The Palaeo-bathymetry of Base Aptian Salt Deposition on the Northern Angolan Rifted Margin: Constraints from Flexural Backstripping and Reverse Post-breakup Thermal Subsidence Modelling

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Abstract

The bathymetric datum with respect to global sea level for Aptian salt deposition in the South Atlantic is hotly debated. Some models propose that the salt was deposited in an isolated ocean basin in which local sea level was between 2km and 3km below the global level. In this study, we use reverse post-breakup subsidence modelling to determine the palaeo-bathymetry of base Aptian salt deposition on the Angolan rifted continental margin. The reverse post-breakup subsidence modelling consists of the sequential flexural isostatic backstripping of the post-breakup sedimentary sequences, decompaction of remaining sedimentary units and reverse modelling of post-breakup lithosphere thermal subsidence. The reverse modelling of post-breakup lithosphere thermal subsidence is carried out in 2D and requires knowledge of the continental lithosphere stretching factor (β), which is determined from gravity anomaly inversion. The analysis has been applied to the ION-GXT CS1-2400 deep long-offset seismic reflection profile and the P3 and P7+11 seismic cross sections of Moulin (2005) and Contrucci et al. (2004) offshore northern Angola. Reverse post-

23 breakup subsidence modelling restores the proximal autochthonous base salt to 200-300m below

24 global sea level at the time of breakup. In contrast, the predicted water-loaded bathymetries of the

25 more distal base salt restored to breakup time are much greater, ranging between 1km and 3km.

26 The predicted bathymetries of the first unequivocal oceanic crust at breakup are approximately

27 2.5km, as expected for newly formed oceanic crust of 'normal' thickness. Several interpretations of

28 these results are possible. Our preferred interpretation is that all Aptian salt on the northern Angola

29 rifted continental margin was deposited 200-300m beneath global sea level and that the proximal

30 salt subsided by post-rift (post-tectonic) thermal subsidence alone, while the distal salt formed

31 during late syn-rift when the underlying crust was actively thinning resulting in additional tectonic

32 subsidence (followed by post-rift thermal subsidence). An alternative interpretation is that the distal

33 salt is para-autochthonous and moved down-slope into much deeper water during and just after

34 breakup. We do not believe that a deep isolated ocean basin, with local sea level 2-3km beneath

35 global sea level as has been proposed, is required to explain the Aptian salt deposition on the

36 northern Angolan rifted continental margin.

Introduction

38 The northern Angolan rifted continental margin has been the subject of extensive seismic surveys

39 (Contrucci et al., 2004; Moulin et al., 2005), due to its hydrocarbon resources. The presence of thick

40 sedimentary packages impacted by a massive middle to upper Aptian salt sequence (up to 5km

41 thickness in places), makes seismic imaging and interpretation of the sub-salt difficult and presents

42 major scientific and technical challenges to understanding crustal structure and tectonic history.

43 Whether the northern Angolan Aptian salt sequence is pre-breakup or post-breakup remains a topic

44 of major debate; also the palaeo-water depths through the breakup period and the mechanisms

45 responsible for generating accommodation space through time are uncertain (Jackson et al., 2000;

46 Karner and Driscoll, 1999; Karner et al., 2003; Karner et al., 1997; Moulin, 2003; Moulin et al., 2005).

47 There is also much debate concerning the geometry and nature of the pre-salt basin, and the

48 underlying crustal basement structure (Contrucci et al., 2004; Karner and Gambôa, 2007; Nurullina,

49 2006). Our analysis of the offshore northern Angolan margin is focussed on three profiles in the

50 Kwanza region; locations are indicated in Figure 1(a). The three profiles include the ION-GXT deep

51 long offset seismic reflection profile CS1-2400 (Figure 1(c)) and the P3 (Figure 1(d)) and P7+11

52 profiles (Figure 1(e)) (Contrucci et al., 2004; Moulin et al., 2005). The purpose of this paper is to

53 provide an understanding of the palaeo-bathymetries of the base Aptian salt deposition (both

54 proximal and distal) along the northern Angolan rifted continental margin and to understand how

55 the salt sits within the broad framework of the ocean continent transition (OCT).

Reverse post-breakup thermal subsidence modelling

56

57 Reconstructed palaeo-bathymetries of base Loeme salt (top Aptian) along the CS1-2400, P3 and

58 P7+11 profiles has been determined using reverse post-breakup subsidence modelling (Kusznir et al.,

59 1995; Roberts et al., 1998). The reverse post-breakup subsidence modelling (Figure 2) consists of

60 the sequential flexural isostatic backstripping of the post-breakup sedimentary sequences,

61 decompaction of the remaining sedimentary units and reverse modelling of post-breakup

62 lithosphere thermal subsidence. The magnitude of reverse post-breakup thermal subsidence is

63 controlled by the continental lithosphere stretching factor (β) (McKenzie, 1978) which we predict

64 from gravity anomaly inversion. The magnitude of β therefore controls the restored model elevation

65 relative to sea level and the predicted palaeo-bathymetry (Roberts et al., 2009; Roberts et al., 1998).

66 We use the CS1-2400 profile to describe in detail the modelling approach.

67 Continental lithosphere stretching factors (β) (McKenzie, 1978) range between one and infinity; for

68 presentation purposes we prefer to use the related parameter, continental lithosphere thinning

69 factor ($\gamma = 1-1/\beta$), which ranges between zero and one.

70 Our gravity anomaly inversion, uses bathymetry (Amante and Eakins, 2009) (Figure 1(a)), satellite

71 derived free air gravity (Sandwell and Smith, 2009) (Figure 1(b)), sediment thickness data from the

72 ION-GXT profile (Figure 1(c) and ocean age isochrons (Müller et al., 1997) to determine continental

73 lithosphere thinning, crustal basement thickness and Moho depth. The gravity anomaly inversion is

74 carried out in the 3D spectral domain using the scheme of Parker (1972) and also incorporates a

75 lithosphere thermal gravity anomaly correction to account for the lithosphere mass deficiency from

76 the elevated geothermal gradient within oceanic and thinned continental margin lithosphere.

77 Failure to include the lithosphere thermal gravity anomaly correction at rifted continental margins

78 leads to predictions of Moho depth and crustal basement thickness which are too great and

79 continental lithosphere thinning factors which are too low. The thermal gravity anomaly correction

80 is dependent on the thermal re-equilibration time since lithosphere stretching and thinning, and

81 therefore on continental breakup age. We have used 110Ma as the age of breakup, after Moulin

82 (2005), for the thermal re-equilibration time to determine the lithosphere thermal gravity anomaly

83 correction, but have also examined sensitivities to ages for thermal re-equilibration which span the

84 period Berriasian (140Ma) to early Albian (110Ma). This range corresponds to the start and end of

85 the main rifting episode in the South Atlantic (Teisserenc and Villemin, 1989). A more detailed

86 description of the gravity anomaly inversion methodology is described in Chappell and Kusznir

87 (2008) and Greenhalgh and Kusznir (2007), whilst the example applications are described in Alvey et

88 al. (2008) and Cowie and Kusznir (2012).

89 Moho depths determined from the gravity anomaly inversion are in good agreement with those

90 determined from the CS1-2400 seismic reflection profile. Moho depths predicted from gravity

91 anomaly inversion for sensitivities to reference Moho depth are shown in Figure 3(a). The reference

92 Moho depth has been calibrated on the CS1-2400 profile using the clear oceanic Moho reflectors.

93 Calibration (Figure 3(b)) shows that a reference Moho depth of 35.5km is required in order to

94　　predict crustal basement thicknesses consistent with those seen in the oceanic domain of the CS1-

95　　2400 seismic reflection profile.

96　　A crustal cross section along the CS1-2400 profile (Figure 4(a)) has been constructed using Moho

97　　depths predicted from gravity anomaly inversion assuming the calibrated reference Moho depth of

98　　35.5km; bathymetry and 2D sediment thickness are from the CS1-2400 seismic profile. The

99　　corresponding continental lithosphere thinning factors (γ) predicted from gravity anomaly inversion,

100　assuming depth uniform stretching and thinning are shown in Figure 4(b). Continental lithosphere

101　thinning factors of zero indicate that there has been no stretching or thinning of the continental

102　lithosphere, whereas a continental lithosphere thinning factor of one indicates that there has been

103　infinite stretching and thinning of the original continental lithosphere and that no continental crust

104　or lithosphere remains.

105　Stretching of continental lithosphere leads to a decrease in crustal basement thickness; however,

106　decompression melting during rifting and seafloor spreading generates oceanic crust, SDRS (seaward

107　dipping reflectors) and magmatic under plating, which increases crustal basement thickness. A

108　correction for magmatic addition has been included within the gravity anomaly inversion method,

109　and uses a parameterization of the decompression melting model of White and McKenzie (1989) to

110　predict the thickness of the crustal magmatic addition (see Chappell & Kusznir (2008) for a detailed

111　explanation). Sensitivities to magmatic addition including a normal magmatic and a magma poor

112　solution have been examined along the CS1-2400 profile (Figure 4(b)). At the western end of the

113　profile we prefer the normal magmatic solution; however, in the central region of the profile we

114　believe that the magma poor solution is preferential.

Palaeo-bathymetry of the base Aptian salt deposition for the CS1-2400 profile

Flexural backstripping and decompaction has been applied to the CS1-2400 profile (Figure 5(a) to remove the salt and post-salt sedimentary layers in order to determine the bathymetry corrected for sedimentary loading to base salt (Figure 5(b)). Flexural backstripping and decompaction assumes shaly-sand compaction and density parameters (Sclater and Christie, 1980) during the removal of the sedimentary layer, whilst the salt layer is given a simple salt lithology (Hudec and Jackson, 2007) (Table 1).

The complex salt movement in this region may appear to be problematic for flexural backstripping. However, within the palaeo-bathymetric restoration we use the base salt as the target surface for backstripping, which allows us to ignore the salt movement, as we flexurally backstrip through the salt to the time of deposition. We are able to disregard the salt movement because as the salt moved the lithosphere would have responded isostatically to compensate.

The bathymetry corrected for sediment loading and decompaction to base salt (Figure 5(b)) is sensitive to the effective elastic thickness (Te) or lithosphere flexural strength (Bertotti et al., 1998; Galán and Casallas, 2010; Roberts et al., 1998). The effective elastic thickness depends on the bending stresses applied to the plate, the rate of stress application, the lithosphere composition and the geothermal gradient (Kusznir and Karner, 1985). Sensitivities to effective elastic thicknesses of 1.5km, 5km and 10km used in our flexural backstripping have been examined. A finite effective elastic thickness is required for syn-rift flexural backstripping in order to preserve fault block topography (Kusznir et al., 1995; Roberts et al., 1998); the use of Airy (local) isostasy in flexural backstripping (corresponding to Te=0km) produces unrealistic internal deformation of individual fault-blocks. Roberts et al. (1998) showed that effective elastic thicknesses between 1.5km and 5km are required for syn-rift extensional settings in order to match observed fault block geometries and

139   dips. Roberts et al. (1998) showed that relatively long wavelengths loads of post-rift subsidence and

140   sediment loading are relatively insensitive to effective elastic thickness. During the post-rift the

141   lithosphere cools and gets flexurally stronger, therefore, in the post-rift the effective elastic

142   thicknesses will be larger, which act to freeze in the structures and the short wavelength isostatic

143   response from the syn-rift. In this study we therefore use a low effective elastic thickness

144   (Te=1.5km) appropriate for syn-rift flexurally backstripping.

145   The application of flexural backstripping and decompaction gives an incomplete palaeo-bathymetric

146   restoration of base salt; we also need to include reverse post-breakup thermal subsidence. We

147   determine the magnitude of reverse post-breakup thermal subsidence by the continental

148   lithosphere thinning factor ($\gamma=1-1/\beta$) which we derive from gravity anomaly inversion. Lithosphere

149   thinning factors from gravity inversion are shown in Figure 5(c); sensitivities for a normal magmatic

150   solution and a magma poor solution have been examined. At the western end of the CS1-2400

151   profile the continental lithosphere thinning factors for a normal magmatic solution are 1.0; whereas

152   for a magma poor solution, the continental lithosphere thinning factors are approximately 0.85. In

153   the central section of the profile, the continental lithosphere thinning factors, for both solutions

154   examined, are between 0.7 and 0.85.

155   The restored palaeo-bathymetry to base salt, including reverse thermal subsidence modelling, is

156   shown in Figure 5(d) assuming a normal magmatic solution and a breakup age of 112Ma. The

157   proximal base salt restores to just below global sea level with an average bathymetry of

158   approximately 0.3km. In contrast, the distal base salt does not restore to near sea level; restored

159   palaeo-bathymetries for the distal base salt (smoothing through fault controlled topography) are

160   between approximately 0.9km and 2.5km below global sea level.   In the deep fault controlled

161   troughs, palaeo-bathymetries for the distal base salt of approximately 4.0km below sea level are

162   predicted.

163   Assuming a magma poor solution (Figure 5(e)), the restored palaeo-bathymetry to base salt also

164   shows that the proximal base salt restores to just below sea level, whilst the distal base salt again

165   does not. The predicted palaeo-bathymetries of the distal base salt range between approximately

166   0.9km and 3km below sea level (smoothing through fault controlled topography); in the deep

167   structural troughs the palaeo-bathymetries are greater (approximately 4.5km below sea level).

168   The lower thinning factors from gravity inversion for the magma poor solution result in less reverse

169   post breakup thermal subsidence and a slightly greater predicted bathymetry for base salt compared

170   with the normal magmatic addition solution. The normal magmatic addition solution (Figure 5(d)) is

171   applicable to the oceanic part of the profile while the magma poor solution (Figure 5(e)) is applicable

172   to the continental end of the profile, with a transitional region in between.

173   The restoration of base salt palaeo-bathymetry (Figures 5(d) and (e)) using reverse post-breakup

174   thermal subsidence modelling only restores thermal subsidence. It does not restore syn-rift (syn-

175   tectonic) subsidence and the consequences of crustal thinning; subsidence arising from syn-tectonic

176   crust and lithosphere thinning is not included in the restoration.

177   In the oceanic domain, depths of approximately 2.5km (± 0.2km depending on magmatic solution),

178   consistent with an oceanic ridge are predicted, for both a normal magmatic and a magma poor

179   solution.

180   An additional sensitivity to the continental lithosphere thinning factors, used to drive reverse

181   thermal subsidence, has been examined for CS1-2400 profile. A continental lithosphere thinning

182   factor of 1.0 (corresponding to β=∞), which gives an upper bound of the restored post-breakup

183   thermal subsidence, has been applied to the entire profile (Supplementary Figure S1). The predicted

184   bathymetry for the base of the distal salt remains almost unchanged at between 2km and 3km

185   below global sea level. This implies that, if the base distal salt was deposited at or just below global

186   sea level, it has subsided not only due to post-breakup thermal subsidence and sediment loading.

187   Due to the thick sedimentary cover and mobile salt (including salt diapirs and canopies), seismic

188   imaging of the salt and pre-salt sedimentary units is difficult, which could lead to errors in our

189   interpretation of the internal structure and thickness of the salt and the pre-salt sedimentary layers.

190   We are however, more confident in our pick of the base salt.   In order to understand the

191   implications of either over or under estimating the thickness of the salt layer we have examined the

192   effect of treating the salt layer as a sedimentary layer with a shaly sand lithology within the gravity

193   inversion and in the reverse post-breakup subsidence modelling (Figure 6). The presence of the salt

194   layer effects the decompaction and thinning factor estimates.   If there was no salt along the margin,

195   this would result in a deeper Moho (Figure 6(a)) and smaller continental lithosphere thinning factors

196   (Figure 6(b)) from the gravity inversion, which in turn would lead to less reverse modelled thermal

197   subsidence and a deeper restoration of the base salt (Figure 6(c)). The largest differences between

198   the palaeo-bathymetric restorations of the base salt with the salt layer compared to that produced

199   without the salt layer are seen in the large troughs at the western end of the profile (approximately

200   0.3km difference). The inclusion or omission of the salt layer does not fundamentally change the

201   predicted palaeo-bathymetry of base salt.

202   Figure 5 (d and e) are calculated using a breakup age within the gravity inversion and reverse

203   thermal post-breakup thermal subsidence modelling of 112Ma. Seismic reflection shows a thick pre-

204   salt sediments up to 8km thick (Unternehr et al., 2010) beneath the proximal salt which almost

205   certainly consists of a lower syn-rift sequence with a sag post-rift sequence above. The rift age in this

206   region is older than breakup and may be as old as 140 Ma (Teisserenc and Villemin, 1989).   The

207   effect of using 140 Ma as the rift age (the age for thermal re-equilibration in the gravity inversion

208   and reverse thermal subsidence modelling) gives a slightly deeper base proximal salt palaeo-

209   bathymetry but does not change the overall result that base proximal salt restores to a much

210   shallower palaeo-bathymetry than the distal salt.

211 In our analysis, we assume depth uniform lithosphere stretching for both the determination of the

212 lithosphere thermal gravity anomaly correction and the reverse post-breakup thermal subsidence

213 modelling and thinning. While the possibility of depth dependent lithosphere stretching and thinning

214 during rifted continental margin formation has been postulated (e.g. Davis and Kusznir (2004)and

215 Kusznir and Karner (2007)), we prefer to assume depth uniform stretching in the absence of reliable

216 fault extension observations.

Reverse post-breakup subsidence for the P3 and P7+11 profiles

218 In addition to the CS1-2400 profile, we have also applied the reverse post-breakup thermal

219 subsidence modelling to the more northerly P3 and P7+11 profiles (Figures 7 and 8). Results are

220 comparable to those predicted for the CS1-2400 profile; with the proximal base salt restoring to

221 approximately sea level whilst the distal base salt restores to between 2km and 3km below global

222 sea level.

223 Predicted thinning factors from gravity inversion, assuming normal magmatic addition, are 1.0 at the

224 western end of both P3 and P7+P11 profiles consistent with the presence of oceanic crust. Predicted

225 palaeo-bathymetries for the western end of both profiles are on average 2.85km, consistent with

226 water depths on newly formed oceanic crust. Continental lithosphere thinning factors predicted

227 from gravity inversion under the salt are dependent on whether normal or magma poor

228 decompression melting is assumed. This difference in thinning factor leads to a difference in the

229 predicted bathymetry of base salt from reverse thermal subsidence modelling. Nonetheless, for both

230 profiles, the predicted palaeo-bathymetries for base proximal salt are at or just below global sea

231 level, while the palaeo-bathymetry of base distal salt is between 2km and 3km. At the extreme

232 eastern end of profile P7+11 the predicted sub aerial exposure of approximately 0.9km is probably

233 an edge effect from the flexural backstripping or a decompaction artifact.

234   Calibration of the reference Moho depth used within the gravity anomaly inversion, for the P3 and

235   P7+11 profiles, gives a reference Moho depth of 37.5km, which is larger than that predicted for the

236   CS1-2400 profile. We have therefore, considered the sensitivity to reference Moho depth within the

237   reverse post-breakup thermal subsidence modelling (Supplementary Figure S2), using CS1-2400 as

238   the example. Increasing the reference Moho depth from 35.5km to 37.5km results in a deeper

239   Moho and smaller continental lithosphere thinning factors predicted from gravity anomaly inversion,

240   and a deeper restoration of the base salt. The largest differences between the palaeo-bathymetric

241   restorations of the base salt for a reference Moho depth of 35.5km compared to that produced with

242   a reference Moho depth of 37.5km are seen in the large troughs at the western end of the profile

243   (approximately 0.35km difference).

244 Location of the distal salt with respect to COB location along the CS1-
245 2400 profile

246   Knowledge of the horizontal position of the distal salt with respect to the continent-ocean boundary

247   (COB) and ocean-continent transition (OCT) structure is important for understanding the

248   depositional context of the base Aptian salt and how the salt sits within the broad framework of the

249   OCT. The structure of the OCT and COB location have been investigated using gravity anomaly

250   inversion, sediment corrected residual depth anomaly (RDA) analysis and subsidence analysis. A

251   detailed description of the methodologies of these techniques is beyond the scope of this paper, but

252   is described in Cowie (2015).

253   The results from these techniques applied to the CS1-2400 profile are shown in Figure 9. We

254   interpret the analysis results as showing three distinct crustal zones along the profile: oceanic crust

255   towards the western end of the profile, hyper-extended continental crust in the centre of the profile,

256   and continental crust at the eastern end of the profile. The dashed lines indicate the boundary

257   between each of these interpreted crustal domains; although these interfaces are shown as a sharp

258   line, in reality they are likely to be transitional boundaries. The COB is identified as the ocean ward

259   start of 'normal' oceanic crust and is identified by changes in crustal basement thickness, inflections

260   in the RDA analysis signal and also changes in the continental lithosphere thinning from subsidence

261   analysis and gravity anomaly inversion.

262   In the interpreted oceanic domain at the western end of the profile, crustal basement thicknesses

263   (Figure 9(a)) predicted from gravity anomaly inversion are approximately 7km, as expected for

264   oceanic crust. Oceanic crust of normal thickness should have a sediment corrected RDA of

265   approximately zero, notwithstanding the contribution of mantle dynamic topography. The slightly

266   positive sediment corrected RDA in this domain (Figure 9(b)) is consistent with the presence of

267   oceanic crust together with some mantle dynamic uplift, as reported by Crosby & McKenzie (2009)

268   for the Angolan margin. Continental lithosphere thinning factors from gravity anomaly inversion and

269   subsidence analysis (Figure 9(c)) are 1.0, also consistent with the presence of oceanic crust. Between

270   the oceanic domain and the hyper-extended continental crust domain, we see an increase in crustal

271   basement thickness and the RDA signal, whilst the continental lithosphere thinning factors decrease.

272   In our interpreted hyper-extended continental crust domain, gravity anomaly inversion predicted

273   crustal basement thicknesses range between 7km and 12km. The sediment corrected RDA increases

274   before plateauing at approximately 1000m, whilst the continental lithosphere thinning factors

275   decrease from 1.0 to between 0.7 and 0.85, which is indicative of thinned continental crust. At the

276   western end of the hyper-extended continental crust domain, the thinning of the continental crust

277   may increase together with the start of magmatic addition as ocean crust is approached. Our

278   interpretation of the presence of hyper-extended continental crust in this domain is significantly

279   different to that proposed by Unternehr et al. (2010), who proposes the presence of serpentized

280   exhumed mantle. Our quantitative analysis results show no evidence of exhumed mantle; exhumed

281   mantle would show a thinner crust from gravity inversion, lower (negative) sediment corrected RDAs

282   and higher continental lithosphere thinning factors. At the eastern end of the profile we interpret

283   continental crust as the crustal basement thickness and sediment corrected RDA increases, whilst

284   the continental lithosphere thinning factors decrease to between 0.2 and 0.4.

285   We have identified the location of the COB on Figure 5, by the dashed line, in order to see where the

286   salt sits within the OCT. We believe that the majority of the salt along the CS1-2400 profile is

287   located to the east of the COB and is underlain by hyper-extended continental crust.

Discussion

289   Predicted palaeo-bathymetries have been determined for the base Loeme salt using 2D-flexural

290   backstripping and decompaction, together with reverse modelling of post-breakup thermal

291   subsidence. Continental lithosphere thinning factors derived from gravity anomaly inversion have

292   been used to determine the reverse post-breakup thermal subsidence. Sensitivities to normal

293   magmatic and magma poor solutions for determining thinning factors from gravity inversion have

294   been examined. For profile CS1-2400, thinning factors, from both the normal magmatic and magma

295   poor solutions, used to drive the reverse post-rift thermal subsidence modelling restore the proximal

296   autochthonous base salt to between 200m and 300m below global sea level at the time of breakup.

297   A similar palaeo-bathymetry for base proximal salt at breakup is predicted for profile P7-11. For

298   profile P3, predicted base proximal salt palaeo-bathymetry is slightly shallower with values at or just

299   below global sea level. In contrast, for all three profiles, reverse post-breakup subsidence modelling

300   restores the distal base salt to between 2km and 3 km below global sea level Even if we apply a

301   continental lithosphere thinning factor of 1.0 to drive the reverse post-rift thermal subsidence along

302   the full length of the three profiles (which is unreasonable), the palaeo-bathymetries of base distal

303   salt do not restore to sea level, demonstrating that it is not possible to generate the subsidence of

304   the base salt by post-rift subsidence alone. The predicted bathymetries at breakup of the first

305   unequivocal oceanic crust are approximately 2.5km as expected for newly formed oceanic crust of

306   normal thickness. As previously mentioned, sensitivities to effective elastic thickness and breakup

307   age have been examined. The value of effective elastic thickness does not significantly change the

308   palaeo-bathymetry predictions.   Changing the breakup age has a small effect on the palaeo-

309   bathymetry predictions but does not change the overall conclusions.

310   We consider several possible explanations of the palaeo-bathymetric restoration of the distal base

311   salt to water depths substantially below sea level:

312   (i) All the Aptian salt along the northern Angolan profiles was deposited between 200m and 300m

313   below global sea level, but the distal salt was emplaced during late syn-rift while the continental

314   crust under it was being actively thinned resulting in additional tectonic subsidence.   This is

315   consistent with seismic evidence, which shows that the distal base salt is extensionally faulted. Also

316   crustal basement thicknesses from gravity inversion, RDA and subsidence analysis, summarised in

317   Figure 9, suggest that the distal salt is underlain by hyper-extended continental crust rather than

318   oceanic crust or exhumed mantle. In contrast to the distal salt, the proximal salt formed in a region

319   where crustal thinning had already taken place, but had ceased. This interpretation requires that the

320   distal salt subsides by syn-rift crustal thinning and post-rift thermal subsidence, whilst the proximal

321   salt subsides by post-rift thermal subsidence alone. Diachronous thinning of the continental crust

322   from inboard to outboard is to be expected from both observation and modelling ,and is consistent

323   with breakup tectonic models proposed by Péron-Pinvidic and Manatschal (2009), Pindell and

324   Kennan (2007), Ranero & Perez-Gussinye (2010) and Brune et al. (2014).

325   (ii) An alternative explanation is that during breakup the distal salt moved down-slope to its present

326   position into much deeper water (and is para-autochthonous). If in the distal regions, the salt is

327   para-autochthonous (or allochthonous) this suggests that it was not deposited in deep water and

328   that the salt should not restore to sea level. This interpretation is similar to that advocated in the

329   Gulf of Mexico by Hudec et al. (2013) and Rowan and Vendeville (2006).

330   (iii) An interpretation which is often invoked (e.g. Burke and Sengör (1988), Burke et al. (2003) and

331   Karner and Gambôa (2007)) to explain the palaeo-bathymetry of the base Aptian salt along the

332   northern Angolan margin is that the Aptian salt deposition occurred in confined environmental

333   conditions (e.g. in a Messinian-type basin, isolated from global sea level). Although a structural

334   barrier in the south is not dismissed, we believe that there is no definite requirement to invoke an

335   isolated ocean basin with local sea level 2km and 3km below global sea level for the deposition of

336   the Aptian salt on the Angolan rifted margin.   A strong argument against the isolated basin

337   interpretation is presented by Pindell et al. (2014) , with reference to the Gulf of Mexico. Pindell et

338   al. (2014) argue that an isolated basin hypothesis is unlikely as it requires a complicated scenario of

339   inter-related events to occur. They propose that first rifting must produce a large basin area in

340   which the depositional surface remains approximately 2km below sea level, there must also be land

341   barriers, which are able to block out the global sea during the formation of the large basin. Then, at

342   the time of salt deposition there needs to have been repeated spill/desiccation cycles and a semi-

343   permeable barrier which continuously allowed just the right amount of sea water into basin so that

344   shallow-water evaporative conditions were maintained until the end of the salt deposition.

345   Our preferred interpretation of our palaeo-bathymetric restoration of the base Aptian salt along the

346   northern Angolan profiles is the first interpretation with a possible contribution from the second

347   interpretation. In summary we believe that both proximal and distal Aptian salt on the Kwanza

348   margin was deposited at a datum 200-300 m below global sea level, but that the distal salt was

349   deposited during late syn-rift while the crust under it was being actively thinned which resulted in

350   additional tectonic subsidence. It is possible that some of the distal salt is para-autochthonous and

351   moved down-slope to its present day position. It is also possible that syn-tectonic (pre-breakup)

352   extension continued post-salt deposition in the distal region.

Figure Captions:

Table 1 – Compaction and density parameters used within the reverse post-breakup thermal subsidence modelling.

Figure 1: Data used in the reverse post-breakup thermal subsidence modelling and gravity anomaly inversion for the northern Angolan rifted continental margin.   (a) Bathymetry (km) (Amante and Eakins 2009), with the location of profiles CS1-2400, P3 and P7+11 indicated. (b) Satellite derived free air gravity (mgal) (Sandwell and Smith 2009). (c) Deep long-offset seismic reflection depth section (PSDM) for the ION-GXT CS1-2400 profile. (d) Seismic velocity model along the P3 profile (Contrucci et al., 2004; Moulin et al., 2005) from seismic refraction data. (e) Seismic velocity model along the P7+11 profile (Contrucci et al., 2004; Moulin et al., 2005) from seismic refraction data.

Figure 2: Schematic series of sequential cross sections showing reverse post-rift thermal subsidence modelling from present day to base post-rift for a hypothetical rift basin (Kusznir et al., 1995).

Figure 3: Calibration of the reference Moho depth used in the gravity anomaly inversion against seismic Moho depths for the CS1-2400 profile on the northern Angolan margin. (a) Sensitivity of Moho depth predicted from gravity anomaly inversion to reference Moho depths of 32.5km, 35km and 37.5km.   (b) Cross-plot of ΔZMoho (the difference between the gravity inversion predicted Moho depth and seismic Moho depth) against the value of reference Moho depth used in the gravity inversion. Calibration gives a reference Moho depth of 35.5km.

Figure 4: (a) Crustal cross section along the CS1-2400 profile, showing Moho depth from gravity anomaly inversion, using the calibrated reference Moho depth of 35.5km. (b) Continental lithosphere thinning profile, predicted from gravity anomaly inversion, along the CS1-2400 profile. Sensitivities to a normal magmatic solution and a magma poor solution have been examined. A normal magmatic solution predicts thinning factors of 1.0 at the western end of the profile and a

376 magma poor solution predicts continental lithosphere thinning factors of approximately 0.85 in this

377 region.

378 Figure 5: Flexural backstripping and reverse post-breakup thermal subsidence modelling along the

379 ION-GXT CS1-2400 profile. (a) Digitized present day cross section along the CS1-2400 profile; the

380 post-salt sedimentary layer is highlighted in blue; pre-salt sedimentary layer in pink; the salt layer is

381 highlighted in yellow; crust is grey and mantle is red. (b) Sediment corrected bathymetry to base salt

382 calculated from flexural backstripping and decompaction, using a Te of 1.5km. (c) Continental

383 lithosphere thinning factor profile, from gravity anomaly inversion, for normal magmatic and magma

384 poor solutions. (d) Reverse post-breakup thermal subsidence modelling along the CS1-2400 profile,

385 assuming a normal magmatic solution. (e) Reverse post-breakup thermal subsidence modelling

386 along the CS1-2400 profile, assuming a magma poor solution.

387 Figure 6: Summary of the integrated quantitative analysis results for the CS1-2400 profile used to

388 determine OCT structure and COB location. (a) Crustal cross section along CS1-2400 profile with

389 Moho depth from gravity anomaly inversion. (b) The sediment corrected RDA and the RDA

390 component from variations in crustal basement thickness both have the same general trend along

391 the profile although the magnitudes differ. This difference gives an indication of the magnitude of

392 residual topography in this region, which we calculate to be approximately +700m of uplift. (c)

393 Comparison of continental lithosphere thinning factors determined using subsidence analysis and

394 gravity anomaly inversion assuming a normal magmatic solution show the same general trend along

395 profile. The dashed lines on the crustal cross section, RDA and continental lithosphere thinning plots

396 indicate the distal extent of unequivocal continental crust and its boundary with oceanic crust, which

397 is a possible interpretation of the COB.

398 Figure 7: Flexural backstripping and reverse post-breakup thermal subsidence modelling along the

399 P3 profile (Contrucci et al., 2004; Moulin et al., 2005). (a) Digitized present day cross section along

400   the P3 profile; the post-salt sedimentary layers are highlighted in turquoise, orange, green and blue;

401   pre-salt sedimentary layer in pink; the salt layer is highlighted in yellow; crust is grey and mantle is

402   red. (b) Sediment corrected bathymetry to base salt calculated from flexural backstripping and

403   decompaction, using a Te of 1.5km. (c) Continental lithosphere thinning factors from gravity

404   anomaly inversion for a normal magmatic and a magma poor solution. (d) Reverse post-breakup

405   thermal subsidence modelling along the P3 profile, assuming a normal magmatic solution. (e)

406   Reverse post-breakup thermal subsidence modelling along the P3 profile, assuming a magma poor

407   solution.

408   Figure 8: Flexural backstripping and reverse post-breakup thermal subsidence modelling along the

409   P7+11 profile (Contrucci et al., 2004; Moulin et al., 2005). (a) Digitized present day cross section

410   along the P3 profile; the post-salt sedimentary layers are highlighted in turquoise, orange, green and

411   blue; pre-salt sedimentary layer in pink; the salt layer is highlighted in yellow; crust is grey and

412   mantle is red. (b) Sediment corrected bathymetry to base salt calculated from flexural backstripping

413   and decompaction using a Te of 1.5km. (c) Continental lithosphere thinning factors from gravity

414   anomaly inversion for a normal magmatic and a magma poor solution. (d) Reverse post-breakup

415   thermal subsidence modelling along the P7+11 profile, assuming a normal magmatic solution. (e)

416   Reverse post-breakup thermal subsidence modelling along the P7+11 profile, assuming a magma

417   poor solution.

418   Supplementary Figure S1: Sensitivity to the effect of over-estimating or under-estimating the

419   thickness of the salt layer along CS1-2400. Two end member sensitivities have been considered: (i)

420   having a salt layer (as used in the paper) (labelled "With Salt") or (ii) treating the salt as just another

421   sedimentary layer (labelled "No Salt").   (a) Crustal cross section from gravity anomaly inversion,

422   showing two Moho depths (both using the calibrated reference Moho depth of 35.5km). The Moho

423   in black is the result of having a salt layer in the gravity anomaly inversion, whereas the Moho in

424   blue is the result of treating the salt layer as just another sedimentary layer. Removing the salt layer

425   from the gravity anomaly inversion results in a deeper Moho depth prediction. (b) Comparison of

426   the continental lithosphere thinning factors, predicted form gravity anomaly inversion for the two

427   sensitivities: with salt (in blue) and no salt (in green). Removing the salt layer from the gravity

428   anomaly inversion results in smaller continental lithosphere thinning factors. (c) The resulting

429   palaeo-bathymetries from reverse post-breakup thermal subsidence modelling for the two

430   sensitivities: with salt (in blue) and no salt (in orange). The "No Salt" sensitivity results in deeper

431   palaeo-bathymetries, the biggest differences are observed in the central section of the profile.

432   Supplementary Figure S2: Sensitivity to changing the reference Moho depth between 35.5km (as

433   calibrated for the CS1-2400 profile) to 37.5km (as calibrated for the P3 and P7+11 profiles). (a)

434   Crustal cross section from gravity anomaly inversion, showing two Moho depths. The Moho in black

435   is the result of using a reference Moho depth of 35.5km and the Moho in purple is the result of using

436   a higher reference Moho depth of 37.5km. If we increase the reference Moho depth along the CS1-

437   2400 profile, this results in a deeper Moho depth prediction. (b) Comparison of the continental

438   lithosphere thinning factors, predicted form gravity anomaly inversion for the sensitivities to

439   reference Moho depth. Using a reference Moho depth of 37.5km (in red) results in smaller

440   continental lithosphere thinning factors along the CS1-2400 profile. (c) The resulting palaeo-

441   bathymetries from reverse post-breakup thermal subsidence modelling for the two sensitivities to

442   reference Moho depth: using a reference Moho depth of 35.5km (in blue) and using a reference

443   Moho depth of 37.5km (in green). The larger reference Moho depth of 37.5km results in deeper

444   palaeo-bathymetries; the biggest differences are observed in the central section of the profile.

445

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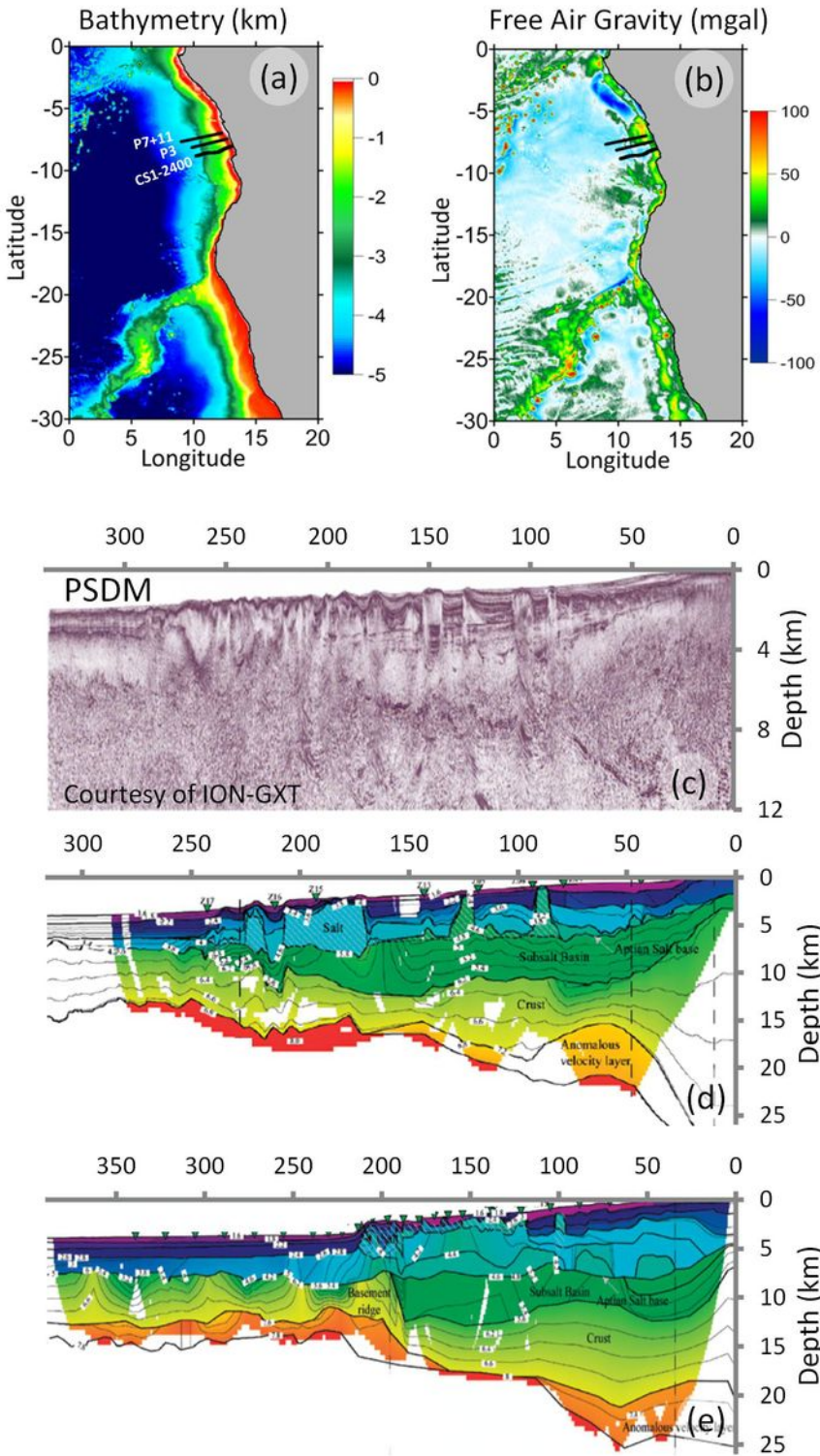547   Earth, v. 85, no. B7, p. 3711-3739.
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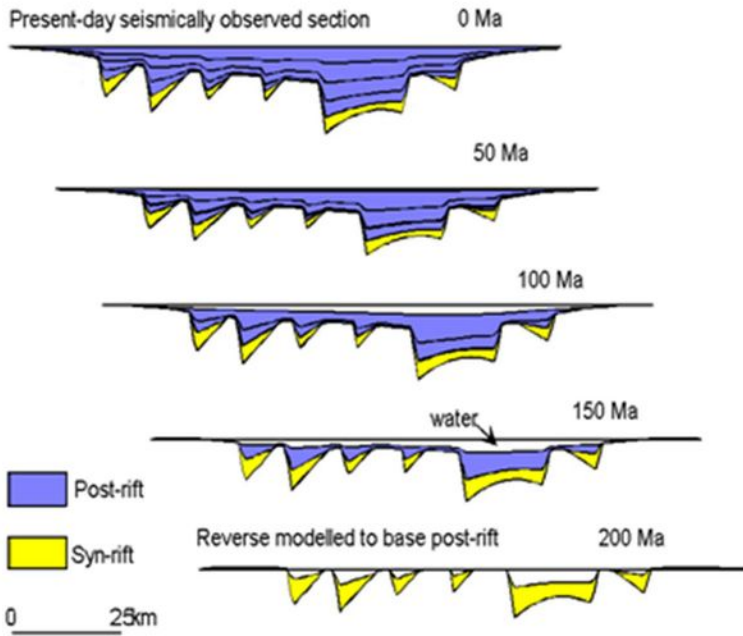553   White, R., and McKenzie, D., 1989, Magmatism at Rift Zones: The Generation of Volcanic Continental
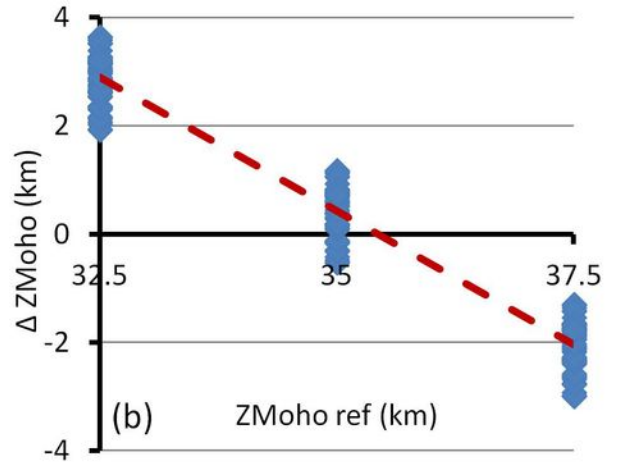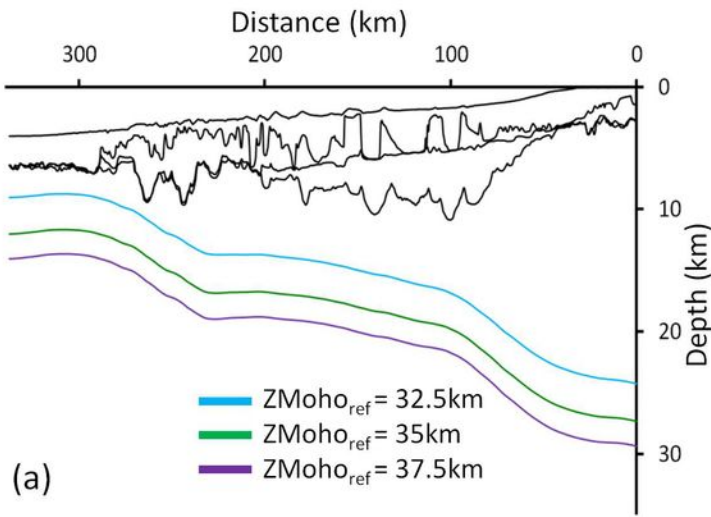554   Margins and Flood Basalts: Journal of Geophysical Research, v. 94, no. B6, p. 7685-7729.
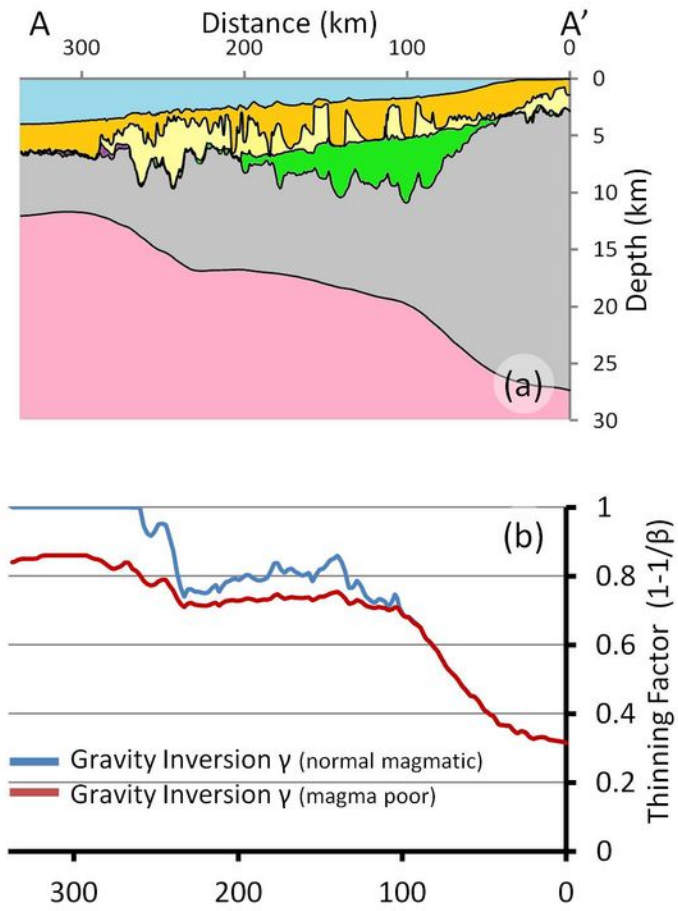555
556

Layer	Lithology	Porosity	Compaction Coefficient (km^{-1})	Density (kgm^{-3})
Post Salt	Shaly-Sand	63	0.51	2720
Salt	Salt	0	0	2200
Pre-salt	Shaly-Sand	63	0.51	2720

Figure 1
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Figure 2
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Present-day seismically observed section — 0 Ma

50 Ma

100 Ma

water — 150 Ma

Reverse modelled to base post-rift — 200 Ma

Post-rift

Syn-rift

0 ⸺ 25km

Figure 3
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Figure 4
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Figure 5

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ION-GXT CS1-2400 profile:

Figure 6
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(a) Moho – with Salt / Moho – no Salt

(b) Thinning Factor – With Salt / Thinning Factor – No Salt

(c) Palaeo-bathymetry – With Salt / Palaeo-bathymetry – No Salt

Figure 7
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P3 profile: (Moulin (2003) & Contrucci et al., (2004))

Figure 8

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P7+11 profile (Moulin (2003) & Contrucci et al., (2004))

Figure 9
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(a) Distance (km) / Depth (km)

Distal Salt — Proximal Salt

Palaeo-bathymetry – Gravity Inversion Thinning Factors
Palaeo-bathymetry – Thinning Factor =1 everywhere

(a)

ZMoho_{ref}=35.5km
ZMoho_{ref}=37.5km

(b)

Thinning Factor – ZMoho_{ref}=35.5km
Thinning Factor – ZMoho_{ref}=37.5km

(c)

Palaeo-bathymetry – ZMoho_{ref}=35.5km
Palaeo-bathymetry – ZMoho_{ref}=37.5km