Sandstone-filled normal faults: A case study from central California

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Abstract

Despite the potential of sandstone-filled normal faults to significantly influence fluid transmissivity within reservoirs and the shallow crust, they have to date been largely overlooked. Fluidized sand, forcefully intruded along normal fault zones, markedly enhances the transmissivity of faults and, in general, the connectivity between otherwise unconnected reservoirs. Here, we provide a detailed outcrop description and interpretation of sandstone-filled normal faults from different stratigraphic units in central California. Such faults commonly show limited fault throw, cm to dm wide apertures, poorly-developed fault zones and full or partial sand infill. Based on these features and inferences regarding their origin, we propose a general classification that defines two main types of sandstone-filled normal faults. Type 1 form as a consequence of the hydraulic failure of the host strata above a poorly-consolidated sandstone following a significant, rapid increase of pore fluid over-pressure. Type 2 sandstone-filled normal faults form as a result of regional

24 tectonic deformation. These structures may play a significant role in the connectivity

25 of siliciclastic reservoirs, and may therefore be crucial not just for investigation of

26 basin evolution but also in hydrocarbon exploration.

27

1. Introduction

29   Understanding the architecture of fault zones has become increasingly

30 important as their characteristics have a significant influence on the migration and

31 entrapment of fluids in the subsurface. In particular, the permeability of fault rocks

32 plays a fundamental role in fluid transmissibility (e.g. Childs et al., 2007). Faults

33 affecting shallow crustal strata commonly display a wide range of fault zone

34 architecture, which varies from very thin gouge or cataclastic horizons, to well-

35 developed damage and core zones (Caine et al., 1996; Kim et al., 2004). In multi-

36 layered, poorly-consolidated, siliciclastic strata (mudstone-sandstone intercalations),

37 fault rocks are typically represented by cataclastic mixtures of sandstone and

38 mudstone smeared along the fault walls. Fine-grained particulate flow, cataclastic

39 material and highly smeared clay content are all factors which hinder fluid flow

40 migration and significantly promote reservoir compartmentalization (Jones et al.

41 1998; Bailey et al., 2002; Bense et al., 2003; Ainsworth, 2006; Childs et al. 1997;

42 2007; Jolley et al. 2007; Fredman et al., 2007). Mineralization, sourced from fluids

43 percolating through a fault zone, is an additional factor that precludes subsequent

44 fluid migration through fault zones. On the other hand, the occurrence of porous and

45 permeable sandstone within a fault zone may strongly enhance its fluid migration

46 capacity.

47   Sand can be incorporated into fault zones due to a variety of reasons listed

48   below (Lewis et al., 2002): i) beds of sandstone are sheared and form deformed

49   ribbons parallel to a fault plane; ii) beds of sandstone are dragged and rotated until

50   they become parallel to the fault plane; iii) fluidized sand is injected along the fault

51   zone discontinuities. Here we focus on the latter case. Two essential preconditions

52   are required for sand fluidization to occur along a fault plane: i) the velocity of flow

53   along the fault plane must be high enough for sand grains to be fluidised; ii) the

54   parent sandstone from which fluidised sand is derived is poorly-consolidated. The

55   first condition is encountered when the velocity of the fluid exceeds the minimum-

56   fluidization velocity of sand (Lowe, 1975). The second condition usually occurs in

57   parts of sedimentary basins that never experienced significant diagenetic

58   modification, and is commonly confined to the first few hundreds of metres of burial

59   (Jonk et al., 2003; Vigorito and Hurst, 2010).

60   Although sandstone intrusions associated with normal faults are occasionally

61   interpreted using subsurface data (Dixon et al., 1995; Shoulders et al., 2007; Koša,

62   2007; Bureau et al. 2013; Yang et al., 2014), they are still poorly-documented at

63   outcrop (Taylor, 1982; Audemard and de Santis, 1991; Jolly and Lonergan, 2002;

64   Lewis et al., 2002; Ribeiro and Terrinha, 2007; Montenat et al., 2007; Siddoway and

65   Gehrels, 2014; Ravier et al., 2015; Palladino et al., 2016; Siddoway et al., 2017). Our

66   case study therefore focuses on well-developed sandstone-filled normal faults

67   (SFNF) exposed in the Panoche/Tumey hills and Santa Cruz areas in central

68   California (Fig. 1), where mainly deep-water clastic strata present ideal conditions for

69   sand intrusion along faults. The aim of this paper is to document these exceptional

70   field examples of SFNF, and to discuss their geometry, origin, timing, and

71   mechanism of emplacement. Their significance in terms of basin evolution, and the

72 potential role they play as either conduits or barriers to fluid flow in hydrocarbon

73 reservoirs is discussed.

74

75 **2. Geological Setting**

76 *2.1. Panoche/Tumey hills area stratigraphy*

77 The Panoche/Tumey hills area comprises a Late Cretaceous to Early

78 Cenozoic stratigraphic sequence deposited along the western margin of the San

79 Joaquin Valley (Moxon, 1988) (Fig. 1a). The San Joaquin Valley infill consists of a

80 thick accumulation of Jurassic to Quaternary marine and non-marine clastic strata

81 that unconformably overlie the Franciscan Complex. Due to its position along an

82 active basin margin, the Panoche-Tumey hills area experienced numerous tectonic

83 phases in different geodynamic contexts. SFNF are found within the Moreno and

84 Kreyenhagen Shale formations both deposited in an ancient forearc basin (Fig. 1a).

85 The Moreno Formation consists of an Upper Cretaceous to Lower Paleocene

86 sequence of lens-shaped turbiditic sandstone, mudstone and diatomaceous

87 mudstone that were deposited in a base-of-slope to the upper slope-shelf

88 environment. The Kreyenhagen Shale (Eocene) comprises a dominantly mudstone

89 sequence containing isolated turbiditic sandstone deposited in a slope to shelf

90 environment (Moxon, 1988; Bartow, 1991; Johnson and Graham, 2007). The upper

91 part of this formation consists of thick packages of diatomaceous mudstones.

92

93 *2.2. Santa Cruz area stratigraphy*

The Santa Cruz coastal area consists of a Miocene sedimentary succession that unconformably overlies the granitic/metamorphic Salinian basement (Clark, 1981; Aydin and Page, 1984; Page et al., 1998) (Fig. 1b). This sedimentary succession consists of the coarse-grained, large-scale cross-bedded tidal/nearshore arkosic Santa Margarita Sandstone, which passes upward into deep-water to shelfal, organic-rich, thickly bedded biosiliceous Santa Cruz Mudstone (Fig. 1b) (Barron, 1986). The Miocene to Pliocene Purisima Formation is the youngest unit recognized in the Santa Cruz area, and comprises, very thick-bedded tuffaceous and diatomaceous neritic siltstones alternating with thick-bedded andesitic sandstones (Johnson and Graham, 2007).

2.3. Tectonic setting

The present structural arrangement of central California (including the two study areas) (Fig. 1), is mainly the result of contractional and strike-slip tectonics operating from the Cretaceous to the Quaternary (Page et al., 1998; Atwater and Stock, 1998). Contractional tectonics resulted from the accretion of the Franciscan complex and the concomitant onset of the Great Valley forearc basin (Ingersoll, 1979; Dickinson and Seely, 1979; Constenius et al., 2000). Strike-slip tectonics is related to the activation of the San Andres Fault zone and other associated faults from the Eocene onward (Sharman et al., 2013). The Panoche/Tumey hills area is located along the eastern flank of the San Joaquin Valley which is part of the Great Valley Basin. Its structure consists of a series of anticlines and synclines often marked at base by thrust planes (Bartow, 1991; Namson and Davis, 1988). The Santa Cruz area consists of a southwest-dipping homocline situated between the

118   San Andreas Fault Zone (SAFZ) and San Gregorio Fault Zone (SGFZ) (see Fig. 1

119   map inset) (Phillips, 1990).

120   Despite the lack of extensional tectonics in this regional tectonic context, the

121   number of normal faults in the study areas is surprisingly high and many of these

122   structures are actually SFNF. The origin of these normal faults is poorly addressed in

123   the literature, although normal fault orientation is often consistent with either outer

124   arc extension in contractional structures (e.g. Palladino et al, 2016) or associated

125   with wrench tectonics (Aydin and Page, 1984). Another possibility for the initiation of

126   normal faults is linked to the exhumation of the Franciscan complex, which is

127   accommodated by extensional tectonics (Krueger and Jones, 1989; Dumitru, 1989;

128   Harms et al., 1992; Unruh et al., 2007; Sousa et al., 2016). In the Panoche/Tumey

129   hills area, the majority of SFNF are systematically oriented NW-SE and WNW-ESE

130   (Fig. 2a), whereas in the Santa Cruz coastal area, the normal faults are dominantly

131   NNW-SSE and N-S trending (Fig. 2b).

132   Although accurate time constraints for SFNF are difficult to ascertain, field

133   observations do provide some important constraints. For example, in the

134   Panoche/Tumey hills area (Fig. 2), SFNF are not documented in stratigraphic units

135   younger than the Kreyenhagen Shale and abruptly terminate at the unconformity

136   delimiting the base the Temblor Formation. This allows us to constrain the age of

137   tectonic deformation to between the middle Eocene (age of the Kreyenhagen Shale)

138   and the Middle Miocene (age of the Temblor Formation). In the Santa Cruz area

139   (Fig. 2), the timing of faulting is less well constrained. As the age of the Santa Cruz

140   Mudstone, the stratigraphic unit hosting SFNF, has been attributed to 7-9 Ma (Late

141   Miocene) (Boehm and Moore 2002), the age of the normal faulting is younger than

142   this. However, the lack of younger units covering SFNF in this area does not allow us

143   to bracket the youngest possible age.

144

145   *2.4. Sand injection complexes in central California*

146   At least three significant sand injection complexes are recognized in central

147   California (Fig. 1): the Panoche Giant Injection complex (PGIC), the Tumey Giant

148   Injection Complex (TGIC) and, the significantly smaller-scale Santa Cruz Injection

149   Complex (SCIC), which comprises several periods of sand injection including sand

150   extrusion (Thompson et al., 1999; Scott et al., 2009; Vigorito et al., 2008; Hurst et al.,

151   2011).

152

153   *2.4.1. Panoche Giant Injection complex (PGIC)*

154   The PGIC (Fig. 1a) consists of a well-defined network of dikes and sills

155   intruded within the Upper Cretaceous to Paleocene Moreno Formation (Vigorito and

156   Hurst, 2010). This injection complex records a large-scale overpressure event that

157   occurred during the Lower Paleocene (Danian) and involved an area of at least 1500

158   km^2 that includes almost 400 km^2 of outcrop (Vigorito and Hurst, 2010). It consists of

159   different architectural elements represented (from the base to top) by parent units,

160   intrusive bodies and extrudites (Vigorito et al., 2008; Hurst et al., 2011; Scott et al.,

161   2013). PGIC parent units comprise turbiditic channel-complexes and isolated

162   sandstone channels occurring in the lower portion of the Moreno Formation (Vigorito

163   et al., 2008). The intrusive bodies consist of cm- to metre- thick interconnected single

164   or multi-layered sills and dikes. Extrudites (Vigorito and Hurst, 2010) comprise

165 mound-like sand bodies cropping out in the Upper part of the Moreno Formation,

166 where they consist of fine- to medium-grained sands linked to the underlying

167 intrusive complex by isolated dikes.

168

169 *2.4.2. Tumey Giant Injection Complex (TGIC)*

170   The TGIC (Fig. 1a) consists of a network of dikes and sills emplaced in the

171 Kreyenhagen Shales (Huuse et al., 2007). The TGIC differs from the PGIC in that it

172 has extensive channelized turbiditic sandstones that are intensely deformed by sand

173 fluidization throughout the injection complex. Sand extrudites are absent in the TGIC,

174 which if ever present were removed by later erosion. The absence of extrudites

175 precludes bracketing the precise timing of sand injection. However, the TGIC

176 intrudes the Kreyenhagen Shale strata of lower to middle Eocene age, and the

177 timing of sand injection cannot be older than this. The Miocene Temblor Formation

178 which unconformable overlies the Kreyenhagen Shale is unaffected by sand

179 injection, meaning that injection pre-dates this unit.

180

181 *2.4.3. Santa Cruz Injection Complex (SCIC)*

182   The SCIC (Fig. 1b) consists of a network of partially tar-saturated and

183 unsaturated dikes and sills emplaced in the Santa Cruz Mudstone (Thompson et al.,

184 1999; Scott et al. 2009). The parent unit of the SCIC is commonly identified as the

185 Santa Margarita Sandstone (Boehm and Moore, 2002; Thompson et al., 2007).

186 Using mineralogical data Clark (1981) and Scott et al. (2009) suggested that multiple

187 parent sandstones existed. The injection complex has a well-developed intrusive

188 network that mainly consists of widely-spaced sills, dikes and locally preserved

189 saucer-shaped intrusions. Individual intrusions generally have thicknesses which

190 range from a few centimetres to a decimetre. Isolated dikes or sills are up to a few

191 metres wide with the Yellowbank/Panther beach sill at least up to 15 m thick

192 (Thompson et al., 1999; Scott et al., 2009). Extruded sands occur as multiple,

193 laterally-discontinuous, mounded units recognized in different stratigraphic levels in

194 the Santa Cruz Mudstone (Boehm and Moore 2002; Hurst et al. 2006). The

195 occurrence of extrudites within the Santa Cruz Mudstone allows the age of

196 emplacement of the SCIC to be constrained to the Late Miocene (7–9 Ma).

197

3. Characteristics of normal faults hosting sand injections in central California

199 The majority of normal faults recognized in the Panoche/Tumey hills and

200 Santa Cruz areas display a range of similarities including: i) moderate to steeply

201 dipping planar to gently undulating fault surfaces, ii) cm to m-scale offsets and iii)

202 graben-like geometry. However, some significant differences linked to the lithology

203 and physical state of the strata at the time of deformation also exist, and these

204 strongly influence the characteristics of the fault zone. Therefore, in order to better

205 understand the mechanical behaviour of SFNF, it is first necessary to describe the

206 main characteristics of the stratigraphic successions cut by these faults.

207 In the Panoche/Tumey hills area (Fig. 1a), faulted successions consist of

208 poorly-consolidated sandstone alternating with packages of mudstone (Fig. 3a, b).

209 The units of interest are the Moreno and the Kreyenhagen Shale formations which

210 are characterized by significant physical anisotropy, with high permeability measured

211 parallel to the bedding planes, and low permeability measured orthogonal to this

212 (Bense and Person, 2006). Hereafter this is referred to as the Panoche/Tumey-type

213 successions.

214   In the Santa Cruz coastal area (Fig. 1b), the faulted succession predominantly

215 consists of well-consolidated bio-siliceous mudstone belonging to the Santa Cruz

216 Mudstone (Fig. 3c, d). Excluding the rare occurrence of a faint parallel lamination,

217 occasional claystone horizons and isolated sandstone bodies, these bio-siliceous

218 mudstones can be considered as an isotropic succession with low permeability in all

219 directions. In this case, the permeability is essentially linked to the secondary

220 porosity created by fracture networks developed in close proximity to tectonic

221 disturbance zones. Hereafter this is referred to as the Santa Cruz-type succession.

222   When different types of lithology such as the Panoche/Tumey- and Santa

223 Cruz-type successions are involved in deformation, the resulting fault rocks and fault

224 zones show significant variability. Fault zones mainly consist of three elements

225 represented by the fault core, damage zone, and undeformed protolith (Caine et al.,

226 1996; Braathen et al., 2009). The fault core is the portion of the fault zone where

227 most of the displacement is accommodated. In the shallow crust, at a depth of less

228 than 1 km, fault cores commonly consist of gouge, breccia, cataclasite/particulate

229 flow and smeared clay. This portion generally forms a low permeability zone within

230 the fault (Knipe et al., 1998; Bense et al., 2003; Bense and van Balen, 2003; Ballas

231 et al., 2015; Peacock et al., 2017). The damage zone forms the intermediate region

232 between the fault core and the undisturbed protolith, and is characterized by small

233 faults and fractures, that are distinguished either by high or low permeability,

234 depending on the lithological characteristics of the protolith. As the fault core can be

235 discontinuously distributed along the fault zone, so that it does not necessarily form a

236 continuous barrier, the fundamental element controlling fluid transmission and,

237 consequently, the emplacement of sand along the fault plane, is the damage zone

238 itself. Depending on fault rock consolidation, the damage zone can display open or

239 closed fractures, while the width of the damage zone is generally observed to

240 increase with larger fault throws (e.g., Knott et al., 1996; Manzocchi et al., 1999;

241 Childs et al., 2009).

242 Damage zones developed in Panoche/Tumey-type successions are generally

243 characterized by closed-fracture networks, cataclastic/deformation bands and mixing

244 zones where sand/mud mixing processes contribute to further reduce the

245 permeability (Heynekamp et al., 1999; Rawling et al., 2001; Bense et al., 2003;

246 Loveless et al., 2011) (Fig. 3b). The average fault zone width ranges from millimetres

247 to some tens of decimetres. Also, the width of the core zone is sometimes dominant

248 with respect to the damage zone thickness. In addition, the width of a fault zone

249 developed in mudstone/sandstone alternations can vary parallel to the fault plane,

250 resulting in the more sandstone-rich parts of the fault zone being wider than those

251 that are dominated by mudstone (Sperrevik et al., 2002; Bense and Person, 2006).

252 In Santa Cruz-type successions damage zones produce a very different

253 permeable, dense, open-fracture network that surrounds the fault core (Fig. 3d).

254 Based on field observations, the fracture network width is directly proportional to the

255 fault throw. It can often extend laterally for many metres or tens of metres so that,

256 the width of the core zone, which can range from some decimetres to 1m, is

257 negligible when compared with the width of the entire fault zone.

258 Low and high permeability damage zones therefore form two end-members

259 that are observed in the Santa Cruz coastal sector and in the Panoche/Tumey hills

260 area respectively. They reflect the brittle and ductile behaviour of the strata involved

261 in the deformation. The differences observed in the two fault zones end-members

262 have a marked impact on conditioning the fluid flow and, consequently, the spatial

263 distribution and geometry of the sandstone intrusions associated with the SFNF.

264

4. SFNF classification

266   Based on our field observations, it is possible to distinguish two main types of

267 SFNF (Fig. 4).

268

4.1. Type 1 SFNF

270   Type 1 SFNF are related to the fluidization of a sandstone parent unit that
271 consists either of pristine depositional sandstones or poorly-lithified sandstone
272 intrusions, and the consequent collapse of the overburden due to the evacuation of
273 sand during an overpressure event (Fig. 4a). The distinctive characteristic of Type 1
274 SFNF is that they nucleate at the top of the remobilized parent unit, and propagate
275 upward without ever cutting through the entire parent sand body. Other important
276 features are the limited vertical extent of these structures, the restricted amount of
277 offset which can vary from a few cm to some metres, and the lack of a well-
278 developed fault zone and associated fault breccias. In most cases, the faults
279 dissipate quickly and resemble syn-depositional faults (Fig. 4a). Evidence for the
280 direction of fluidized sand transport is provided by dragging of layers of the host
281 strata in the sense of the fluid movement, and by the distribution of mudstone clasts
282 along the fault. This suggests that the sand is commonly injected upward, or along-
283 strike. Type 1 SFNF are commonly developed in sill zones (*sensu* Vigorito and
284 Hurst, 2010). Subsurface examples of similar faults have been interpreted previously
285 from the North Sea (Dixon et al., 1995).

286

4.2. Type 2 SFNF

Type 2 SFNF are tectonically-related sandstone-filled normal faults (Fig. 4b). Unlike the previously described Type 1, Type 2 SFNF cut through the entire parent sandstone body. In the study areas, it is possible to distinguish two main sub-categories (Type 2a and Type 2b) that are described below.

4.2.1. Type 2a SFNF

Type 2a SFNF are related to episodes of regional extensional tectonics (Fig. 4b). They generally consist of a master fault plane and a series of associated antithetic and synthetic minor faults that have small offsets and graben-like geometry. Unlike Type 1 SFNF, Type 2a SFNF do not display a progressive decrease in offset toward terminations. The measured offsets range from a few centimetres to some metres, while apertures can locally reach 1.5 m. The occurrence of dip-slip oriented slickensides provides a clear indication of normal fault kinematics. Fault zones can be variably developed depending on characteristics of the succession, and the injected sand either entirely fills spaces between breccia clasts, or is predominant and contains isolated 'floating' clasts.

4.2.2. Type 2b SFNF

SFNF linked to regional contractional tectonics occur as a consequence of outer-arc extension and flexural slip (Fig. 4c). Outer-arc extension produces a series of normal faults that are typically arranged in a radial pattern around fold hinges. They are very common in the Panoche/Tumey hills area (Fig. 1) and are recognized

310   in the field on the basis of their trend, which is commonly subparallel to that of major

311   fold hinges, and by the triangular-shaped geometries that progressively taper

312   downward toward fold cores (Palladino et al., 2016). Small-scale Type 2b SFNF may

313   also develop in association with flexural slip folding of a multi-layered succession.

314   According to Gross et al. (1997), these structures usually form because of pull-apart

315   opening and block rotation mechanisms that create space for syn-tectonic sand

316   injection.

317

318   **5. Outcrop examples of SFNF**

319   SFNF crop out in numerous localities throughout in the Panoche/Tumey hills

320   and Santa Cruz areas. Three key localities, displaying the best preserved SFNF, are

321   selected as outcrop examples and include Tumey Gulch and Monocline Ridge in the

322   Panoche/Tumey hills area, and Panther Beach near Santa Cruz (Fig. 1).

323

324   *5.1. Tumey Gulch*

325   Tumey Gulch, in the southwestern side of the study area, consists of a

326   kilometre-scale anticline in which the Moreno Formation is exposed in the eroded

327   fold core (Fig. 1a). Here, on both flanks of the fold, well-preserved sets of conjugate,

328   closely-spaced, Type 1 and Type 2 SFNF are preserved. Two outcrops, named O1

329   and O2, are considered below.

330   Type 1 SFNF recognized in the outcrop O1 consists of conjugate normal

331   faults that display small (cm) offsets and sandstone-filled apertures of a few

332   centimetres (Fig. 5a). Faults die out upward over tens of centimetres, so that the

333 overlying beds remain unaffected by deformation (Fig. 5b, c). These SFNF are

334 located in the lower portion of the Moreno Formation and, in particular, at the top of

335 strongly remobilized sandstone units belonging to the PGIC.

336 The outcrop O2 shows both Type 1 and Type 2b SFNF. In Fig. 6 an array of

337 Type 1 SFNF overlies a deformed, lens-shaped turbidite channel sandstone, which

338 is at least 2 m thick and displays evidence of pervasive sand fluidisation caused by

339 fluid ingress and increased pore-fluid pressure. The most intense fluidisation

340 occurred in the upper portion of the sandstone as shown by the irregular shape of

341 the top surface. Most Type 1 SFNF occur where the sandstone pinches out. Here,

342 the limited thickness of the sandstone allowed lateral sand evacuation, which in turn

343 caused the failure of the overburden, and the successive injection of the fluidized

344 sand along faults (Fig. 6a, b). A fundamental characteristic of the outcrop is that

345 sandstone-filled structures only develop above the remobilized sandstone. SFNF do

346 not transect the depositional sandstone, as shown by the undeformed basal surface.

347 This is a diagnostic criteria that allows differentiation between Types 1 and 2 SFNF.

348 Type 2b SFNF recognized in the outcrop O2 form conjugate sets that have

349 sandstone-filled apertures ranging from a few centimetres to some tens of

350 decimetres, and offsets varying from a few decimetres to metres (Fig. 7a, b). Fault

351 spacing varies from a few decimetres to several metres. Injected sandstone displays

352 laminations parallel to the fault wall, and this is the only internal characteristic

353 present. Mudstone clasts, together with slightly cemented sandstone belonging to

354 the host strata are quite common within the sand injection. Kinematic indicators as

355 well as slickensides are locally preserved, although they tend to be removed during

356 the sandstone emplacement process. Evidence of pre-existing fault gouge is very

357 rare. In most cases, faults display planar surfaces, although local curvatures giving

358 rise to releasing steps and dilational jogs, are sometimes present. The effects of

359 post-emplacement compaction are preserved as segmentation of dikes and fault-

360 plane curvature. WSW-ENE trending Type 2b SFNF (Fig. 7c) recognized in the

361 outcrop O2, are consistent with outer arc extensional faults recognized in the Tumey

362 Gulch area (Palladino et al., 2016).

363

364 *5.2. Monocline Ridge*

365   Monocline Ridge is a NE-dipping monocline situated along the western side of

366 the San Joaquin Valley (Fig. 1a). Numerous well preserved outcrops of Type 1 SFNF

367 are present along this structure. Outcrop O3 (Fig. 8a, b) consists of a SW-dipping

368 array of sandstone-filled reverse faults and Type 1 SFNF cutting through the

369 Kreyenhagen Shale. The occurrence in this area of sandstone-filled contractional

370 structures was documented by Palladino et al. (2016). SFNF have apertures of some

371 centimetres and offsets of a few tens of centimetres. Neither fault gouge nor

372 kinematic indicators are preserved along the fault surface. Rare cm-scale mudstone

373 clasts 'float' in the sand matrix. In Fig. 8b, Fault 1 consists of a single fault surface

374 filled with an almost constant thickness of sandstone, while Fault 2 is a composite

375 fault comprising different lozenge- shaped, *en echelon*, sandstone-filled segments.

376

377 *5.3. Panther Beach*

378   Well-preserved Type 2a SFNF are exposed along the entire coastal section

379 between Santa Cruz and Davenport (Fig. 1b). A key example is represented by

380 Outcrop O4 at Panther Beach (Fig. 9a, b). This outcrop consists of a NE-SW

381 oriented SFNF (Fig. 9c) that cuts the diatomaceous Santa Cruz Mudstone. The fault

382 plane is strongly undulose, fault throw is ~10 cm and fault aperture ranges between

383 1 and 5 cm. Fault zone thickness is significantly reduced and fault gouge is almost

384 absent while remobilized sand fully fills the fault zone. Where the fault cuts the

385 mudstone marker bed, slight clay smear occurs and sandstone infill loses its

386 continuity.

387

388 **6. Mechanisms driving emplacement of sand injections along normal faults**

389 Fluidized sand can be intruded along normal fault planes as a result of two

390 main mechanisms: i) fluidized sand sourced from an over-pressured unit lift the

391 overburden causing hydrofracturing of the host strata and forced filling (propping) of

392 the newly-formed fault. In this case, fault generation is triggered by overpressure and

393 the sand is intruded into the newly-formed faults. Type1 SFNF are the result of this

394 process; ii) overpressured fluidized sand fills low-pressure voids developed along a

395 fault plane. Failure in host strata is not solely associated with overpressure but

396 rather, to external factors such as regional tectonics. Type 2 SFNF typically originate

397 by this process.

398 Sand injection occurs along a newly-formed fault or, exploits a pre-existing

399 discontinuity (fault or fracture). Exploitation of pre-existing faults depends upon the

400 degree of cohesion and cementation of the tectonically-generated structure and,

401 whether pore-fluid overpressure (P_f) exceeds the lithostatic overburden and the

402 tensile stress associated with opening of the fracture plane. Commonly, sand

403 fluidisation into open structures is predominantly in the upper (200-500 m) sub-

404   surface within poorly-consolidated and only lightly compacted strata (Vigorito and

405   Hurst, 2010; Hurst et al., 2011).

406

407   *6.1. Emplacement of sand injections along Type 1 SFNF*

408   Type 1 SFNF typically breach the overburden of a poorly-consolidated

409   sandstone body (either a pristine depositional unit or a pre-existing sandstone

410   intrusion) when P_f exceeds the fracture gradient of the overburden (Fig. 10a). In

411   order to achieve this, rapid ingress of pore-fluid is required to initiate hydraulic

412   fracture and sand fluidisation. As overpressure is build, for example when a dike

413   connects a sandstone with deeper overpressured units, sand grain fluidization is

414   initiated and sand begins to mobilise into the fault (Fig. 10a). In particular, where the

415   dike connects with the sandstone and new sand is added to the system, the

416   overpressured sand body will show important modifications in the shape, as well as

417   irregular top surfaces and scallops (Hurst et al., 2011). Concurrently, as the pore-

418   fluid pressure exceeds the fracture gradient of the overburden plus its tensile

419   strength, a hydrofractured belt consisting of faults and fractures forms in the host

420   strata along the top of the sandstone body from which sand is being fluidised. Then,

421   fluidized sand, driven upward by buoyant force, begins to flow toward lower-

422   pressured zones represented by the overlying mechanical discontinuities.

423   Immediately after, the lateral evacuation of sand from necked zones can cause the

424   further collapse of the overburden, already weakened by the formation of the

425   hydrofractures, which is accommodated by further faulting and fracturing (Fig. 10b).

426   Dilation along normal faults and fractures, sustained by the fluid overpressure,

427   favours the emplacement of fluidized sand within the newly-formed structures.

428

429   *6.2. Emplacement of sand injections along Type 2 SFNF*

430   Faults that intersect an isolated over-pressured sandstone (Fig. 10c)

431   determine the location of the rupture of the surrounding low impermeability host

432 strata by causing a sudden disturbance in the fluid pressure. Specifically, as a fault is

433 a low pressure zone relative to the sandstone unit, a pressure gradient with flow

434 directed toward the fault surface develops instantaneously (Fig. 10d). The resulting

435 discharge of fluid results in an abrupt drop of P_f in the sandstone, a process that

436 continues until the hydrostatic gradient is restored (Sibson, 1990; 1992). Under

437 certain circumstances, the influx of high-pressured water into the fault zone can have

438 a two-fold effect: i) if P_f exceeds the overburden pressure present in the hangingwall

439 block, it contributes to prop open the newly-formed discontinuity; ii) If the movement

440 of the pore fluid produced during pressure equilibration exceeds the minimum

441 fluidization velocity of sand (for example equal to 0.3-1 cm/s for well-sorted, fine-

442 grained sands), it imposes a drag force that mobilizes sand grains. In such a

443 situation, poorly-lithified sandstone begins to fluidize and injects into cavities along

444 the fault plane (Fig. 10e). In cases where faulting is triggered by the remobilization

445 process (see the previous section), the origin and distribution of the newly-formed

446 extensional faults within an undisturbed and homogeneous top seal is controlled by

447 the stress field acting around the overpressured sandstone. In this case, for a fault to

448 be propped open, pore pressure (Pf) must exceed the minimum principal stress ($\sigma3$)

449 plus the tensile strength (T): Pf> $\sigma3$+T.

450

451 **7. Discussion**

452 *7.1. Favourable conditions for SFNF emplacement*

453 Although normal faults developed in the PGIC, TGIC and the SCIC display

454 differences related to the structure of damage zones (Fig. 3), they all frequently host

455 sandstone intrusions. It is thus important to understand the conditions that promote

456 sand emplacement into such a diverse range of structures. As discussed previously,

457 the emplacement of remobilized sand along a fault is strictly related to the ascent of

458 fluids from a source of high fluid-pressure located deeper in the faulted succession.

459 Depending on the state of fracturing in the host strata, the fluid ingress is either

460 focussed along the fault zone, or dissipated into adjacent strata thereby losing the

461 potential to fluidize sand. Obviously, the emplacement of SFNF is strictly related to

462 the first scenario.

463   In poorly-consolidated strata, such as the Panoche/Tumey-type successions

464 (Fig. 3a), which are characterized by ductile behaviour and low fault-parallel

465 secondary permeability, the ascending over-pressured fluid is hindered by obstacles

466 such as mudstone units, whereas fluid transfer is facilitated along vertical conduits

467 represented by faults (Fig. 3b). In addition, the characteristic of poorly-consolidated,

468 finely interbedded mudstone and sandstone, fault-related deformational

469 mechanisms, such as dragging, ductile flow and clay smear all contribute toward the

470 formation of narrow damage zones and an inner fault-parallel layering, which forces

471 fluid to move along the fault zone. Consequently SFNF is widespread in the PGIC

472 and TGIC, and locally forms closely-spaced swarms (Figs. 7-8).

473   In well-consolidated host rock, such as the Santa Cruz type succession (Fig.

474 3c), the development of high fault-parallel secondary permeability, favoured by the

475 brittle behaviour of the deformed rocks, does not typically permit sandstone intrusion

476 along faults. However, even under these unfavourable conditions, the injection of

477 sand along isolated fault planes occurs. As the width of the fault damage zone in this

478 succession is directly proportional to the amount of the fault displacement,

479 sandstone intrusion is still possible where small displacements occur (Fig. 9). Faults

480 with small offsets do not have space to develop a complete fault zone, such that the

481 core zone is almost absent and the damage zone is poorly-developed.

482

7.2. Cross-cutting relationships

484 Type 1 and Type 2 SFNF consist of very similar structures generated by very

485 different processes described in the previous sections. Commonly, the processes

486 creating these two types of structures are unrelated, but in specific circumstances it

487 is possible that Type 1 SFNF and Type 2 SFNF coexist. In our examples their

488 coexistence implies formation, at different times, with the time of sand injection

489 separated by ~20 Ma (Fig. 11). In particular, Type 1 SFNF formed concurrently with

490 the emplacement of the main sand injection complexes (PGIC, TGIC and SCIC) and

491 their age is the same as the hosting complex. Type 2 SFNF, although also

492 associated with these complexes, represent a younger tectonically-controlled

493 sandstone intrusion event that postdates the emplacement of the main injection

494 complexes. Evidence for Type 2 SFNF overprinting older sand injection complexes

495 in central California are demonstrated by cross-cutting relationships described in the

496 following sections.

497

7.2.1. Panoche/Tumey hills

499 In the Panoche/Tumey hills area, Type 2 SFNF represent an episode of sand

500 injection that post-dates the emplacement of PGIC, TGIC and Type 1 SFNF (Fig. 1).

501 Clear evidence of these relationships is observed throughout the study area and in

502 particular along Monocline Ridge (Fig. 2).

The outcrop O5 (Fig. 12a, b) shows a set of mesoscale, WNW-ESE oriented conjugate Type 2 SFNF (Fig. 12c) that dissect the Kreyenhagen Shale , together with an older generation of cm- to dm-thick, tabular, sandstone intrusions belonging to the TGIC. Fault displacement commonly ranges from a few millimetres to several centimetres, while apertures vary from a few centimetres to tens of decimetres. Sand intruded along fault planes appear to be directed both upwards and downwards (Fig. 12d). However, the occurrence of fragments of the host strata unrelated to the fault walls leads us to believe that lateral transport was also possible. It is interesting to note that sand remobilization mainly occurs along the fault segments that are located immediately above and below the deformed sandstone units. Within the faulted sandstone, no evidence of sand fluidization is preserved and the presence of the fault plane is marked by the occurrence of deformation bands (Fig. 12e). In this case, sand fluidization only occurred along the margins of the sandstone at the contact with the host strata, whereas the inner portion was unaffected.

7.2.2. Santa Cruz area

In the Santa Cruz area (Fig. 2), Type 2 SFNF clearly dissect an older generation of sandstone intrusions belonging to the SCIC (Fig. 13). Outcrop O4, at the southern end of Panther Beach, 10 km west of Santa Cruz, consists of a cliff composed of diatomaceous mudstone and a few cm-scale tar-saturated, low-angle dikes, which are repeatedly cut by a series of conjugate faults with cm-scale offsets (Fig. 13a, b). Here, a well-preserved example of a WNW-ESE-trending Type 2a SFNF has an offset of 15 cm and cuts a low-angle dike (Fig. 13c). In detail, the fault plane consists of bifurcating and anastomosing fault segments and fractures

connected by damage-zone linkages. Extensional steps and dilational jogs are very common and are a diagnostic record of brittle deformation in the mudstone. The faulted sandstone displays hangingwall and footwall drag folds, and a progressive increase in the number of fractures toward the damage zone. Along some of the fault segments, sandstone intrusions generated by the partial fluidization of the deformed dike are observed. In particular, the segment of the dike located in the hangingwall bifurcates, with one branch connecting with the sandstone in the footwall, while another branch intrudes upward along the tectonic discontinuity (Fig. 13b). Sand fluidization and lateral sand evacuation processes may explain the observed thinning of the dike in the fault zone.

7.3 Implications for reservoir connectivity

The distribution and transmissibility of fluids within reservoirs is strongly affected by the presence of faults that act either as conduits or barriers to fluid flow (Child et al., 1997; Knipe, 1997; Manzocchi et al., 1998; Aydin, 2000; Bailey et al., 2002; Faulkner et al., 2010). Occurrence of injected sand along fault planes forming the SFNF, has significant effect on enhancing and perpetuating cross- and along-fault permeability in otherwise poorly-connected siliciclastic strata. In the light of our outcrop observations, it appears that most SFNF displacements occur below the resolution of seismic data typical of oilfield locations. Lack of resolution of these fault-related sandstones compromises the appraisal of the volume of strata within which permeable, connected reservoir volume exists. In practice this can lead to substantial underestimation of hydrocarbon recovery if the presence and significance of SFNF remain unidentified.

551   Recognition of SFNF is particularly important for reservoirs with

552   Panoche/Tumey-type successions (Fig. 3). Because of juxtaposition between

553   reservoir and non-reservoir facies, and the formation of a low permeability gouge,

554   faults that dissect Panoche/Tumey-type successions are likely to behave as

555   hydraulic barriers that reduce cross-fault fluid flow (Rawling et al., 2001; Bense et al.,

556   2003; Caine and Minor, 2009) (Fig. 14a). Occurrence of SFNF in these types of

557   successions may provide enhanced connectivity between sandstone that are

558   otherwise displaced by faults (Fig. 14b). If clay smear and fine-grained cataclastic

559   material are present along fault walls this may be eroded by turbulent granular flow

560   during sand fluidization and injection thus enhancing connectivity across a fault

561   plane (Fig. 14c). Fault-strike and fault-dip modifications of faults during sand injection

562   and by the emplacement of sandstone intrusions favour connectivity in reservoir

563   intervals.

564   Reservoirs with a Santa Cruz -type succession (Fig. 3), generally have faults

565   that produce fracture permeability which prevent the emplacement of sand along

566   normal faults. However, where this type of succession is characterized by low

567   deformation, isolated normal faults with small offsets may host injected sand. This

568   makes a strong contribution to enhanced gross permeability of non-reservoir strata

569   by enhancing the permeable network and new conduits for fluid migration.

570   Arrays of SFNF that cuts through sub-horizontal sandstone are expected to

571   give rise to meso- and large-scale wing-like and conical sandstone intrusions, which

572   should not be confused with those emplaced in the absence of tectonic influence

573   (Huuse et al., 2007). In particular, parallel arrays of constantly dipping SFNF can be

574   responsible for the formation of stepped sills (Fig. 15a, b), while conjugate sets of

575   SFNF may give rise to saucer-shaped and conical geometries (Fig. 15c, d).

576 Structurally-controlled wing-like sandstone intrusions can be identified in seismic
577 sections as they lack the characteristic jack-up that lifts beds that overlie sandstone
578 intrusion (Szarawarska et al., 2010). Despite having structurally- and non-
579 structurally-controlled sandstone intrusions that display broadly similar geometry, it is
580 crucial to discriminate between the two categories when evaluating the behaviour of
581 subsurface fluid migration. SFNF may have specific reliance to planning and
582 optimizing hydrocarbon recovery by influencing fluid distribution in hydrocarbon
583 reservoirs. By contrast, SFNF may represent a persistent open drainage (seal-
584 breach) through which fluids continuously leak thereby limiting hydrocarbon
585 accumulation and generally facilitating ease of drainage of all basin-derived fluids
586 (Cartwright et al., 2007).

587 The occurrence of SFNF in a hydrocarbon reservoir can significantly increase
588 the general connectivity. Under favourable conditions, this result in enhanced
589 permeability and an increase in the reservoir rock volume. However, with
590 unfavourable conditions, SFNF can promote considerable hydrocarbon leakage by
591 connecting reservoir rocks with either the topographic surface or other permeable
592 horizons in the stratigraphic succession.

593

8. Summary and conclusions

595 Details of sand-filled normal faults (SFNF) recognized from two areas in
596 central California, in which contrasting normal fault characteristics associated with
597 larger sand injection complexes are present, are documented for the first time in this
598 paper. SFNF were intruded into Late Cretaceous and Eocene host strata in the
599 Panoche/Tumey hills, and in Miocene strata along the coast north of Santa Cruz.

Two main SFNF types are recognized: i) Type 1 SFNF form in response to the rapid increase of pore fluid over-pressure in poorly-consolidated sandstone, and the consequent hydraulic failure of the overlying host strata; ii) Type 2 SFNF form as a consequence of regional tectonic deformation, and the resulting draining of fluidized sand toward the tectonic structures.

SFNF occur in host strata that are either poorly-consolidated, as in the case of Panoche/Tumey-Type successions, or well-consolidated, as in the Santa Cruz examples. Development of sand-filled normal faults is more likely in the first case due the ductile behaviour of the deformed strata. SFNF in the Santa Cruz strata are far less common and form only where limited fault throw occurs and within poorly-developed fault core zones.

The recognition of SFNF is crucial when enhancing the understanding of subsurface fluid migration in the very shallow crust and when associated with hydrocarbon reservoirs. Although the structures we describe are below seismic resolution, they form a permeable network, with fluidized sand acting as a natural proppant that increases the connectivity of reservoirs even in adverse geological conditions. SFNF are thus a new element that must be added to the conventional methods of fault seal analysis and in particular when developing reservoir where sandstone intrusions are present.

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882

883 **Figure caption**

884

885 **Fig. 1**. Geological map of the study area in California (see inset map for general
886 location): a) Geological map of the western margin of the San Joaquin Valley and

887 associated stratigraphic column (modified from Bartow, 1996); b) Geological map of

888 the Santa Cruz coastal area and associated stratigraphic column (modified from

889 Boehm and Moore, 2002). The stratigraphic position of the giant sand injection

890 complexes cropping out in the study areas is marked. Outcrop locations and places

891 referred to in the text are also shown.

892

893 **Fig. 2**. Simplified structural maps of a) the Panoche/Tumey hills, and b) the Santa

894 Cruz areas showing the preferential SFNF orientations. a) In the Panoche/Tumey

895 hills area, stereoplots (equal-area, lower hemisphere) show preferential NW-SE and

896 WNW-ESE oriented SFNF. b) In the Santa Cruz coastal area, SFNF orientations

897 shown on stereoplots are dominantly NNW-SSE and N-S trending.

898

899 **Fig. 3**. Main types of successions and corresponding fault zone features recognized

900 in the study areas. a) Panoche/Tumey-type successions comprise poorly-

901 consolidated host rock. b) The resulting fault zone generally consists of closed-

902 fracture networks and fine-grained gouge with low permeability. Therefore, faults in

903 Panoche/Tumey-type successions result in a general reduction of the fluid

904 transmissibility. c) Santa Cruz-type successions comprise a well-consolidated host

905 rock. d) Fault zones developed in these successions generally consist of a

906 permeable fracture network surrounding the fault core. Faults in Santa Cruz-type

907 successions generally enhance connectivity and are considered the most efficient

908 pathways for fluid migration. The dashed blue lines indicate the distribution of

909 permeability within the different fault zones.

910

Fig. 4. Two main types of SFNF recognized in central California. a) Type 1 SFNF related to pressure build-up. b) Type 2a SFNF related to regional extensional tectonics. c) Type 2b SFNF related to regional contractional tectonics. See further explanation in the text.

915

Fig. 5. Type 1 SFNF from outcrop O1 in the Tumey Gulch area. a), SFNF displaying centimetre-scale offsets and openings of a few centimetres. Note that the different sandstone layers, separated by mudstone horizons, are actually connected with each other through sand filling the SFNF. b) Photograph and c) associated line drawing of conjugate sets of Type 1 SFNF displaying centimetre-scale offsets. Faults die out upwards over tens of centimetres, and the overlying beds remain unaffected by the deformation. Anomalous curvatures of fault planes are related to post-emplacement compaction.

924

Fig. 6. Type 1 SFNF from outcrop O2 in the Tumey Gulch area. a) Photograph and b) associated line drawing of a SFNF array overlying a remobilized turbidite sandstone body. Fluidisation processes are particularly evident along the irregularly-shaped top surface of the sandstone. SFNF cut just a few metres of overburden while the basal surface remains unaffected by faulting. Note also the anomalous curvature shown by the fault planes due to post-emplacement deformation processes.

932

933 **Fig. 7**. Type 2a SFNF from outcrop O2 in the Tumey Gulch area. a) Photograph and

934 b) associated line drawing of conjugate sets of SFNF showing offsets varying from a

935 few decimetres to metres, and apertures ranging from a few centimetres to some

936 tens of decimetres. Sandstone-filled vertical fractures, consistent with a vertically

937 oriented σ1, are also present. Note the SFNF segmentation in the upper part of the

938 outcrop due to post-emplacement compaction. c) Lower hemisphere equal area

939 stereographic projection showing the orientation of the sandstone-filled fault planes

940 (great circles).

941

942 **Fig. 8**. Type 1 SFNF from outcrop O3 in Monocline Ridge. a) Photograph and b)

943 associated line drawing of an array of alternating SFNF and sandstone-filled reverse

944 faults. SFNF show apertures of some centimetres and offsets of few tens of

945 centimetres. Fault 1 displays an almost constant thickness of sand infill while Fault 2

946 shows different lozenge-shaped, en echelon, sandstone-filled segments. Lower

947 hemisphere equal area stereographic projection shows the orientation of the fault

948 planes (great circles).

949

950 **Fig. 9**. Type 2a SFNF from outcrop O4 in the Santa Cruz coastal area. a)

951 Photograph and b) associated line drawing of a SFNF within the Santa Cruz

952 Mudstone. c) Lower hemisphere equal area stereographic projection shows the

953 orientation of the fault planes (great circles).

954

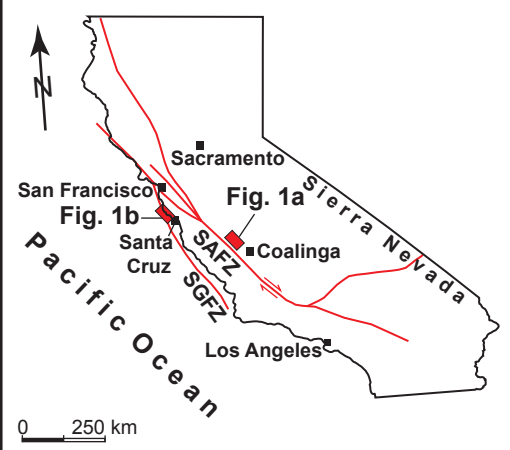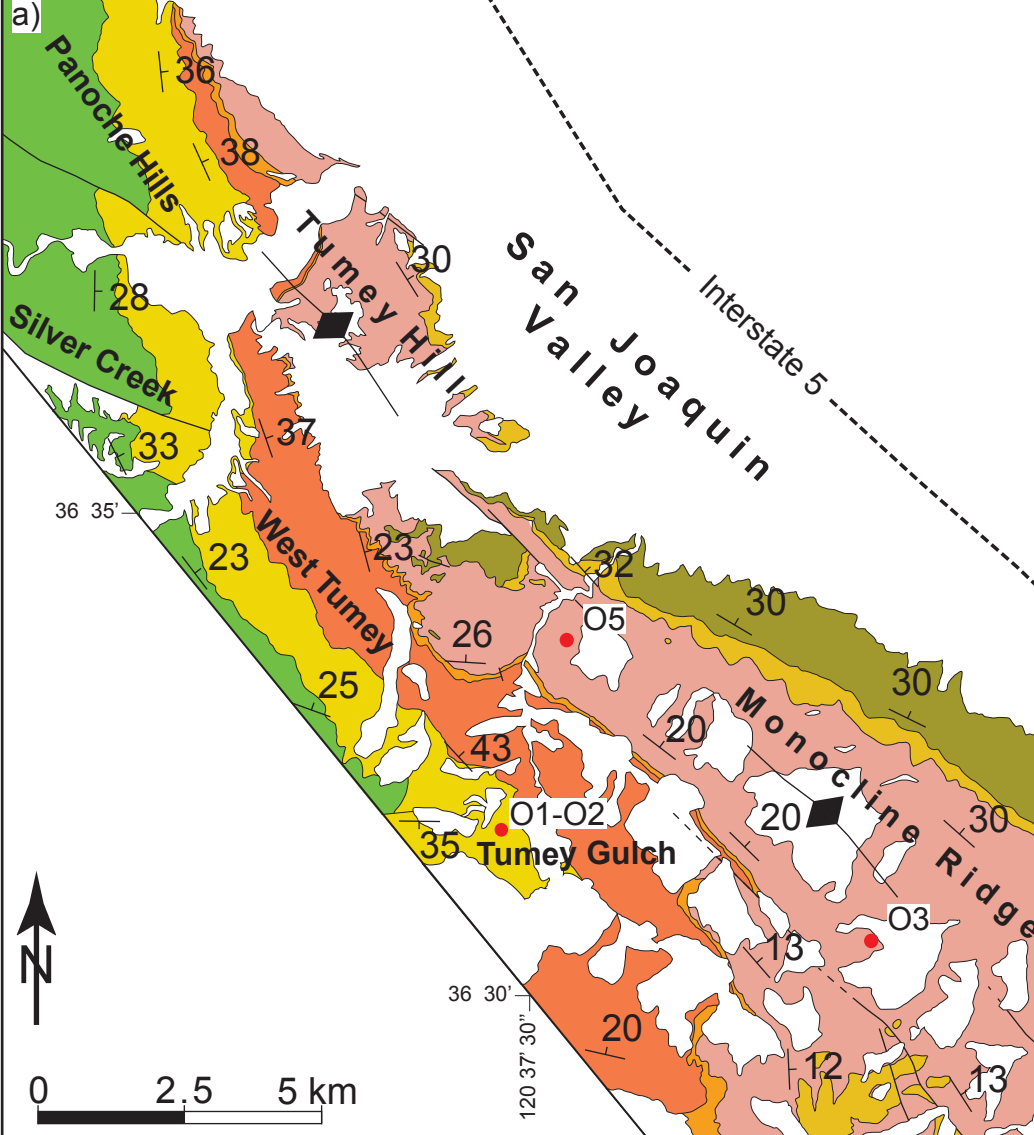**Fig. 10**. Model for the formation of Type 1 SFNF. a) Overpressure in an isolated sandstone layer is built up by the rapid ingress of pore-fluid through a dike connected with deeper overpressured units. Overpressure and the consequent change in shape of the sandstone body causes the failure of the overburden, and the initial injection of fluidized sand along fractures and faults forming a hydrofractured belt. b) These processes evolve with the progressive upward evacuation of sand from the sandstone body and the development of new SFNF. Model for the formation of Type 2 SFNF. c) During the pre-faulting stage, the fluid pressure is equally distributed in the sandstone. d) A fault cutting through the sandstone results in a sudden disturbance in the fluid pressure. The onset of a fluid pressure gradient drives the transfer of fluid from the sandstone toward the low pressured area represented by the fault plane. e) If the fluid reaches the minimum fluidization velocity, the fluidized sand can be carried in suspension and emplaced along the tectonic discontinuity.

Fig. 11. Simplified model of the cross-cutting relationships between Type 1 SFNF and Type 2 SFNF as observed in the PGIC, TGIC and SCIC. a) Emplacement of a sand injection complex. The different architectural elements are organized as proposed by Vigorito et al. (2008). Type 1 SFNF form concomitantly with this event and the age of the faults, as well as that of the entire complex, is obtained by dating the mudstones at the base of the extrudites. b) The emplacement of Type 2 SFNF occurs during a faulting event postdating the emplacement of the main complex. The age of these faults can be determined using standard methods (model is not to scale).

979

Fig. 12. Type 2a SFNF from outcrop O5 in Tumey Gulch. a) Photograph and b) associated line drawing of SFNF cutting through a pre-existing sandstone intrusion. The host strata consist of diatomaceous mudstones. c) Lower hemisphere equal area stereographic projections showing the orientation of the normal fault planes (great circles and contours). d) Detail of the outcrop O4 showing the intense sand remobilization characterizing the upper margin of the sandstone body, and the fluidized sand intruded along the fault plane. e) Close up showing detail of the fault plane. Note the occurrence of deformation bands and host rock fragments.

988

Fig.13. Type 2a SFNF from outcrop O4 in Panther Beach. a) Photograph and b) associated line drawing of SFNF cutting through a low-angle dike. Note the thinning of the faulted dike in the vicinity of the fault plane due to the transfer of fluidized sand along the tectonic structure. c) Lower hemisphere equal area stereographic projection showing the orientation of the normal fault plane (great circles).

994

Fig. 14. Impact of SFNF affecting Panoche/Tumey-type succession on reservoir connectivity. a) Ordinary fault cutting through Panoche/Tumey-type successions produces impermeable fine-grained gouge and interrupts the lateral continuity of the sandstone bodies resulting in a barrier to fluid flow transmission. b) The occurrence of sand along the SFNF plane enhances cross- and along fault connectivity. Note that the offset sandstone layers are still connected after the faulting event. c) Details of the SFNF plane during sand emplacement. The arrival of fluidized sand is

1002 preceded by water. The impermeable fault gouge along the fault walls is removed by

1003 the turbulent flow.

1004

1005 **Fig. 15**. Diagram showing the main characteristics of structurally- and non-

1006 structurally-controlled meso- and large-scale wing-like and conical sandstone

1007 intrusions. a) Stepped and b) conical geometries that are unrelated to regional

1008 tectonics are very common in sand injection complexes. In both cases, sand

1009 emplacement causes jack-up of the overburden that can be recognized at outcrop or

1010 in seismic sections. c), SFNF can produce stepped geometries when a sandstone

1011 body is offset by a fault. However the lateral connectivity between the single steps is

1012 still maintained by the sand contained along the fault plane. d) Conjugate SFNF can

1013 also produce conical-like intrusions connecting the sandstone segments offset by the

1014 fault. In the latter two cases, jack-up of the overburden is not developed. This feature

1015 helps discriminate between structurally- and non-structurally-controlled sandstone

1016 intrusions either at outcrop or in seismic sections.

a)

Panoche Hills

36

38

28

Silver Creek

33

37

Tumey Hills

23

23

25

43

26

32

Tumey Gulch

San Joaquin Valley

30

Monocline Ridge

20

20

30

30

20

13

22

12

13

15

n=24
Fault planes

n=27
Fault planes

n=21
Fault planes

n=15
Fault planes

n=29
Fault planes

n=32
Fault planes

Legend

Kreyenhagen Shale

Moreno Formation

Santa Cruz Mudstone

Faults

Anticline

Syncline

20
Bedding attitude

Key outcrop location

N

0   2.5 km

b)

n=12
Fault planes

n=11
Fault planes

n=21
Fault planes

n=14
Fault planes

n=10
Fault planes

Shark Tooth

Bonny Doon

Panther Beach

Laguna Beach

Santa Cruz Costal area

10

4 Miles Beach

8

Santa Cruz

N

0   2   4 km

Undeformed succession	Fault zones characters	Description
Panoche/Tumey-Type succession a)	b) Protolith / Protolith / Core zone / Deformation bands	Poorly-consolidated host rock Ductile behaviour Closed fractures Narrow fault zone High bed-parallel primary permeability Low fault-parallel secondary permeability
Santa Cruz-Type succession c)	d) Damage zone / Protolith / Core zone / Protolith	Well-consolidated host rock Brittle behaviour Open fractures Wide fault zone Low primary permeability High fault-parallel secondary permeability

Mudstone   Biosiliceous mudstone   Sandstone   Fault core rock   --- Water table   ↗ Fluid flow trajectory

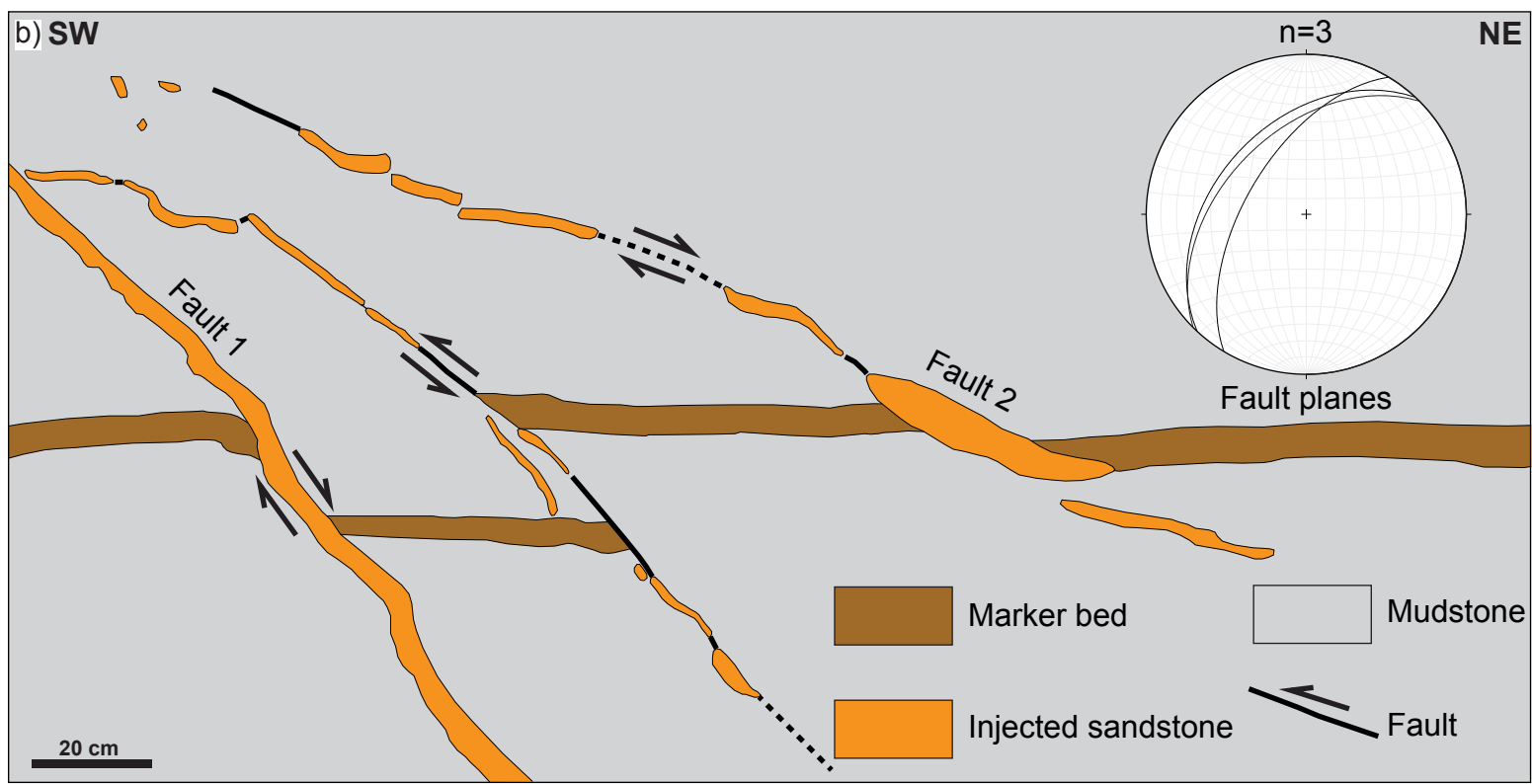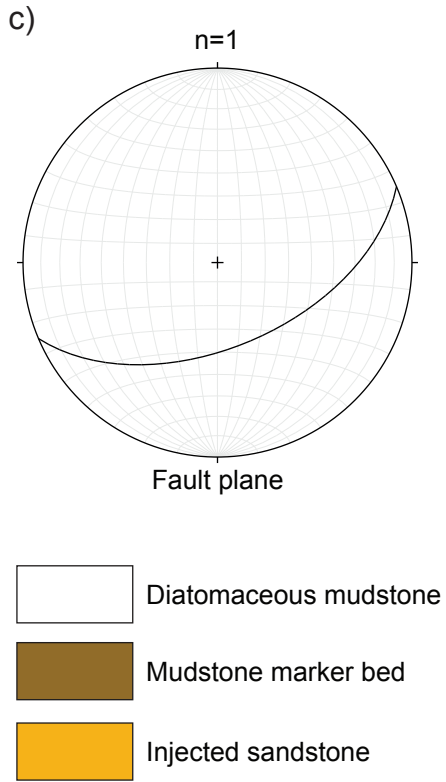| TYPE 1	TYPE 2	
a) **Overburden collapse extension**	b) **Regional extensional tectonics**	c) **Outer-arc extension**
	TYPE 2-a	TYPE 2b
Pressure build up-related faults	**Regional tectonics-related faults**	
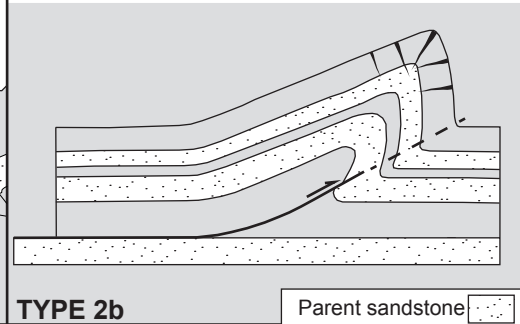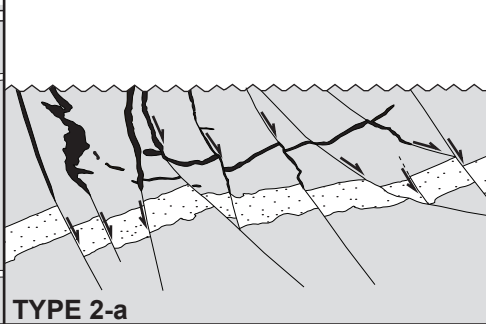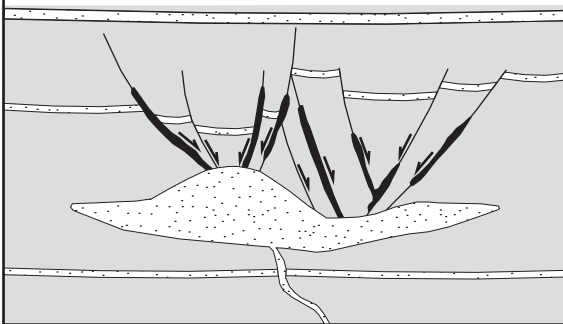
Parent sandstone

Injected sandstone

a)

b) SW   NE

LEGEND

Quaternary cover

Marker bed

Thinly-bedded mudstone-sandstone couplets

Injected sandstone

Sandstone-filled fault

Pristine or slightly remobilized sandstone

50 cm

a)

b)

Segmentation

Fractures

N   20 cm   S

c)

n=3

Fault planes

LEGEND
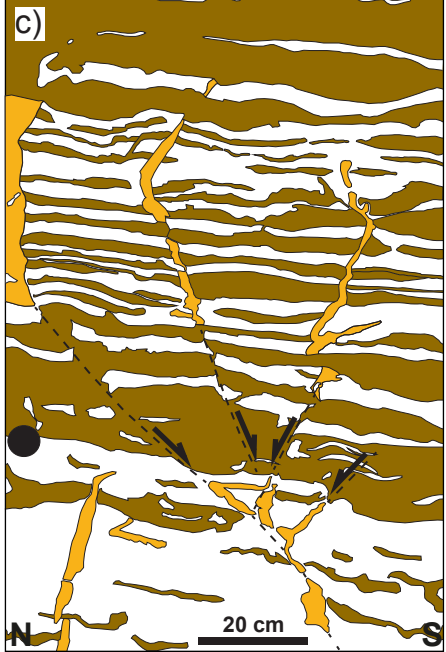
	Quaternary cover
	Depositional sandstone bed
	Marker bed
	Injected sandstone
	Mudstone

a)

b) SW   n=3   NE

Fault 1

Fault 2

Fault planes

Marker bed   Mudstone

Injected sandstone   Fault

20 cm

a)

b)

N   30 cm   S

c)

n=1

Fault plane

Diatomaceous mudstone

Mudstone marker bed

Injected sandstone

Type 1 SFNF

a) b)

Type 2 SFNF

c) d) e)
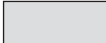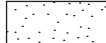
Pristine sandstone	Intensely modified/injected sandstone	Fluid flow trajectory
Mudstone	Marker bed	Future normal fault	Active normal fault	Inactive normal fault

a)

Extrudites

Intrusive complex

Parent units

Sea-floor

Type1 SFNF

Type1 SFNF

Fig. 6

b)

Type 2 SFNF

Type 2 SFNF

Type 2 SFNF

Fig. 12

Sandstone intrusion

Remobilized parent unit

Mudstone

Active fault

Inactive fault

SFNF

a)

b) NW   SE

Bedding

■ Sandstone
□ Diatomaceous mudstone

30 cm

Fig. 12d

c)

n=12

Fault planes

n=12

Fault planes

d)

Fig. 12e

10 cm

e)

Deformation band

Host rock
fragments

10 cm

a)

b)

Low-angle dike

Drag fold

10 cm

SW   NE

c)   n=1

Fault plane

Parent sand body

Remobilized sandstone

Clay horizon

Fault core zone

Legend:
- Fault gouge
- Sandstone
- Mudstone
- Fluid flow trajectory

a) Jack-up

b) Jack-up

c)

d)

Pre-existent sandstone
(pristine depositional unit or sandstone intrusion)

Marker bed

Injected sandstone

Fault