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Extreme mantle uplift and exhumation along a transpressive transform fault

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Abstract :

Mantle exhumation at slow-spreading ridges is favoured by extensional tectonics through low-angle detachment faults^{1, 2, 3, 4}, and, along transforms, by transtension due to changes in ridge/transform geometry^{5, 6}. Less common, exhumation by compressive stresses has been proposed for the large-offset transforms of the equatorial Atlantic^{7, 8}. Here we show, using high-resolution bathymetry, seismic and gravity data, that the northern transform fault of the St Paul system has been controlled by compressive deformation since ~10 million years ago. The long-lived transpression resulted from ridge overlap due to the propagation of the northern Mid-Atlantic Ridge segment into the transform domain, which induced the migration and segmentation of the transform fault creating restraining stepovers. An anticlockwise change in plate motion at ~11 million years ago⁵ initially favoured extension in the left-stepping transform, triggering the formation of a transverse ridge, later uplifted through transpression, forming the St Peter and St Paul islets. Enhanced melt supply at the ridge axis due to the nearby Sierra Leone thermo chemical anomaly⁹ is responsible for the robust response of the northern Mid-Atlantic Ridge segment to the kinematic change. The long-lived process at the origin of the compressive stresses is directly linked to the nature of the underlying mantle and not to a change in the far-field stress regime.

49 When Darwin stopped in the St. Peter & St. Paul's islets in 1832, he recognised that the
50 rocks exposed there were not volcanic and postulated that the mechanism for their
51 formation was different from that building other oceanic islands¹⁰. The islets, formed by
52 variably serpentinitised and mylonitised peridotites^{11,12}, are currently uplifting at rates of
53 1.5 mm/yr¹². Previous work suggested that the exposure of such large volume of
54 ultramafic rocks resulted from an abnormally cold upper mantle¹³⁻¹⁵ or cold
55 lithosphere¹⁶ in the Equatorial Atlantic and that the islets were either part of an
56 extensional flexural ridge, as observed in other transform faults^{6,13} or linked to
57 compression⁸. Our data reveal that the islets are part of a major uplift of the lithospheric
58 mantle due to a 10 Myr long period of transpression at the transform boundary¹⁷.
59 Similar push-ups exist along continental strike-slip faults^{18,19} but this is the first time
60 one has been fully mapped in the oceanic lithosphere near a present-day spreading
61 centre. Understanding the processes responsible for its formation will shed new light on
62 the behaviour of large transform boundaries and their response to changes in both local
63 and far-field stresses as well as on mechanisms leading to mantle exhumation at
64 spreading centres.

65

66 Four transform faults and three intra-transform ridge segments, cumulating a 630 km
67 offset, form the complex St. Paul transform system (Fig. 1 & Supplementary Fig. S1).
68 Tectonic patterns and lithology reveal that the St. Peter & Paul's islets are part of a
69 major, 200 km-long, 30 km-wide submarine shear zone that accommodates
70 transpressive stresses along the northern transform fault of the St. Paul system¹⁷ (Fig.
71 1). Most dredged samples are breccias of mylonitic peridotite and ultramylonites that
72 underwent various degrees of serpentinisation and deformation (Supplementary Fig.
73 S2). The morphology and the distribution of the deformation in the transform fault allow
74 three tectonic domains in the shear zone to be defined: the Western Transfer Zone
75 (WTZ), the Central Transpressive Zone (CTZ) and the Eastern Shear Zone (ESZ) (Fig. 2).

76

77 An important segmentation of the transform fault with associated push-up ridges
78 resulting from dextral transpression characterizes the WTZ (Fig. 2a). Eastwards, a series
79 of left-stepping restraining bends and offsets in the transform, associated with a large
80 topography, form the distinct tectonic pattern of the CTZ. Thrust faults (Figs. 1, 2b & 3)
81 mark the base of its south flank, overlapping the crust formed at the north intra-
82 transform segment. These thrust faults, imaged by seismic reflection data (Fig. 3), are
83 associated with the exposure of mylonitised peridotites and deformed sediments at this
84 crustal contact. They form positive flower structures resulting from transpression at the
85 restraining offsets along the shear zone (Fig. 2b). The area is seismically very active and,
86 while most of the events have strike-slip focal mechanisms, a few compressive events²⁰
87 near the islets confirm the presence of thrust faults. The ~3500 m-high Atobá Ridge,
88 located at the largest offset of the transform fault, is a major push-up ridge in the centre
89 of the wider transpressive feature, marking the location of the most intense
90 deformation²¹. The gravity-derived density structure over this portion of the shear zone

91 and the nature of the rocks sampled on both the islets and the flanks of the Atobá ridge
92 (Fig. 4 and Supplementary Figs. S2 & S3) imply the presence of a core of uplifted,
93 relatively unaltered high-density mantle beneath the islets and an anomalously thick
94 low density layer on the ridge flanks, especially the southern one. We suggest that the
95 thickening of the low-density layer derives from a local deepening of the
96 serpentinisation front. Accordingly, the 500°C isotherm, that can be considered the limit
97 of the serpentinisation process²², lies at a depth of 25 km below the Atobá ridge (Fig. 4)
98 i.e. deeper than the inferred maximum depths of the low-density layer, supporting the
99 idea that the low-density material is related to hydration of mantle rocks. In the ESZ
100 (Fig. 2c), the transform fault crosses a deep basin similar to the transform fault basins
101 observed elsewhere in the St. Paul system (Fig. 1 and Supplementary Fig. S1). The basin
102 morphology suggests the absence of significant transpression in this section of the shear
103 zone. Close to the intra-transform segment, the transform becomes a double fault. This
104 reveals that even in the more linear part of the transform domain the motion is not
105 purely strike-slip.

106

107 The oblique segments and the offsets disrupting the main trend of the western
108 transform boundary developed after several episodes of southward propagation of the
109 northeastern segment of the Mid-Atlantic Ridge (MAR) in the last 10 Myr, as revealed by
110 the lengthening of its abyssal hills. The absence of asymmetric faulting at this large-
111 offset ridge-transform intersection implies that the robust segment receives enough
112 melt supply to counteract the cold-edge effect of the transform fault²³ (Figs. 1 & 2a). The
113 short northern intra-transform segment, although comparatively less robust, did not
114 retreat to accommodate the propagation of the MAR segment, leading to an overlap of
115 both spreading segments. The morphology of the intra-transform segment, with sub-

116 parallel abyssal hills mapped on both flanks, and the basalt samples recovered on and
117 off axis are consistent with spreading dominated by volcanic processes for at least the
118 last 10 Myr. However, contrary to the MAR, this small segment did not increase in
119 length, reflecting the difference in melt supply between the segments.

120

121 The change in the tectonics of the northern boundary of the St. Paul system started ~11
122 Ma, when a 5° counterclockwise change in the spreading direction between the South
123 America and Nubia plates occurred, inducing extension at large-offset left-stepping
124 transforms in the Central and Equatorial Atlantic^{5,24}. The origin of the St. Paul
125 transpressive shear zone relates to the way the spreading geometry locally adjusted to
126 this plate motion change. We construct an evolutionary scenario describing the
127 responses of the transform to a sequence of far and local stress changes (Fig. 5). The 11
128 Ma counterclockwise rotation locally resulted in the transtensional formation of a
129 flexural transverse ridge along the northern border of the transform fault. This same
130 event resulted in the synchronous growth of the Vema transverse ridge at 11°N⁵.
131 Shortly after, the spreading ridge segments started to adjust to the new spreading
132 geometry, with the lengthening of the MAR segment, while the intra-transform segment
133 to the East remained roughly stable. As the MAR segment kept propagating south, the
134 western part of the transform started to segment and this non-uniform adjustment
135 resulted in the formation of restraining bends and offsets, inducing localized
136 transpression on the western portion of the flexural transverse ridge. The resulting
137 structure is bounded by low-angle thrusting along the external faults of the system (Fig.
138 2). The four lengthening events, marked by the steps in the transform boundary,
139 correspond to progressively slower propagation rates, as the ridge geometry adjusted to
140 the local stresses (Fig. 5). The oldest and largest offset corresponds to a fast

141 displacement of the western transform segment from its main trend. This event created
142 the first compressive stresses at the transverse ridge. As the transform fault adjusted
143 southwards during the second event, the increase in the fault segment offset induced
144 higher stresses that begun to form the sigmoidal push-up Atobá ridge. The following
145 episode, of smaller amplitude, formed a smaller restraining bend, continuing to sustain
146 the uplift of the Atobá ridge and forming the southern part of the CTZ. The most recent
147 evolution also displays southward deviations of the shear zone resulting in
148 transpressive deformation in the WTZ. The morphology, focal mechanisms, and
149 evidence for uplift in the Atobá Ridge show that transpression is still active in the
150 western part of the shear zone. Such an active deformation implies that the plate
151 boundary did not reach a steady-state geometry and that the changes in the spreading
152 geometry are still being accommodated, although at relatively lower present-day rates.
153 Despite their similar offset, the Vema and the northern St. Paul transform show a
154 different sequence of adjustments both starting with the same kinematic change. The
155 Vema transform reacted with a single short transtensive adjustment while St. Paul
156 records a multiple set of events over a larger time-span. A plausible cause of this
157 different behaviour is the influence of the Sierra Leone hotspot, which may have
158 enhanced the magma supply of the MAR segment just north of St Paul transform⁹.
159 Lengthening of ridge segments due to increased magma supply is well documented
160 along the MAR²⁵ and may be an important mechanism here. Geochemical data^{9,14,26} show
161 the existence of a mantle composition boundary within the St. Paul system, with an
162 enriched mantle beneath the MAR segment north of the system extending to the
163 northern intra-transform segment. The volcanic morphology of these segments possibly
164 reflects the nature of the mantle, which favours enhanced melting.

165

166 Continental shear zones where restraining step-overs result in transpressive flower-like
167 structures and push-up ridges, exposing mylonites and ultra-mylonites at the surface
168 are well documented^{18,19}. The observed structural and petrologic patterns at the St Paul
169 northern transform boundary are similar, with multi-segmented and sub-parallel faults
170 away from the step-ups and oblique faults close to them. Associated thrust faults uplift
171 large reliefs and expose deep rocks distributed along bands parallel to the main strike-
172 slip fault zone, forming positive flower structures. At the centre of these features, the
173 higher topography is associated with a push-up block, oblique faults and intense
174 deformation^{18,21}. The MAR half-spreading rate (16 mm/yr)²⁷ yields convergence rates of
175 32 mm/yr at the step-overs and transpressive segments of the fault. This amount of
176 shortening is sufficient to uplift a 100 km-long block by more than 3500 m, with
177 present-day uplift rates of 1.5 mm/yr¹², comparable to those estimated for structures
178 observed along continental strike-slip faults^{18,19}.

179

180 The evolution of the northern St. Paul plate boundary, where the southward migration
181 of both the MAR segment and the transform fault is progressively accommodated
182 through bends, offsets and oblique structures over a wide shear zone, lead to a
183 particular situation in the mid-ocean ridge system, with long-lived regional-scale
184 transpression along the transform. Whereas most exposed mantle rocks near mid-
185 ocean ridges result from extensional tectonics along detachment faults, our study
186 reveals that the peridotites and mylonites of the St. Peter & Paul's islets result from a
187 major uplift of the oceanic lithosphere along a transpressive shear zone due to local
188 stresses which have been active during a time much longer than usually necessary for a
189 plate boundary to adjust to a kinematic change. This may also be the case along other
190 major transform faults, although probably at a smaller scale. Here we show that even

191 large-offset transforms, materializing large contrasts in lithosphere thickness, may
192 deform due to the local stresses induced by the increase in melt supply at the spreading
193 ridge. Mantle composition and temperature may therefore trigger the local response of
194 the lithosphere. To understand deformation at large transforms, mantle processes must
195 not be neglected.

196

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265

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267

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276

277 Author contributions

278

279 M.M. and S.S. conceived the COLMEIA project. M.M. led the COLMEIA cruise. M.M, A.B.
280 and D.B. acquired, processed and interpreted the different data sets and wrote the
281 paper. M.L. provided complementary bathymetry data, processed and interpreted the
282 different data sets and wrote the paper. N.F. interpreted the bathymetry data. E.A., A.A.
283 and P.O. interpreted the seismic data for sediment thickness. D.M. built the crustal age
284 model and acquired the data during the COLMEIA cruise. T.C., B.M., I.B., C.H., A.M., C.S.
285 and I.P. acquired the data during the COLMEIA cruise.

286

287 Additional information

288

289 Supplementary information is available in the online version of the paper. Reprints and
290 permissions information are available online at www.nature.com/reprints.
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294

295 Competing financial interests

296 The authors declare no competing financial interests.

297

298 Figure captions

299

300 Figure 1. 1a. Location of the St Paul shear zone and other notable features of the
301 Equatorial Atlantic. The Sierra Leone hotspot⁹ location is shown by the red star. 1b.
302 Multibeam bathymetry of the St. Paul shear zone. A black star shows the location of the
303 St. Peter & St. Paul's islets. The thick black lines represent the present-day active
304 transform faults, with the arrows showing the direction of plate motions. The black lines
305 with the ticks represent the thrust faults. The white lines show the present-day
306 spreading axes. The labelled rectangles show the areas detailed in Figure 2.

307

308 Figure 2. Shaded bathymetry of three different portions of the northern St. Paul shear
309 zone. 2a. West Transfer Zone (WTZ) displaying a multi-segmented transform fault sub-
310 parallel to the current spreading direction and three en-echelon push-up ridges. 2b.
311 Central Transpressive Zone (CTZ) displaying step-overs of the transform fault on either
312 side of the St Peter and Paul's islets. The Atobá Ridge is located at the central step. The

313 base of the south flank of the CTZ displays a series of thrust faults. 2c. Eastern Shear
314 Zone (ESZ) where the transform fault crosses a deep basin. Fault captions as in Figure 1.

315

316 Figure 3. Fully migrated reflection seismic line crossing the St. Paul shear zone (a)
317 (location shown in the inset) and interpreted cartoon (b) showing the thrust faults at
318 depth associated with the mylonite exposures and the positive flower structure. The
319 sediment cover also shows intense deformation. The processing techniques are
320 described in the Methods section.

321

322 Figure 4. Thickness map of a 2800 kg/m^3 density layer, that can correspond to crust
323 and/or to altered mantle, derived from the gravity data and superimposed on a shaded
324 high-resolution bathymetry. The density distribution is consistent with the rocks
325 sampled in the islets and on the submarine flanks of the CTZ (Supplementary Figure S2).
326 The black lines show the depth of the $500 \text{ }^\circ\text{C}$ isotherm contoured at a 1 km step. The
327 model parameters and method of calculation are described in the Methods section. The
328 black star shows the St. Peter & Paul's islets. Fault captions as in Figure 1.

329

330 Figure 5. Sketch of the evolution of the St. Paul shear zone from a configuration prior to
331 the change in plate motion at $\sim 11 \text{ Ma}$ on the top to the present boundary geometry, on
332 the bottom. Blue areas mark extensional features, red are compressive and gray shows
333 the inactive parts of the ridge. The large arrows show the spreading directions and the
334 thin black vertical arrow show the propagation of the northern MAR segment. The thin
335 oblique arrows show the direction of the local stresses.

336

337 Methods

338

339 Gravity modelling.

340 The gravity data obtained during the cruise²⁸ were processed in the conventional way
341 (Eötvös, drift and latitude corrections) to compute the free-air anomalies before being
342 merged into a grid, together with satellite-derived free-air anomaly data^{29,30} to obtain
343 the free-air anomaly used in this study. The density model consists of three layers of
344 constant density: the sediment cover, the crust or altered mantle (or their density
345 proxy) and the normal mantle, respectively with densities of 2400, 2800 and 3300
346 kg/m³ and 1030 kg/m³ for the water. Modelled densities do not attempt to reproduce
347 the complex reality inferred from the petrology, but consider densities that may be close
348 to altered and serpentinised peridotites, mylonites and crustal rocks. To construct a
349 sediment thickness grid, we used the values derived from the interpretation of the
350 seismic lines obtained during the cruise as well as available data from older cruises and
351 extrapolated them to the neighbouring areas. The sedimentary infill reaches 300 to 500
352 m in the nearby basins, but most of the area presents only relatively thin sediment cover
353 (less than 100 m). As the seismic lines are spaced further apart than the echosounder
354 sampling, the resolution of the sediment grid is not as good as the bathymetry, so for the
355 model, we interpolated the high-resolution bathymetry²⁸ onto a 1 km step grid,
356 compatible with the sediment thickness grid, after projecting all data from geographic
357 degrees to UTM kilometres. From the bathymetry and the sediment thickness, we
358 calculated the basement topography. To calculate the Mantle Bouguer anomaly, we
359 assumed a constant, 6 km-thick “crust” (or its proxy, a 2800 kg/m³ density layer), using
360 the basement as the top of the layer. The gravity effect of this model was computed in
361 the Fourier domain using the multi-layer method, developed to account for both rapidly
362 varying topography and shallow water depths³⁰ and subtracted from the free-air

363 anomaly grid yielding the Mantle Bouguer anomaly. Before inverting for the layer
364 thickness variations from the assumed 6 km constant “crust”, we removed the effect of
365 the cooling of the lithosphere. Several thermal models were tested: a simple age
366 model^{31,32} and passive flow models^{33,34} using different values for the thermal
367 conductivity. As differences were only minor between the model results and expressed
368 mostly as a broad regional trend, we chose to keep the age model. Moreover, the passive
369 flow models tend to overemphasize the cold-edge effect, which our bathymetry data
370 suggest is not so marked here, despite the large offset. The 2800 kg/m³ layer thickness
371 displayed in Figure 4 is obtained by adding the computed thickness variations to the 6
372 km thick “crust”.

373

374 Seismic processing

375 The seismic lines were acquired with a 24 channels streamer using two air guns with
376 105 and 85 cubic inches²⁸. All lines were processed using software Sispeed v5.5
377 developed by IFREMER. Common mid-point gathers were stacked and migrated using a
378 simple velocity model with a sound velocity of 1500 m/s assigned for both water and
379 sediments. After processing, interpretation was performed using Kingdom 8.5 software.
380 The quality of the seismic lines in this rough topography area was checked by
381 comparison between the sea bottom reflector derived from the seismic profiles and the
382 topography derived from the high-resolution multibeam bathymetry. Only in a few
383 areas, where the seismic lines closely parallel high scarps, significant differences due to
384 lateral echoes were found. A few seismic lines crossing the CTZ were migrated with a
385 more complex model for the velocity of the sound in the sediments and the basement,
386 accounting for the increase in the sound velocity with depth, in order to better identify
387 the reflectors in the basement. The model consists of a sediment layer with a velocity of

388 1750 m/s followed by a 300 m thick layer with a velocity of 2000 m/s and then a series
389 of 500 m-thick layers with a velocity increase of 500 m/s each. The last horizon, at a
390 depth of 5800 m from the top of the oceanic crust, seismically separates the crust from
391 the mantle with a velocity 7500 to 8000 m/s. The line shown in Figure 3 was processed
392 with this full migration model.

393

394 Crustal age modelling

395 Since the proximity of the magnetic equator hinders the identification of magnetic
396 anomalies, we analysed the evolution of this part of the St. Paul system through a
397 kinematic reconstruction using the most recently published poles of rotation³⁵.
398 Theoretical crustal ages were calculated using the present day geometry of the mid-
399 oceanic ridge and these poles.

400

401 Data availability

402 Gravity and seismic data were acquired during the COLMEIA cruise²⁸. The multibeam
403 bathymetry used in this work came mainly from the COLMEIA cruise²⁸, completed with
404 data from PRIMAR96³⁶ and S7 (R/V Strakhov)³⁷ cruises. Satellite gravity data²⁹ used to
405 complement the ship data are available at http://topex.ucsd.edu/grav_outreach/#grid.
406 The global relief dataset³⁸ ETOPO1 used to draw Figure 1 is available at
407 <https://www.ngdc.noaa.gov/mgg/global/global.html>. The data that support the findings
408 of this study are available from the corresponding author upon request.

409

410 Code availability

411 The FORTRAN code used to calculate the gravity anomalies³⁰ is available from the
412 corresponding author upon request.

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414

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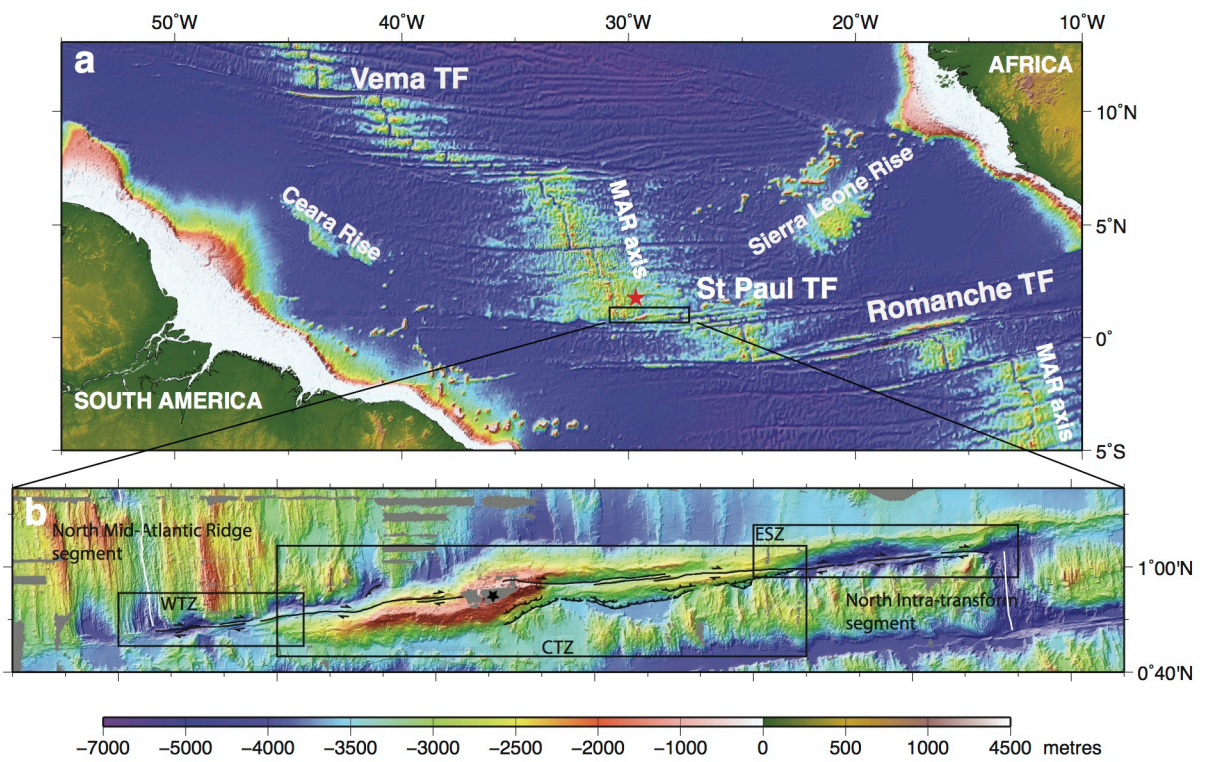
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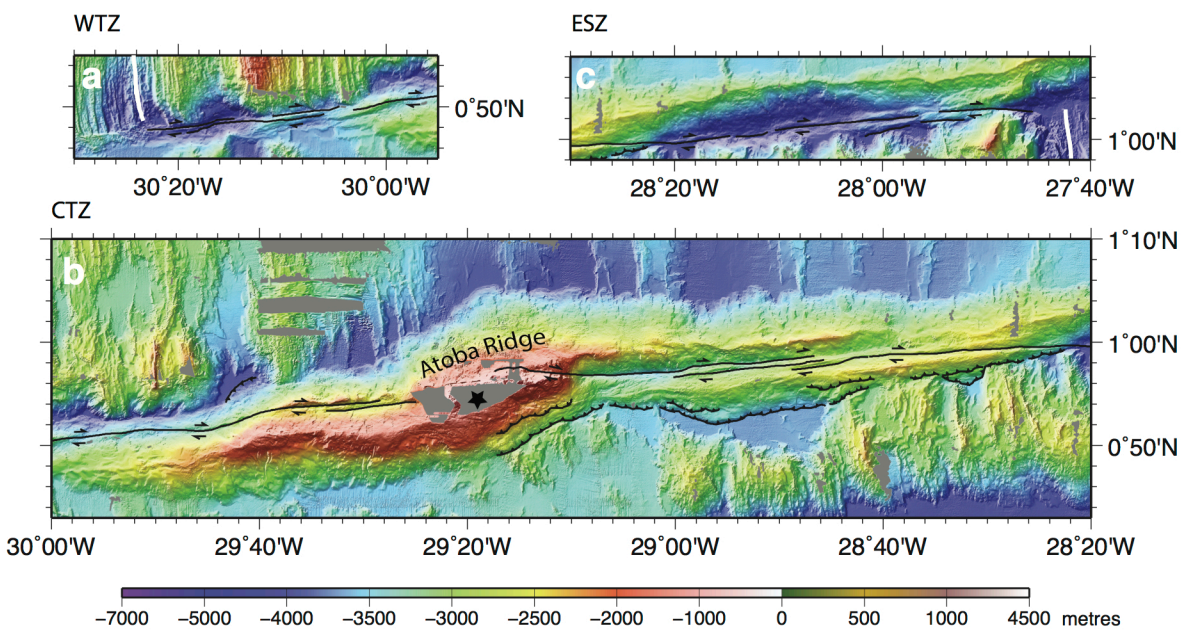
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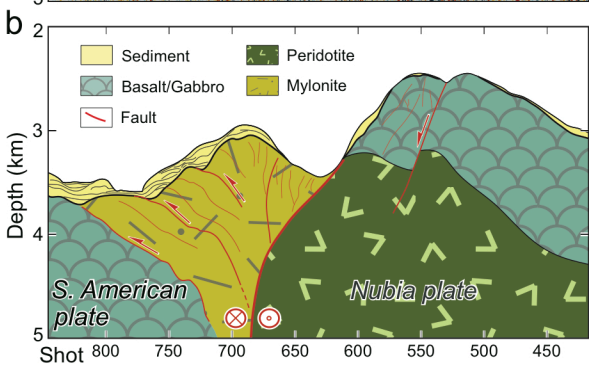
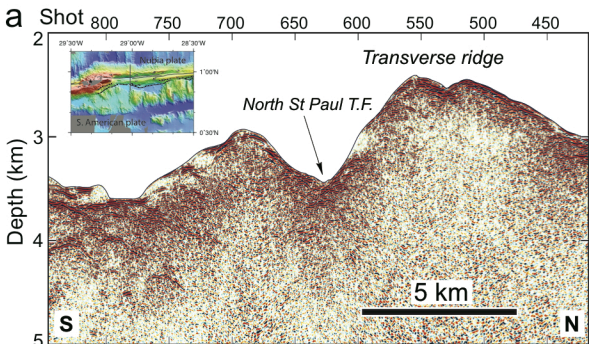
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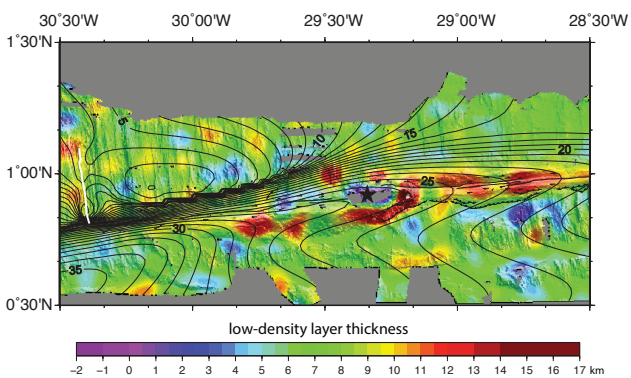
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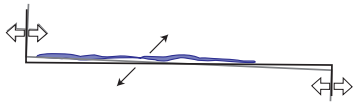




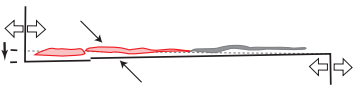
prior to the 5° counterclockwise rotation
> 11 Ma



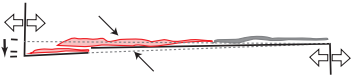
change in the spreading geometry
transpressive uplift of the flexural ridge
11-10 Ma



first southward propagation
compressional growth of the
flexural ridge
10-8 Ma



second propagation step
onset of the push-up ridge
8-5 Ma



third propagation step
growth of the push-up ridge
formation of the graben
5-3 Ma



present day propagation
growth of the push-up ridge
en-echelon small pressure ridges

