterfly Canyon)
Mudstone volume fraction	V_M/V_T	0.11	0.06
Sandstone volume fraction	V_S/V_T	0.89	0.94
Normalized effective dip horizontal permeability	k_d	47.5%	70.0%
Normalized effective strike horizontal permeability	k_s	72.8%	90.0%
Normalized effective vertical permeability	k_v	2.4%	2%
Ratio of vertical permeability by horizontal permeability	k_v/k_h	0.0399	0.0025

921

Input parameters

A)
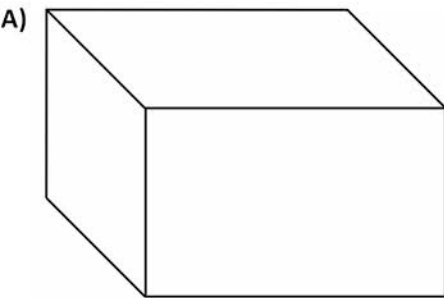
Ellipsoidal elemental volume
Dimensions: L_E, W_E, H_E
Cross-set density: D
Preserved dimensions: L_A, W_A, $\mathbf{H_A}$*
Cross-set orientation: $\boldsymbol{\Theta}^\dagger$
(Figures 2, 3, 4 and 9)

B)
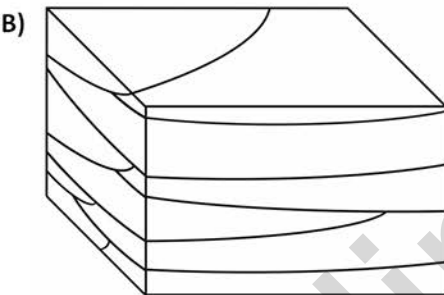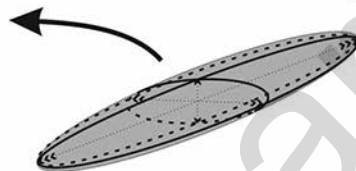
Foreset-toeset template surface
Parabolic curvature: A
Foreset thickness: $\mathbf{F_T}$*
Dip angle of the toeset: $\boldsymbol{\alpha}$*
Dune climb angle: δ
(Figures 2, 3, 5, 10 and 11)

DIP

STRIKE

C)
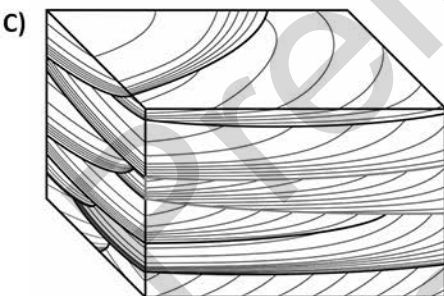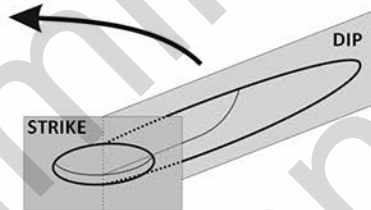
Mudstone drapes
Mudstone frequency function: $f(M, N, O)$
Mudstone drape coverage: M_C
Mudstone patch dimensions: MP_L, MP_W
(Figure 12)

Mudstone frequency function f

1

0

Toeset   **Distance**   Foreset

D)

A)
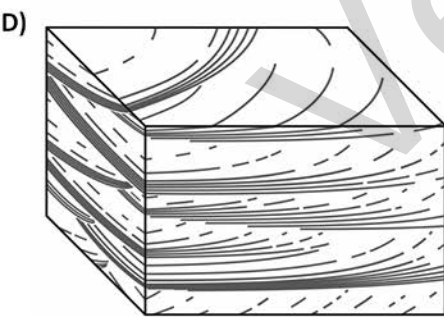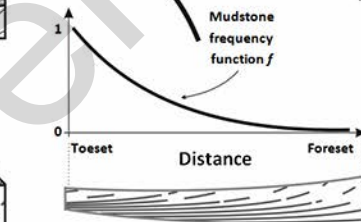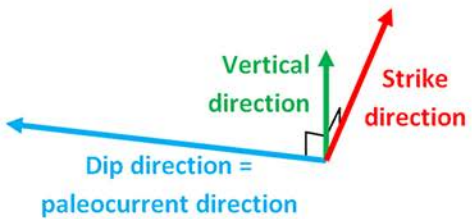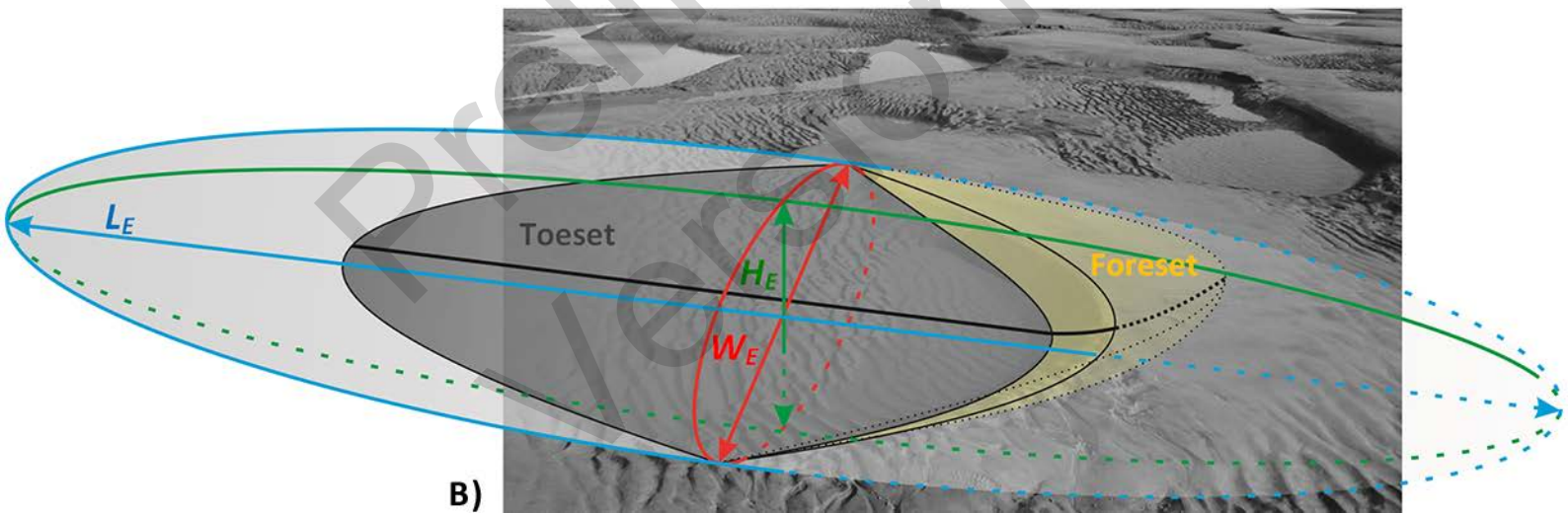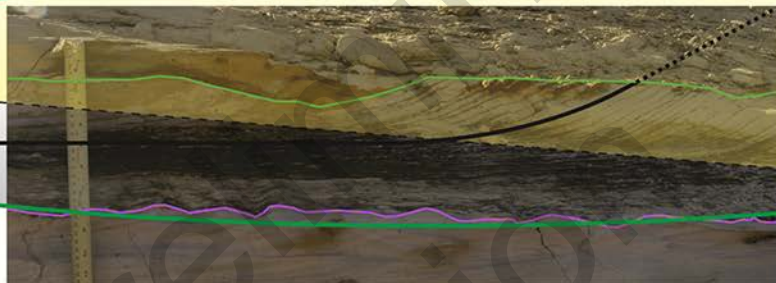
B) Foreset
Toeset
Top boundary
of the cross-bed set
Erosive base
of the cross-bed set
Γ
δ

C) L_E
H_s
W_E

20 cm

A) Strike direction — Dip direction — 50 cm

B) Top boundary of the cross-bed set — H_A — W_A — Erosive base of the cross-bed set

C) H_E — W_E — Z direction (cm) — Y direction (cm)

A. 200 km

Egypt

Cairo

Nile

B.

Butterfly Canyon

Dir Abu Lifa

Gecko Nose

Qasr el Sagha

C. Gecko Nose close-up

10 m

5 km

N29.62°

N29.60°

N29.58°

E30.60°   E30.65°   E30.70°

N = 196

N110|N210
0.0

N290
-17.0m

N030
12.5m

3.0m

A)

Length (m)

B)

B) Cross-bed set preserved width W_A (m)

Foreset thickness F_T (cm)

A) Dip-oriented cross-section

B)

C) 3m / 1m

D) 1m

A) Dip-oriented cross-section

B)

C) 3m | 1m

D) 1m

Figure axis labels:
- Y-axis: Heterolithic sandstone effective permeability k_e (md)
- X-axis: Initial sandstone permeability k_s (md)

Curve labels: k_s BC, k_s GN, k_d BC, k_d GN, k_v GN & BC

Legend:
Gecko Nose model
— — k_d
—— k_s
······ k_v

Butterfly Canyon model
—·—· k_d
— — k_s
······ k_v