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► **To cite this version:**

N. Espurt, S. Brusset, P. Baby, P Henry, M. Vega, et al.. Deciphering the Late Cretaceous-Cenozoic structural evolution of the North Peruvian forearc system. *Tectonics*, 2018, 37 (1), pp.251-282. 10.1002/2017TC004536 . hal-01792862

HAL Id: hal-01792862

<https://hal.science/hal-01792862>

Submitted on 15 May 2018

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1 **Deciphering the Late Cretaceous-Cenozoic structural evolution of the**
2 **North Peruvian forearc system**

3

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14

15 **Key Points:**

- 16 • The North Peruvian forearc system structure is driven by buried imbricate thrust
17 systems bounding thrust-top sedimentary depocenters
- 18 • The Late Cretaceous-Cenozoic accretion and uplift of the forearc system was
19 punctuated by zones of crustal normal to strike-slip faulting
- 20 • The forearc system evolution was controlled by subduction dynamics, thick sediment
21 accumulation, and bathymetric asperities
22

23 Abstract

24 The link between plate tectonics and the evolution of active margins is still an ongoing task to
25 challenge since the acceptance of plate tectonic paradigm. This paper aims at deciphering the
26 structural architecture and uplift history of the North Peruvian forearc system to better
27 understand the evolution and the mechanics that govern the Late Cretaceous-Cenozoic
28 building of this active margin. In this study, we report surface structural geology data,
29 interpretation of seismic reflection profiles, apatite fission-track data, and the construction of
30 two offshore-onshore crustal-scale balanced cross sections. The structure of the North
31 Peruvian forearc system is dominated by an accretionary style with northwestward
32 propagation of thrust-related structural highs involving continental/oceanic basement rocks,
33 and off-scraped sediments. The thrust systems bound thick thrust-top forearc depocenters
34 mainly deformed by crustal normal to strike-slip faults and thin-skinned gravitational
35 instabilities. The sequential restoration of the margin calibrated with apatite fission-track data
36 suggests a correlation between uplift, shortening and plate convergence velocity during Late
37 Cretaceous and Miocene. Pliocene-Quaternary shortening and uplift of the coastal zone is
38 rather related to the subduction of asperities during convergence rate decrease. The
39 development of crustal normal to strike-slip faulting and subsidence zones might be the
40 consequence of slab flexure, local basal erosion along subduction fault, and/or oblique
41 subduction associated with sediment loading control. We conclude that the evolution of the
42 North Peruvian forearc system was controlled by subduction dynamics, strong sediment
43 accumulation and recent ridge subduction, and it recorded the orogenic loading evolution of
44 the Andes over the Cenozoic.

45 1 Introduction

46 Forearc systems develop on the subducting oceanic lithosphere ahead of the overriding
47 orogenic wedge/magmatic arc [Dickinson and Seely, 1979; Dickinson, 1995]. From sea to
48 land, these systems are classically composed of: a distal trench basin, an outer subduction
49 wedge, including a frontal accretionary prism and a middle prism (structural high) overlapped
50 by trench-slope basins, and an inner crustal wedge corresponding to the orogenic
51 wedge/magmatic arc overlapped by a forearc depocenter [Bailleul et al., 2007; Noda, 2016].
52 Modern forearc systems are tectonically active and associated with faulting, vertical motions
53 and volcanism, and they are the site of largest and most destructive earthquakes and tsunamis
54 [e.g., Bilek, 2010; Schurr et al., 2012; Hall et al., 2012; Villegas-Lanza et al., 2016; Saillard
55 et al., 2017; Benavente et al., 2017]. Although it is widely accepted that forearc deformation
56 is the product of both compressional and extensional tectonics [Noda, 2016], the temporal and
57 spatial variations as well as the origin of these tectonics mechanisms are still poorly
58 understood. As well as, the deep large-scale structural architecture of these systems remains
59 poorly defined [e.g., Shiki and Misawa, 1982; Chanier et al., 1999; Barnes et al., 2002;
60 Laursen et al., 2002; Melnick et al., 2006; López et al., 2008; Saura et al., 2008; Mukti et al.,
61 2012; Moore et al., 2015; Mora-Bohórquez et al., 2017]. Several studies pointed out that the
62 dynamics of the subduction (direction, velocity, flexure), subducting plate relief (roughness,
63 seamount, ridge), degrees of sediment influx at the trench, plate contact conditions, overriding
64 plate tectonics and magmatic arc history might exert a strong control on the structural style
65 (accretion or erosion), and development of many forearc systems on Earth [e.g., Royden,
66 1993; Le Pichon et al., 1993; Lallemand et al., 1994; Dickinson, 1995; Von Huene and
67 Lallemand, 1990; Clift and Vannucchi, 2004; Fuller et al., 2006; Regalla et al., 2013; Takano
68 et al., 2013; Carminati et al., 2014; Tsuji et al., 2015; Martinod et al., 2016; Noda, 2016;
69 Collot et al., 2017].

70 Forearc regions have been generally discarded by petroleum industry mostly because
71 of their high structural and stratigraphic complexities, polyphase tectonic histories, active
72 tectonics and their inferred low petroleum potential. The giant Talara petroleum province of
73 the North Peruvian forearc system (~4°S) is one of the striking exceptions to this generally
74 held idea [Moberly *et al.*, 1982; Carozzi and Palomino, 1993; Higley, 2004; Fildani *et al.*,
75 2005] (Figure 1). This frontier zone represents a challenge for future georesource explorations
76 and strategies in forearc areas. Apart from stratigraphic and provenance data [Fildani *et al.*,
77 2008; Hessler and Fildani, 2015; Witt *et al.*, 2017], the Cenozoic tectonic evolution of this
78 forearc system has never been documented in terms of structural reconstruction of different
79 episodes of its deformation.

80 The active Andean margin of Ecuador, Peru and northern Chile (1°N-33°S) is
81 described as a type example of modern erosion margin [*e.g.*, Von Huene and Lallemand,
82 1990; Collot *et al.*, 2002; Clift *et al.*, 2003; Hoffmann-Rothe *et al.*, 2006]. However, the
83 results presented here show that the tectonic style of the northern Peruvian margin is mostly
84 dominated by accretion of crustal and sedimentary rocks during the Cenozoic. Contrary to
85 other forearc basins of the Peruvian Andes, the North Peruvian margin is characterized by a
86 thick Cretaceous to Quaternary siliciclastic succession up to ~11 km-thick that extends
87 onshore and offshore [Gutscher *et al.*, 1999a; Collot *et al.*, 2002; Fernández *et al.*, 2005]. The
88 modern margin receives large clastic sedimentary influx from the Guayas River in Ecuador,
89 and Tumbes and Chira Rivers in Peru [Salomons *et al.*, 2005]. Numerous and high quality
90 2D-3D onshore-offshore seismic reflection data indicate that the structure of the basin is
91 complex with extensional tectonic regime and gravitational sliding at surface [Shepherd and
92 Moberly, 1981; Moberly *et al.*, 1982; Deniaud *et al.*, 1999; Witt *et al.*, 2006; Witt and
93 Bourgois, 2010; Bourgois, 2013], probably controlled by strong sediment accumulation,
94 together with offshore strike-slip systems, and prominent structural imbricates of continental
95 and/or oceanic material [Séranne, 1987]. This study integrates a multi-disciplinary approach,
96 including structural geology, interpretation of seismic reflection profiles, cross section
97 balancing and apatite fission-track data in order to decipher the structure of the North
98 Peruvian forearc system, and provide a complete subduction-scale evolutionary scenario
99 during the Late Cretaceous and Cenozoic. We provide new insights into the comprehension
100 and quantification of the tectonics and geodynamics processes of the subduction zone and
101 associated forearc system.

102 2 Geological background

103 2.1 Tectonic context

104 The Nazca (Farallon)-South American plate convergence system is characterized by a
105 rapid westward displacement of the continental South American plate above the oceanic
106 Nazca (Farallon) plate since the Upper Cretaceous [Frutos, 1981; Marrett and Strecker,
107 2000]. In northern Peru, the subduction of the Nazca plate beneath the South American plate
108 is N83°E trending, oblique to the N30-40°E trend of the Northern Andes [Villegas-Lanza *et al.*,
109 2016]. The Nazca and South American plates move at an absolute rate of 22 mm/yr and
110 47 mm/yr, respectively [Gripp and Gordon, 2002]. Somoza and Ghidella [2012] showed that
111 the westward motion of the South American plate may have been constant (between ~30 and
112 ~40 mm/yr) during the last 40 Ma whereas the eastward motion of the Nazca (Farallon) plate
113 has changed over this period. Plate reconstructions of Somoza and Ghidella [2012] suggest
114 that the Late Cretaceous-Cenozoic convergence history between the Nazca and South
115 American plate is characterized by an increase of the convergence rate between Paleocene to
116 Late Oligocene (from 4 to 14 cm/yr) including two accelerations at ~56-43 Ma and ~32-24
117 Ma, followed by a global decrease between Miocene to present day. The Late Oligocene-

118 Early Miocene convergence peak coincides approximately with the breakup of the Farallon
 119 plate and creation of Cocos and Nazca plates [Lonsdale, 2005; Somoza and Ghidella, 2012].
 120 In northern Peru and Ecuador the variations in the convergence rate are more or less
 121 correlated with deformational stages in the forearc zones [e.g., Daly, 1989; Jaillard and Soler,
 122 1996; Jaillard et al., 1997] and pronounced arc magmatic productivity [Schütte et al., 2010].
 123 The Ecuadorian margin suffers the collision of Cretaceous oceanic terranes during the Late
 124 Paleocene-Early Eocene [Jaillard et al., 1997]. There is no evidence for oceanic terranes
 125 along the northern Peruvian margin, except in the Paita area (Figure 1a), where oceanic
 126 boulders are found in the Early Eocene conglomerates of the Mogollon Formation [Pecora et
 127 al., 1999]. In addition, plate model reconstructions [e.g., Sdrolias and Müller, 2006] show that
 128 the age of the subducting oceanic lithosphere under the northern Peruvian margin varied
 129 through the Cenozoic from ~60-70 Ma (Paleocene) to ~20-30 Ma (present).

130 Nazca (Farallon)-South America plate convergence system has been associated with
 131 subduction of numerous topographic asperities during the Cenozoic times [e.g. Gutscher et
 132 al., 2002; Espurt et al., 2008]. For instance, in Ecuador, the subduction of the broad Carnegie
 133 ridge began ~8-15 Ma ago [Daly, 1989; Gutscher et al., 1999a; Schütte et al., 2010], ~3-5 Ma
 134 ago [Michaud et al., 2009; Collot et al., 2009], or ~1-2 Ma ago [Lonsdale and Klitgord, 1978]
 135 and is uplifting the Ecuadorian forearc zone [Pedoja et al., 2006]. In northern Peru, the
 136 enigmatic Inca Plateau subducted in the Middle Miocene [Gutscher et al., 1999b] or
 137 somewhat earlier [Skinner and Clayton, 2013] and would be responsible for slab flattening
 138 (northern edge of the Peruvian flat slab segment). Currently, N50–55°E trending aseismic
 139 ridges/scaps (Sarmiento, Alvarado and Grijalva) are being subducted obliquely beneath the
 140 northern Peruvian margin and southern Ecuadorian margin (Figure 1). These 1-2 km-high and
 141 20-40 km-wide asperities migrate southward along the margin [Lonsdale, 2005].

142 The study area belongs in the Huancabamba deflection zone where the structural strike
 143 of the Andes shows a significant rotation (Figure 1a). North of the Huancabamba deflection,
 144 the North Peruvian forearc system is part of the NNE-trending Northern Andes, overprinting a
 145 Triassic-Jurassic rift well defined in Ecuador [Spikings et al., 2016]. The post-Oligocene
 146 rotations are ~25° clockwise north of the deflection, in the Lancones basin [Mitouard et al.,
 147 1990] (Figure 1b). Recent large-scale analyses of GPS data in Peru and Ecuador [Nocquet et
 148 al., 2014; Chlieh et al., 2014; Villegas-Lanza et al., 2016] suggest that the North Peruvian
 149 forearc system currently belongs to the rigid forearc Inca Sliver that encompasses the
 150 southernmost Ecuador and Peru. This sliver moves at 4-5 mm/yr southeastwards (Figure 1a).

151 The North Peruvian forearc system extends 200-km-wide onshore and offshore
 152 between the Peru trench and the Western Cordillera volcanic arc (Figure 1a). It is a
 153 tectonically active system related to the post-Jurassic geodynamics of the Nazca (Farallon)
 154 and South American convergence plate system [Jaillard et al., 1990]. The North Peruvian
 155 forearc system displays a complex structural architecture with a southeastern onshore domain
 156 including basement highs, such as the Amotape High and subsurface Carpitás-Zorritos High,
 157 and a northwestern offshore domain characterized by a shallow-water (120 mbsl) flat-topped
 158 high so-called Banco Peru [Fernández et al., 2005; Auguy et al., 2017; Calvès et al., 2017],
 159 located ~50 km seaward from the coastline (Figure 1b). These NE-trending structural highs
 160 delimit four major depocenters of Cretaceous and Cenozoic siliciclastic strata (Lancones,
 161 Talara, Tumbes and Trench-Slope forearc depocenters) reaching locally more than 9 km in
 162 thickness (Figure 1b). These depocenters are deformed by numerous normal growth faults and
 163 gravitational instabilities, and strike-slip faults in the offshore Tumbes depocenter [Séranne,
 164 1987; Witt and Bourgois, 2010]. The offshore Tumbes depocenter connects northward with
 165 the Guayaquil basin, which is described as a pull-apart basin [Travis et al., 1974; Shepherd
 166 and Moberly, 1981; Deniaud et al., 1999; Witt and Bourgois, 2010] (Figure 1a).

167 Exhumation history of the North Peruvian margin is poorly constrained by
168 geochronological and thermochronological data. Some apatite and zircon fission-track, and
169 apatite (U-Th)/He studies in the Ecuadorian and North Peruvian forearc zones suggest that the
170 exhumation may have started in Late Cretaceous-Paleogene (65-45 Ma) and Eocene (45-39
171 Ma) [Spikings *et al.*, 2005; Wipf, 2006; Spikings *et al.*, 2010]. Stratigraphic and provenance
172 data of Fildani *et al.* [2008] and Hessler and Fildani [2015] in the Talara depocenter suggest
173 that the relief of the Amotape High was in place since the Early Eocene with transverse and
174 longitudinal drainage systems.

175 2.2 Stratigraphy

176 The tectono-stratigraphy of the North Peruvian forearc system is summarized in
177 Figure 2 and described hereafter.

178 2.2.1 Paleozoic-Triassic Amotape continental basement

179 Continental basement rocks (named the Amotape basement) form the large Paleozoic
180 outcrops of the Amotape High and La Brea (Figures 1b and 3). They are composed of highly
181 deformed Mississippian, Devonian and older (Ordovician?) metasediments, schists and
182 gneisses (Figure 4a) [e.g., Witt *et al.*, 2017]. Metamorphic rocks are locally covered by
183 Pennsylvanian turbidites of the Chaleco de Paño Formation and Permian limestones (Figure
184 4b). Paleozoic rocks are intruded by Triassic granite with ages ranging from 230 Ma to 220
185 Ma [Sánchez *et al.*, 2006; Witt *et al.*, 2017]. Subsurface and field data provide evidence for
186 metamorphic and granitic basement below the Talara depocenter and the Carpitás-Zorritos
187 High [Fernández *et al.*, 2005] (Figures 1b and 3).

188 The Amotape basement corresponds to the southward prolongation of the Ecuadorian
189 Eastern Cordillera (so-called Cordillera Real), and it connects southward with the Coastal
190 Cordillera of Peru (Paita and Illescas Highs; Figure 1a). To the south, the Amotape basement
191 connects to the outer shelf high of Trujillo and Salaverry basins [Romero *et al.*, 2013; Witt
192 *et al.*, 2017]. The Amotape basement is interpreted to form a continental block accreted onto the
193 South American margin in the Early Permian [Ramos, 2009] or Early Cretaceous [Mourier *et al.*,
194 1988; Winter *et al.*, 2010]. It is also interpreted as a rifted fragment of South America
195 (western Pangaea) within a back-arc setting in the Triassic [Riel *et al.*, 2014; Spikings *et al.*,
196 2015; Witt *et al.*, 2017].

197 2.2.2 Cretaceous series of the Lancones depocenter

198 The Lancones depocenter exhibits a ~4 km-thick Albian to Campanian sedimentary
199 succession deposited in forearc basin settings associated with small intrusive bodies [Jaillard
200 *et al.*, 1999; Valencia and Uyen, 2002; Winter *et al.*, 2010] (Figures 2 and 3). The series are
201 connected eastward with the Celica continental arc [Lebras *et al.*, 1987; Jaillard *et al.*, 1999],
202 and pinchout northwestward onto the Amotape High.

203 The basal Albian series consist of massive conglomerates of the Gigantal Formation
204 and conglomerate channels, grainstones and shales of the Pananga Formation. These series
205 are mainly exposed along the southeastern flank of the Amotape High. The conglomerates
206 contain clasts exclusively sourced from the Amotape basement and the Celica arc. The upper
207 Albian Muerto Formation consists of oil-bearing limestones and black shales. Southeastward,
208 the Muerto Formation shows volcanoclastics and breccias intercalations corresponding to the
209 Lancones Formation. The overlying Cenomanian and Turonian rocks consists of turbidites,
210 shallow marine volcanoclastic sandstones and grey to black shales of the Huasimal, Jahuary
211 Negra and Encuentros Formations. This package is unconformably overlain by Campanian

212 coarse-grained sandstones of the Tablonos Formation. The Cretaceous succession is topped by
213 shallow marine black shales and sandstones of the Pazul/Redondo Formation.

214 South of the Huaypirá fault, Cretaceous series are unconformably overlain by Eocene
215 strata of Chocan, Verdun and Chira Formations, and Late Eocene or Oligocene Mirador
216 Formation particularly developed in the Sechura basin [*Valencia and Uyen, 2002*] (Figures 1
217 and 2). No evidence of Cretaceous strata has been described in the northern part of the Talara
218 depocenter. However, Cretaceous series are known in subsurface from exploration wells south
219 of Mancora city [*Fernández et al., 2005*] (Figure 1b).

220 2.2.3 Cenozoic series of the Talara and Tumbes depocenters

221 Detrital U-Pb zircon ages suggest that Cenozoic sediments of the onshore Talara
222 depocenter are mainly sourced from the Paleozoic basement of the Western Cordillera of Peru
223 and Amotape High [*Hessler and Fildani, 2015; Witt et al., 2017*] (Figure 1). Paleocene-
224 Eocene series correspond to fluvial to deep-marine strata, reaching up to 3.5 km-thick in the
225 northern Talara depocenter, and more than 9 km-thick to the south [*Séranne, 1987; Higley,*
226 *2004; Fernández et al., 2005*]. Paleocene series are only known in exploration wells south of
227 the study area. In the study area, the Amotape basement is unconformably covered by Early
228 Eocene alluvial-fluvial series simplified as Mogollon-Salinas Formation (Figures 4a,b)
229 [*Higley, 2004; Fernández et al., 2005; Fildani et al., 2008*]. It is composed of massive
230 conglomerates, grainstones including wood and vertebrate remains, and upper grey to red
231 shales [*Fildani et al., 2008; Antoine et al., 2015*]. Locally, the basal part of the Mogollon
232 Formation is formed by quartz conglomerate and grey shales of the San Cristobal Formation.
233 The Middle Eocene series are simplified as basal Talara Formation and upper Verdun
234 Formation deposited in deepwater environment [see details in *Fildani et al., 2008*]. The
235 Talara Formation consists of dark brown shales and grainstones intercalated with turbiditic
236 channels, breccias, mudstones and tuff layers. The Verdun Formation is interpreted as a
237 turbiditic system of thick conglomerate and sandstone intervals interbedded with thin-bedded
238 sandstone and mudstone. The Late Eocene Chira Formation consists of marine mudstone
239 deposited in a shallow marine environment. Subsurface data suggest that thinner
240 Paleocene(?)–Eocene series are also present at the base of the onshore Tumbes depocenter
241 [*Fernández et al., 2005*].

242 Latest Eocene(?)–Oligocene sequences are characterized in the field and subsurface by
243 the appearance of coarse-grained fluviodeltaic sequences above a subaerial erosional surface
244 [*Fernández et al., 2005*]. The sequences consist of the massive Gilbert delta system of the
245 Latest Eocene or Oligocene Mirador Formation (Figure 4c) followed by prograding
246 fluviodeltaic sequences of the Oligocene Mancora Formation intercalated with white to pink
247 arkosic and quartzitic sandstone, tuff, and conglomerate sequences of the Plateritos Formation
248 (Figure 4d) [*Pozo, 2002; Vega, 2009*]. Although Oligocene strata are cut by normal faults,
249 subtle (compressional?) growth strata geometries are locally recognized in the Plateritos and
250 Mancora sequences along the Bocapan River (Figure 4e). The Late Oligocene–Early Miocene
251 Heath formation consists of organic-rich dark brown to light grey lutites, siltstones and some
252 limestones and marls deposited in deepwater environment (more than 1 km depth). The Early
253 Miocene Zorritos Formation consists of aggradational to prograding marine-terrestrial and
254 subordinated varicolored shales sequences deposited within a flood to marine influenced
255 coastal plain setting. The Middle Miocene begins with a regional unconformity produced by
256 the erosion of the former platform and generation of valleys filled and covered by the
257 marginal marine and deltaic Middle Miocene Cardalitos and Late Miocene Tumbes
258 Formations and Latest Miocene–Pliocene Mal Pelo Formation [*Fernández et al., 2005*]. The
259 uppermost Late Pliocene–Pleistocene La Cruz Formation and more recent sequences

260 unconformably overlay the underlying Mal Pelo sequences. Deposits consist of regional grey-
 261 green claystone, some sandy interbeds with common shell fragments and dolomitized
 262 limestones.

263 Onshore, Pliocene-Pleistocene deposits correspond to marine terraces (including so-
 264 called Tablazos) along the coastline of the Talara depocenter [Bosworth, 1922; DeVries,
 265 1988; Macharé and Ortlieb, 1994; Pedoja *et al.*, 2006; Darrioulat, 2011] and alluvial terraces
 266 including well-rounded blocks of granite close to the Amotape High.

267 **3 Surface and subsurface structural architecture**

268 The northern Peruvian margin is characterized by a coastal desert [Garreaud, 2009]
 269 providing an extremely good cross-sectional exposure of sedimentary units and geological
 270 structures (Figures 4 and 5). To constrain the structural architecture of the North Peruvian
 271 forearc system, we used new field structural data, ten seismic reflection profiles (RIB93-01,
 272 VMX09-01, VMX09-23, AIP92-15, PC99-11, BPZ23-16, PXII99-02, and L1, L2 and L3
 273 extracted from 3D seismic cubes), and wells provided by PERUPETRO S.A. (see Figures 1b
 274 and 3 for location). New onshore geological mapping (Figure 3) was performed using
 275 preexisting 1:100.000 INGEMMET (Instituto Nacional Geológico, Minero y Metalúrgico del
 276 Perú) geological maps, field data and satellite images. Seismic profiles were depth-converted
 277 using the Move software and seismic velocities of sedimentary intervals (e.g., Etrys *et al.*,
 278 2002; Totake *et al.*, 2017) from exploration wells (supporting information Table S1).

279 The morphostructure of the North Peruvian forearc system includes seven structural
 280 units according to the geological map, field and subsurface data, and the cross sections which
 281 are presented in this study. From arc to sea, these units are: the Lancones forearc depocenters,
 282 the Amotape High, the Talara forearc depocenter, the Carpitás-Zorritos High, the Tumbes
 283 forearc depocenter, the Banco Peru and frontal prism, and the subducting Nazca plate (Figure
 284 1b). In the following, the structural architecture and kinematics of the North Peruvian forearc
 285 system is presented along two N137°E- to N93°E-trending cross sections: a northeastern
 286 transect A and a southwestern transect B (Figures 1b, 3 and 5).

287 **3.1 The Lancones forearc depocenter**

288 The southeastern edge of the North Peruvian forearc system is formed by the
 289 Lancones forearc depocenter involving Cretaceous strata. Cretaceous strata are deformed by
 290 NW-verging thrust-related anticlines (e.g., Totoras, Gallinazos, Jabonillos and Jahuaycito
 291 anticline) locally reactivating the onlap surface of the Cretaceous strata against the Amotapes
 292 basement (Figures 5 and 6). Field data and interpretation of seismic line PXII99-02 indicate
 293 that thrust faults may correspond to reactivated basement normal faults inherited from an
 294 Early Cretaceous extensional period (Figures 7a and 8) as suggested by Jaillard *et al.* [1999]
 295 and Winter *et al.* [2010]. Inversion and thrusting was recorded by Late Cretaceous growth
 296 strata in the Encuentros Formation [Jaillard *et al.*, 1999; Andamayo, 2008].

297 The Lancones depocenter shows NE- to E-trending Cenozoic normal faults that cut the
 298 pre-structured folds and thrusts (Figures 1b, 3 and 5). A major N35°E-trending 40-50°SE-
 299 dipping fault corresponds to the Cuzco-Angolo normal fault which separates the Amotape
 300 High from the Lancones depocenter. South of the study area, E-trending S-dipping La
 301 Encanada and Huaypirá normal fault zones cut obliquely across compressional structures and
 302 Amotape High [Valencia and Uyen, 2002; Andamayo, 2008].

303 **3.2 The Amotape High**

304 The Amotape High represents a prominent range located between the Lancones and
305 Talara depocenters, reaching elevations of ~1500 masl and exposing Paleozoic rocks and
306 Triassic intrusions (Figures 1b, 3 and 5). It forms a ~140-km-long with a maximum width of
307 ~20 km bulge onlapped by tilted Cretaceous and Cenozoic strata. The backlimb of this
308 anticline is formed by 10°SE-dipping Early Cretaceous strata while the forelimb is formed by
309 12°NW-dipping Early Eocene (Figures 4a and 5). Paleozoic strata of the forelimb are strongly
310 deformed by a NNE-trending SE-dipping fault zone (Figure 3). South of cross section A,
311 metamorphic and igneous rocks are thrust onto Paleozoic metasediments. Northward, the
312 mapping suggests that the thrust zone is unconformably overlain by Early Eocene strata
313 (Figure 3). This thrust fault may explain the high structural relief of the Amotape High in
314 comparison to the lower topography (~250 masl) of the Talara depocenter (Figure 5).

315 3.3 The Talara forearc depocenter

316 The Talara forearc depocenter develops between the Amotape and subsurface
317 Carpitás-Zorritos High (Figures 3 and 5). Its structure consists of a ~5-10°W-dipping
318 homocline of Eocene to Miocene strata bounded northwestward by a major NE-trending SE-
319 dipping listric normal faults system, the Carpitás-Trigal fault system, associated with
320 antithetic normal faults (e.g., Cabeza de Vaca fault; Figures 5 and 9) [Séranne, 1987]. Surface
321 data indicate that Early-Middle Eocene strata are in unconformable or in normal fault contact
322 with the Amotape basement rocks at the southeastern edge of the Talara depocenter (Figures
323 3, 4a,b and 5).

324 The interpretation of seismic profile BPZ23-16 shows the overall unconformity of the
325 Early Eocene series on the Amotape basement (Figure 10). No Cretaceous-Paleocene strata in
326 this part of the Talara depocenter are found. Field and subsurface data show evidence for
327 rapid change in thickness in Eocene sediments associated with growth normal faulting. No
328 major thrusts emerge into the Talara depocenter [Quispe Alcalá, 2010]. However, we found
329 numerous kinematic indicators for thrusting occurring before and after normal faulting in the
330 Early-Middle Eocene series (Figures 7b,c).

331 At depth, the interpretation of the seismic profile BPZ23-16 suggests that basement
332 normal faults are associated with low-angle SE-dipping décollements (Figure 10). We
333 interpret these décollements as NW-verging thrust slices that extend below the Amotape
334 High. This suggests that the structure and uplift of the Amotape High and inner Talara
335 depocenter could be controlled by basement thrust imbrications at depth. Erosional surface
336 and suspected growth strata geometry (see 2.2.3) observed in western flank of the Amotape
337 High may provide an Early Eocene-Oligocene record for basement shortening.

338 3.4 The Carpitás-Zorritos High

339 The coastal Carpitás-Zorritos High separates the Talara and Tumbes forearc
340 depocenters (Figure 1b). This structural high constitutes a major petroleum play where
341 numerous exploration wells reached metamorphic/granitic rocks of the Amotape basement
342 (Figures 3 and 5). Subsurface data indicate that this structural feature forms a relay system of
343 two basement culminations at shallow-depth level beneath relatively thinner Eocene-Miocene
344 sedimentary cover (~500 m) in comparison to the forearc depocenters [Fernández *et al.*,
345 2005]. The southeastern Carpitás High is separated from the northwestern Zorritos High by
346 the Tronco Mocho SE-dipping normal fault system (Figure 5; section A). Landward, the
347 Carpitás High is bounded by the Carpitás-Trigal fault system. Along section A, the
348 northwestern flank of the Carpitás High shows spectacular detachments, roll-overs and raft
349 structures in the Heath Formation [Vega, 2009] (Figure 11). These structures are interpreted
350 as gravitational instabilities on the seaward-dipping paleo-slope of the Carpitás High.

351 Whereas the Carpitás High basement is unconformably overlain by Early Eocene
352 strata of the Mogollón-Salinas Formation, the interpretation of seismic profile L1 (Figure 12)
353 and well data show that the Zorritos High basement (granite) is unconformably overlain by
354 Oligocene fluvial-deltaic sequences of the Plateritos and Mancora Formations. Subsurface
355 data also suggest that the Tronco Mocho normal faults are connected with the Amotape
356 basement. This fault system was probably active during the sedimentation of the Late
357 Oligocene-Early Miocene Heath Formation and somewhat sealed by the Early Miocene
358 Zorritos Formation (Figure 12). At depth, the interpretation of the seismic profile L1 also
359 shows evidence for small compressional reactivation of the Tronco Mocho fault system. Here,
360 we suspect that the footwalls of the normal faults are deformed by small NW-verging thrusts
361 propagating with short-cut trajectories and intercutaneous prism (Figure 12). Numerous Plio-
362 Pleistocene perched marine terrace sequences (Tablazos) along the coastal area at more than
363 300 masl indicate recent uplift of the Carpitás-Zorritos High [DeVries, 1988; Séranne, 1987;
364 *Pedroja et al.*, 2006; *Darrioulat*, 2011].

365 3.5 The Tumbes Forearc depocenter

366 The offshore Tumbes depocenter develops ~50 km ahead of the coastline between the
367 Carpitás-Zorritos High and Banco Peru (Figure 1b). The synthetic seismic profiles of Figures
368 13 and 14 show that this depocenter depicts two stacked progradational sedimentary wedge
369 systems of Eocene to Holocene series up to 11 km-thick along section B. The lower wedge
370 consists of a seaward prograding wedge of Eocene-Early Oligocene series. In the western side
371 of the Carpitás and Zorritos highs, the subsurface data show the pinchout of the inferred Early
372 Eocene series onto a steep dip basement paleo-slope. Eocene series depict deep thrust-related
373 anticline structures unconformably overlain by Early Oligocene series of the Mancora
374 Formation (at the distance of ~60 km in Figure 13 and ~37 km in Figure 14). The upper
375 wedge is formed by Late Oligocene to Holocene series deformed by numerous Miocene to
376 present syn-depositional growth faults and rollovers. The upper wedge is gravitationally
377 detached seaward from the underlying wedge above Late Oligocene-Early Miocene ductile
378 shales of the Heath Formation as regionally observed in the field (Figure 11). The
379 décollement has a dip of about 12°. In the seaward side of the basin, the sliding of the upper
380 wedge is linked to compressional structures and mud diapirism related to the Heath Formation
381 [Fernández *et al.*, 2005; Vega, 2009]. More seaward, the series of the Tumbes depocenter
382 pinch out onto the Banco Peru and are cut by the NNE-trending Banco Peru fault zone.

383 The Tumbes depocenter also shows NE-trending extension including NE- and SW-
384 dipping listric normal faults [Fernández *et al.*, 2005; Auguy *et al.*, 2017] (Figure 1b). Strike-
385 slip behavior may have also occurred along the Banco Peru fault zone. This geodynamic
386 change is interpreted as the Neogene(?) to present pull-apart basin evolution of the Tumbes
387 depocenter as a result of the northern escape of the North Andean block [Witt and Bourgois,
388 2010].

389 3.6 The Banco Peru and frontal structures

390 The offshore structural architecture is dominated by the broad structural high of the
391 Banco Peru located between the Tumbes depocenter and the trench axis (Figure 1b). Along-
392 strike, this structure extends from the onshore Talara depocenter to the Gulf of Guayaquil
393 [e.g., Collot *et al.*, 2002; Auguy *et al.*, 2017; Calvès *et al.*, 2017] (Figure 1). The structural
394 interpretation of seismic profiles VMX09-23 and RIB93-01 of section B (Figure 13) suggests
395 that this major structure was generated by imbrication of three or more thrust sheets made of
396 off-scraped sediments (distal equivalents of the Eocene, Oligocene, and Miocene strata
397 observed onshore) including oceanic mafic bodies (intrusives and volcanic) [Shepherd and

398 *Moberly*, 1981; *Fernández et al.*, 2005]. It is covered by Oligocene to Plio-Pleistocene series
 399 strongly affected by normal faulting and gravitational sliding. The flat-topped geometry of the
 400 Banco Peru could be interpreted as a wave-cut platform [*Calvès et al.*, 2017].

401 The landward side of the Banco Peru imbricate is characterized by SE-dipping normal
 402 to strike-slip faults of the Banco Peru fault zone. The faults branch onto a major ~20-25° SE-
 403 dipping fault (Figures 13 and 14). The interpretation of the seismic profiles suggests that the
 404 fault connects at depth onto the subduction plane rather than in the shallower ductile shales of
 405 the Heath Formation. This structural configuration has been previously proposed for strike-
 406 slip forearc model [*Noda and Miyakawa*, 2017] and described in the Ecuador forearc [*Collot*
 407 *et al.*, 2004], Cascadia forearc [*McNeill et al.*, 2000] and Naikai forearc [*Tsuji et al.*, 2015],
 408 and also suggested in the Central Peruvian forearc [*Azalgara*, 1993; *Romero et al.*, 2013]. The
 409 seaward side of the imbricate, the Trench-Slope depocenter, is characterized by seaward
 410 gravitational instabilities and sediment mass wasting. Subsurface data indicate the top of the
 411 oceanic plate and the basal décollement of the Banco Peru imbricate at about 8 kmbsl (Figure
 412 13). Subsurface data also indicate that a large volume of sediment (~3 km-thick) is
 413 underplated beneath the Banco Peru imbricate. Near the trench, tectonic slices are maybe
 414 related to an active frontal prism of small size. These structural observations are similar to the
 415 ones described more southward in the Paita region [*Bourgeois et al.*, 1989] and along the
 416 southern Ecuadorian margin of the Guayaquil basin [*Collot et al.*, 2002; *Calahorrano*, 2005;
 417 *Collot et al.*, 2011] (Figure 1a).

418 3.7 The subducting oceanic Nazca plate

419 The good seismic resolution at depth of seismic lines VMX09-23 and RIB93-01 of
 420 section B (Figure 13) shows the geometry of subducting oceanic Nazca plate beneath the
 421 forearc prism. The subducting plate dips approximately 6° southeastwards from the Trench-
 422 Slope depocenter to the Tumbes depocenter. Along-strike bathymetric data of the Nazca plate
 423 were used to approximately evaluate the size and the position of the subducting ridges
 424 beneath the forearc prism [*Lonsdale*, 2005]. The Alvarado 1 and 2, and Sarmiento ridges are
 425 1-2 km-high and 20-40 km-wide asperities smoothed by oceanic sediments. We propose that
 426 these ridges extend beneath the Trench-Slope depocenter, Banco Peru and Talara depocenter,
 427 respectively (Figures 1b, 13 and 14). The subduction of the Sarmiento ridge might be
 428 associated with a Plio-Pleistocene coastal uplift [*Séranne*, 1987; *Pedoja et al.*, 2006].

429 4 Timing of deformation as revealed by apatite fission-track dating

430 4.1 Methodology and sampling

431 Apatite fission-track thermochronology allows to constrain the vertical motions of the
 432 compressional basins through time and the pre-deformational basin architecture in order to
 433 provide a reliable estimation of the eroded relative stratigraphic thicknesses [*e.g.*, *Espurt et*
 434 *al.*, 2011; *Parra et al.*, 2012; *Sánchez et al.*, 2012; *Gautheron et al.*, 2013]. Apatite fission-
 435 track thermochronology uses the partial stability of defects produced by the fission of ²³⁸U,
 436 controlled by temperature [*Green et al.*, 1989]. Apatite fission-tracks record the cooling of
 437 rocks below ~110°C during their exhumation [*e.g.*, *Gallagher et al.*, 1998].

438 Analyses were performed on nine rock samples from the Talara and Lancones
 439 depocenters, and Amotape High (eight Cretaceous-Eocene sedimentary rocks and one Triassic
 440 igneous rock) (see locations in Figure 15). Samples were analyzed using the laser ablation–
 441 inductively coupled plasma–mass spectrometry method at Apatite to Zircon, Inc., laboratory
 442 (see details of the method in *Hasebe et al.* [2004] and *Chew and Donelick* [2012]). Because
 443 samples are mainly sedimentary rocks with multicompositional apatites (mean maximum

444 diameters of fission-track etch figures parallel to the c axis, Dpar), we used central ages
 445 [*Galbraith and Laslett, 1993*]. To determine the last cooling event, we statistically
 446 decomposed sample grain-age distributions into component ages (supporting information
 447 Figure S1) using the RadialPlotter software [*Vermeesch, 2009*]. In addition, inverse thermal
 448 simulations were conducted using apatite fission-track ages, track lengths and kinetic
 449 parameters in the HeFTy software, and geological constraints [*Ketcham, 2005*; see *Parra et*
 450 *al., 2012* for more details] (Figure 16). Complete results are provided in Table 1. Age errors
 451 are reported at 1σ .

452 4.2 Results

453 Apatite fission-track central ages range from 15.8 ± 0.6 to 52.5 ± 3.1 Ma, mean track
 454 lengths from 12.2 ± 0.1 to 13 ± 0.1 μm , and mean Dpar from 1.9 to 2.4 μm (Table 1). Age
 455 statistically decompositions (Figure S1) indicate that samples of the Talara depocenter
 456 (samples 1, 2, 3, 4, 5 and 9) have three components in the grain-age distribution: the age of
 457 the old component is ~ 118 Ma, the ages of the middle component range from 63.1 to 50.5 Ma,
 458 and the ages of the young component range from 38.8 to 28.8 Ma. Samples of the Amotape
 459 High and Lancones depocenter (samples 6, 7 and 8) show younger age component ranging
 460 between 22.7 to 14.8 Ma. By comparing the central/young apatite fission-track ages with the
 461 respective stratigraphic ages of the analyzed samples, we show that samples of the Talara
 462 depocenter have fission-track ages older, close to or younger than their stratigraphic ages
 463 (~ 52 -38 Ma). Samples from the Amotape High and Lancones depocenter have younger
 464 fission-track ages than their stratigraphic ages (~ 230 -52 Ma).

465 Additionally, our apatite fission-track ages are younger than the ones (including
 466 apatite and zircon fission-track, and apatite (U-Th)/He ages) obtained along-strike in the
 467 Ecuadorian segment of the Amotape High and to the south in the Paíta High [*Spiking et al.,*
 468 *2005*; *Wipf, 2006*] (Figure 1a). These lateral units may have recorded older cooling onset
 469 between ~ 65 and 45 Ma or experienced a smaller burial (partial reset ages?) under Cenozoic
 470 series.

471 The dispersion in apatite fission-track ages requires thermal modeling to better
 472 constrain cooling and onset of exhumation. Samples of the Amotape High and Lancones
 473 depocenter (samples 6, 7 and 8) and one sample of the Talara depocenter (sample 2) were
 474 modeled using geological constraints, apatite fission-track results (ages, track lengths, Dpar
 475 values), and present surface temperature of $20 \pm 5^\circ\text{C}$ (Figure 16). For each sample, the
 476 thermal simulations suggest a Middle-Late Eocene reheating/burial after Late Cretaceous-
 477 Early Eocene deposition, followed by a Late Eocene-Oligocene (36–27 Ma)
 478 cooling/exhumation. The thermal simulation of sample 6 (Triassic Amotape granite) indicates
 479 an initial Late Cretaceous-Early Eocene (~ 80 -50 Ma) cooling. This initial event might be
 480 recorded by the major unconformity of Early Eocene strata of the Mogollon-Salinas
 481 Formation on basement in the northwestern side of the Amotape High (Figures 4a,b and 5).
 482 The Late Eocene-Oligocene cooling event is attested by major erosion and strong depositional
 483 environment changes from marine to terrestrial conditions with sedimentation of the Mirador,
 484 Plateritos and Mancora sequences in the Talara and Tumbes depocenters (Figures 4c-e).
 485 Finally, we believe that youngest fission-track ages (22.7-14.8 Ma) have recorded the cooling
 486 of the samples through the $\sim 110^\circ\text{C}$ isotherm (Figure 16). This Neogene cooling might be
 487 recorded by the erosional surface occurring at the base of the Middle Miocene Cardalitos
 488 sequences in the offshore Tumbes depocenter (Figures 2, 13 and 14) [*Fernández et al., 2005*].

489 5 Crustal-scale geometry and evolution of the North Peruvian forearc system

490 5.1 Crustal-scale cross sections

491 To evaluate and discuss the control of the surface and deep processes on the structural
492 building of the North Peruvian forearc system throughout the Late Cretaceous-Cenozoic
493 period, field, subsurface, and present-day seismicity events data ($M_w > 5$) from the “Instituto
494 Geofísico del Perú” catalog 2005-2013 (<http://www.igp.gob.pe>) were used to construct and
495 interpret two ~200 km-long crustal-scale balanced cross sections from the Peru trench to the
496 volcanic arc (Figure 17). The frontal structure of cross section A has not been represented
497 because subsurface data are not available in this part of the margin. The section orientations
498 are parallel to the present-day direction of tectonic transport [Nocquet *et al.*, 2014; Chlieh *et*
499 *al.*, 2014; Villegas-Lanza *et al.*, 2016] and perpendicular to the trend of the structures (Figures
500 1b and 3). The cross sections have been constructed using the Move structural modeling
501 software on the basis of thrust/extensional tectonic concepts [Dahlstrom, 1969; Boyer and
502 Elliott, 1982; Suppe, 1983; Suppe and Medwedeff, 1990; McClay, 1990; Shaw *et al.*, 2005].
503 The reconstruction of the subducting plate geometry supported by deep seismicity events
504 shows a landward increase in the dip of the subduction thrust fault. This reconstruction
505 provides constrain for the present geometry and crustal area of the overriding upper plate.

506 Crustal-scale cross sections of Figure 17 suggest that the structure of the northern
507 Peruvian margin was dominated by an accretionary prism over the Nazca subducting plate.
508 The deep compressional features have been mostly hidden by thick Cenozoic sedimentary pile
509 and gravitational sliding, and synchronous or later extensional and strike-slip faulting
510 [Séranne, 1987; Witt and Bourgois, 2010]. North of the Talara city (Figure 1b), field cross
511 sections and well data suggested extensional tectonic and gravitational slidings interfering
512 with SE-verging thrusts [Séranne, 1987; Quispe Alcalá, 2010]. Our geometrical interpretation
513 based on seismic reflection profiles is, however, more consistent with NW-verging thrust
514 systems and seaward thrust propagation in the study area. Cross section construction suggests
515 that the structural culmination of the inner Amotape High might result in the imbrication of at
516 least three northwest-verging basement thrust sheets. The Lancones depocenter was
517 transported northwestward and uplifted by the Amotape imbricate. Subsurface data and cross
518 section balancing suggest that the Carpitás High may be also interpreted as the imbrication of
519 three northwest-verging thrust sheets involving the basement rocks and inferred off-scraped
520 sediments (see below). As pointed out in section 3.6, the offshore domains developed by
521 accretion of off-scraped sediment (including oceanic mafic bodies) constituting the Banco
522 Peru imbricate and the frontal active prism. The present-day seismicity events throughout the
523 study area might suggest active basement faulting beneath the onshore domain (Figure 17).

524 The atypical accretionary style of the North Peruvian forearc system is similar to the
525 ones described in Colombia and southern Chile forearc zones [e.g., Laursen *et al.*, 2002;
526 Melnick *et al.*, 2006; Lopéz *et al.*, 2008; Encinas *et al.*, 2012] and might result from major
527 trench sediment infill in the study area [Collot *et al.*, 2002]. Strike-slip component interfering
528 with the dominant thrusting style can be associated with oblique subduction of the Nazca
529 plate beneath the Northern Andes [Villegas-Lanza *et al.*, 2016; Alvarado *et al.*, 2016; Noda
530 and Miyakawa, 2017].

531 5.2 Sequential restoration

532 Offshore forearc systems are classically composed of a distal trench basin, an outer
533 subduction wedge (frontal accretionary prism and structural high) overlapped by trench-slope
534 sediments, and an inner crustal wedge corresponding to the orogenic wedge/magmatic arc
535 overlapped by forearc sediments [see Noda, 2016 and references therein]. If this definition
536 matches with the structural architecture of the onshore Tumbes depocenter, we show that at
537 the scale of the margin, the structure of the North Peruvian forearc system results in the

538 accretion of successive forearc systems (Figure 17). To understand the temporal and spatial
539 variations and the origin of the tectonics mechanisms that controlled the growth of the prism
540 through the Late Cretaceous to Cenozoic, the regional cross section B across the North
541 Peruvian forearc system was restored at five pre-deformational stages, which are illustrated in
542 Figure 18. The cross section has been sequentially restored using the Move fault parallel flow
543 and flexural slip algorithms according to the aforementioned data and apatite fission-track
544 results (i.e., paleoburial and exhumation history). Bed area and length are conserved during
545 consecutive deformation states. Because the prism shows major lateral and vertical variations
546 in lithology and thickness of the sedimentary series the estimation of decompaction is
547 difficult. Nevertheless, cross section restoration without sediment decompaction shows
548 correct structural interpretation in such complex configuration [e.g., *Nunns, 1991; Zhou et al.,*
549 *2006*]. In addition, we assume that the strike-slip motion along the Banco Peru fault zone is
550 small [*Witt and Bourgeois, 2005*] and would not significantly affect the structural geometry but
551 might affect the shortening or extension amounts [e.g., *Wallace, 2008*]. Although the onshore
552 area was affected by post-Oligocene rotation [*Mitouard et al., 1999*] no clear field evidence of
553 strike-slip faulting over the Talara-Lancones area, is found [*Laj et al., 1989*]. Major strike-slip
554 faulting is described in the arc and more to the north [e.g., *Witt et al., 2006; Riel et al., 2014;*
555 *Alvarado et al., 2016*]. Finally, the sequential restoration respects paleo-bathymetries of the
556 sedimentary units [*Fernández et al., 2005; Vega, 2009; Fildani et al., 2008*] and paleo-sea
557 levels [*Haq et al., 1987*].

558 Hereafter, we describe the successive stages of deformation.

559 5.2.1 Late Cretaceous-Early Eocene stage (Figure 18a).

560 At this stage, the margin has been previously deformed during the Late Coniacian-
561 Early Campanian interval and probably until the Eocene as response to initial construction of
562 the Andes [*Jaillard et al., 1999; Hessler and Fildani, 2015*]. The Cretaceous series of the
563 Lancones depocenter exhibit a wedge-shaped geometry thinning northwestward onto the
564 Amotape basement. This wedge was deformed by NW-verging thin- and thick-skinned
565 thrusts. The Amotape and Carpitás Highs can be interpreted as an 80 km-wide thrust sheet
566 made of continental basement including second order thrusts and normal faults. The
567 Amotape-Carpitás thrust system and the Lancones depocenter were uplifted and exposed
568 above the sea level in the Early Eocene.

569 The reconstruction suggests that the Lancones depocenter had been passively
570 transported northwestward as a thrust-top basin on the hanging-wall of the Amotape thrust
571 system during Late Cretaceous and Early Eocene. This result is consistent with
572 thermochronological studies suggesting that the Paita High and western Cordillera (lateral
573 prolongation of the Amotape High) may have experienced a large range of cooling onset
574 between ~65 and 45 Ma [e.g., *Wipf, 2006*]. Our reconstruction is also consistent with several
575 studies which show evidence for major shortening during Late Cretaceous-Early Eocene in
576 northern Peru [e.g., *Noble et al., 1990; Naeser et al., 1991; Jaillard and Soler, 1996*].
577 According to our thermochronological and geological data, the crustal stacking and uplift in
578 the Amotape-Carpitás thrusts system has been sealed by Early Eocene strata. To the west, the
579 Carpitás High is subject to extension associated with landward dipping normal faults
580 (reactivation of inherited thrust faults?). Seaward, distal and thin Early Eocene series were
581 deposited along the seaward dipping trench-slope basin and in the trench axis. The restored
582 cross-section and crustal balancing suggest the underplating of a 5 km-high, 120 km-wide
583 tectonic slice under the Amotape-Carpitás continental thrust sheet, responsible for the uplift of
584 the Amotape-Carpitás thrust system and Lancones depocenter. The subduction of this inferred
585 deep tectonic slice might be interpreted as the southern prolongation of broad Cretaceous

586 oceanic terranes accreted to Colombia and Ecuador margins during Late Cretaceous-Eocene
587 period [Lebras *et al.*, 1987; Jaillard *et al.*, 1995, 1997; Borrero *et al.*, 2012].

588 5.2.2 Middle-Late Eocene stage (Figure 18b).

589 The restoration suggests that Middle-Late Eocene transgressive marine deposits of the
590 Talara, Verdun and Chira Formations are associated with major subsidence on the order of 4-
591 5 km located more than 150 km away from the trench. The restoration argues in favor of a
592 geodynamic model where reactivation of existing basement thrusts as normal faults and newly
593 formed normal faults mainly occur southeast of the Carpitás High. The reconstruction of a
594 thick Middle-Late Eocene sedimentary wedge is consistent with apatite fission-track reset
595 ages and paleo-burial data in the inner Talara-Amotape-Lancones zone (see Figure 19 and
596 section 6.1. for discussion). The restoration confirms that the Lancones and Talara
597 depocenters were connected in agreement with the stratigraphic correlations in Late Eocene
598 series infilling these depocenters [Valencia and Uyen, 2002]. Northwestward, the basement
599 culmination of the Carpitás High is overlain by a thin (~0.5 km) Eocene succession. We
600 model that the Carpitás High formed a seaward-verging thrust sheet overthrusting distal
601 Eocene sediments previously deposited above the oceanic plate (trench-slope depocenter?).
602 More seaward, we infer that a frontal wedge was maybe active. The restoration suggests that
603 the deep tectonic slice of Cretaceous oceanic terranes was subducted to a mean depth of ~25
604 km without major internal shortening. Comparison of Early and Late Eocene states suggests
605 that ~24 km of slip has been accommodated by the Carpitás thrust sheet. The crustal
606 extension affecting the Carpitás thrust sheet to the southeast is estimated at 4.7 km minimum.
607 The Middle-Late Eocene episode of subsidence contemporaneous with upper plate crustal
608 extension in the inner part of the forearc system has been also described along the southern
609 Ecuadorian forearc zone [Jaillard *et al.*, 1997]. Our restoration shows that subsidence and
610 crustal extension could have occurred simultaneously or just after underthrusting of the
611 inferred deep tectonic slice. The total amount of internal shortening is ~22 km.

612 5.2.3 Oligocene stage (Figure 18c).

613 Geological evidence, thermochronological data and thermal modeling suggest that
614 uplift of the Amotape High reactivated between 36 and 27 Ma (Figures 4 and 16). This is
615 correlated with stratigraphic and tectonic studies through the Ecuadorian margin and northern
616 Peruvian Andes, which indicate a strong compressional event in Late Eocene-Oligocene
617 [Noble *et al.*, 1990; Naeser *et al.*, 1991; Jaillard *et al.*, 1995, 1997]. We propose that this
618 cooling episode associated with major paleogeographic modifications (from marine to fluvial-
619 deltaic depositional environment) might result from renewed crustal stacking in the Amotape
620 thrust system. According to stratigraphic observations, the reconstruction includes that the
621 basement of the Carpitás thrust system was located above sea level. The steep dip of the
622 Carpitás paleo-slope suggests seaward tilting related to the growth of the Carpitás thrust
623 system. The restoration suggests that ~29 km of internal shortening were accommodated by
624 crustal slices and sediment underplating in the Amotape and Carpitás thrust systems. The
625 metamorphic and crystalline substratum of Amotape and upper Carpitás thrust sheets were
626 eroded during the Early Oligocene, whence it fed fluvial conglomerates made of pebbles of
627 basement quartzite and granite (i.e., Mirador, Plateritos, and Mancora Formations) into the
628 peripheral Talara and Tumbes depocenters. At this stage, the lower sedimentary sequences of
629 the Tumbes depocenter form a prograding wedge (trench-slope depocenter?) transported
630 seaward above the newly formed Banco Peru thrust system. The restoration suggests that
631 thick (~3 km) Eocene-Oligocene sedimentary sequences that were accumulated onto the
632 oceanic crust are off-scraped and accreted in the Banco Peru thrust system.

633 5.2.4 Late Oligocene-Early Miocene stage (Figure 18d).

634 In the Late Oligocene-Early Miocene stage, the thrusting decreased (less than ~6 km
635 of internal shortening) and was associated with subsidence and the progradation of thick
636 (more than 8 km-thick) deltaic sequences of the Heath and Zorritos Formations. Continuous
637 crustal thickening of the Amotape High is related to cooling of the deepest samples through
638 the ~110°C isotherm at ca. 15 Ma. The restoration suggests that the Carpitás thrust system
639 was progressively deactivated. Subsidence associated with extension occurred on both side of
640 the Carpitás High, contemporaneous with the sedimentation of Heath Formation shales.
641 Seaward, sedimentary sequences are actively deformed by the Banco Peru thrust system. In
642 the Tumbes depocenter the sedimentary sequences describe a dissymmetric thrust-top
643 syncline on the hanging-wall of the Banco Peru thrust system. This syncline is deformed by
644 numerous gravitational raft tectonic structures and mud diapirism. The reconstruction
645 suggests that the high sedimentation rate during deposition of the Late Oligocene-Early
646 Miocene sequences onto the seaward-dipping inherited paleo-slope of the Carpitás High (and
647 to the north in the Zorritos High; Figure 14) controlled the seaward gravitational sliding in the
648 Tumbes depocenter. Similarly, the Banco Peru imbricate controlled gravitational sliding of
649 the Late Oligocene-Early Miocene series on its seaward flank. The Tumbes depocenter forms
650 an ideal trap for sediments at the rear of the active Banco Peru High. The restoration shows
651 that the formation of the Banco Peru normal fault zone (probably with a strike-slip
652 component) connected at depth onto the subduction fault might be likely due to the inversion
653 of an old thrust of the Banco Peru thrust system. This normal to strike-slip(?) fault zone
654 accommodates high sediment loading in the axis of the Tumbes depocenter. Major
655 sedimentation in the trench axis promotes formation of a new frontal imbricate also associated
656 with gravitational instabilities.

657 5.2.5 Middle-Late Miocene stage (Figure 18e).

658 During the Middle-Late Miocene stage, the structures are overlapped by the
659 transgressive Cardalitos Formation followed by prograding deltaic series of the Tumbes
660 Formation. Onshore, the Cardalitos Formation filled incised valleys [Vega, 2009]. Offshore,
661 the series deposited above a submarine unconformity may be associated with turbiditic or
662 ocean currents. This erosional surface also coincides with the last Miocene uplift event (see
663 section 4.2). The restoration suggests that the internal shortening decreases (~2.6 km) while
664 the apparent normal slip (~4 km) in the Banco Peru fault zone and gravitational sliding remain
665 active. Seaward, we infer that the prism overthrusts distal Late Oligocene-Late Miocene
666 sediments accumulated in the trench axis onto the basal detachment of the Banco Peru thrust
667 system.

668 5.2.6 Pliocene-Present day stage (Figure 18f).

669 The Pliocene to present-day period was associated with the offshore sedimentation of
670 the Mal Pelo, La Cruz and recent deltaic sequences. The seaward progradation of these thick
671 deltaic series at the trench axis was subjected to major gravity-driven deformation above
672 Heath Formation shales weak level. Lateral extrusion of the North Andean block may be
673 responsible for strike-slip motion along the Banco Peru fault zone and NE-trending extension
674 in the Tumbes depocenter [Witt and Bourgois, 2010]. Although the present seismicity along
675 the margin indicates active crustal deformation, the restoration shows that the inner prism was
676 poorly deformed since the Pliocene. As revealed by offshore subsurface data, a large volume
677 of distal sediment (~3 km-thick) was accreted to the prism and underthrust (~31 km of
678 displacement) beneath the Banco Peru imbricate during at least the Pliocene. We infer that the
679 recent coastal uplift and moderate active deformation beneath the onshore domain is

680 controlled by the subduction of the Sarmiento and Alvarado 1-2 ridges [*Macharé and Ortlieb,*
 681 1994; *Pedoja et al.*, 2006; *Darrioulat*, 2011; *Villegas-Lanza et al.*, 2016]. Current small
 682 sediment influx in the trench axis can be explained by the active uplift of the Banco Peru as a
 683 result of sediment underplating and ridge subduction as well as by the opening of the
 684 Guayaquil basin to the north [*Witt and Bourgois*, 2010]. The sediment trapping behind the
 685 Banco Peru in the Tumbes depocenter might be enhanced by the recent NE-trending extension
 686 and creation of accommodation space.

687 5.3 Shortening rate assessment

688 The minimum amount of horizontal shortening inferred for this sequentially restored
 689 section is ~92 km. We are aware of the fact that strike-slip motion in the Tumbes depocenter
 690 and internal normal faulting may modify slightly this shortening value. The calculated
 691 shortening rates during the Cenozoic are plotted in Figure 20 together with uplift episodes and
 692 convergence rates [*Somoza and Ghidella*, 2012]. The sequential restoration shows that major
 693 shortening rates occurred between Middle Eocene-Early Oligocene (stages b and c; ~3
 694 mm/yr) then between Pliocene to present (stages e and f; ~5 mm/yr). The Farallon break (~24
 695 Ma) is followed by a major decrease of the shortening. Although we cannot provide a Late
 696 Cretaceous restored state, we speculate shortening during the Paleocene-Early Eocene uplift
 697 as the Eocene-Oligocene shortening itself coincides with forearc uplift and convergence rate
 698 increase (Figure 20). This shortening increase is also more or less synchronous with magmatic
 699 pulse in the continental arc [*Schütte et al.*, 2010]. Post-Miocene to present shortening is
 700 associated with forearc uplift through a convergence rate decrease.

701 6 Discussion

702 6.1 Paleo-thickness reconstruction and burial history

703 Apatite fission-track results indicate that post-Early Eocene sediment accumulation
 704 and burial differ in the study area. Figure 19 shows the detailed restoration of the Talara-
 705 Amotape-Lancones area along cross section B with projected apatite fission-track samples at
 706 the end of Eocene. Assuming that the top of the Late Eocene series (Chira-Verdun
 707 Formations) is slightly seaward-dipping (~2°), this pre-deformational basin architecture
 708 indicates that the Middle-Late Eocene sedimentary pile reached more than 4.5 km in thickness
 709 above the Amotape High and northwestern edge of the Lancones depocenter. This thick
 710 paleo-sedimentary pile would have favored reset of apatite fission-track system of the Early
 711 Eocene and older rocks (samples 6, 7 and 8) below the ~110°C closure temperature. In the
 712 Talara depocenter, the sedimentary fill would have been insufficient to totally reset the apatite
 713 fission-track system of samples 1, 2, 3, 4, 5 and 9. These results suggest that the offsets along
 714 the normal faults do not influenced apatite fission-track cooling age (i.e., hanging-wall
 715 exhumation) and that cooling was more controlled by thrusting. In addition, no evidence of
 716 Cenozoic intrusions or volcanism, which could influence the thermal history of the samples, is
 717 found in the study area. This reconstruction is consistent with present-day geothermal gradient
 718 of ~20-21°C/km observed in onshore exploration wells (*PERUPETRO S.A.* data). In addition,
 719 this thick paleo-sedimentary pile is consistent with high vitrinite reflectance values (0.9%-
 720 1%) measured in Cretaceous series of the Lancones depocenter [*Valencia and Uyen*, 2002].

721 In contrast to paleogeographic reconstructions of *Fildani et al.* [2008] and *Hessler and*
 722 *Fildani* [2015], our restoration shows that the Paleozoic basement of the Amotape High was
 723 totally covered by Middle-Late Eocene strata and no basement relief existed close to the study
 724 area. However, the presence of Amotape basement clasts into Middle and Late Eocene series
 725 as indicated by *Fildani et al.* [2008] and *Hessler and Fildani* [2015] may be also explained by

726 longitudinal drainage from the north [*Carozzi and Palomino, 1993*] where Paleozoic
727 basement was exposed above sea level.

728 6.2 Forearc kinematics and subduction dynamics

729 Natural examples and analog models [*e.g., Daly, 1989; Heuret et al., 2007; Regalla et al., 2013; Martinod et al., 2016*] showed that forearc shortening and large-scale subsidence
730 can be influenced by the dynamics of plate convergence. In the northern Peruvian margin, the
731 overall increase in the convergence rate observed between the Nazca (Farallon) and South
732 American plates during Paleocene to Late Oligocene [*Somoza and Ghidella, 2012*] is
733 correlated with shortening rate increase in the forearc system. In detail, the Paleocene to Late
734 Oligocene plate convergence history is marked by two accelerations at ~56-43 Ma and ~32-24
735 Ma that are approximately correlated with uplift events in the inner forearc system (Figure
736 20). This suggests that convergence rate acceleration leads to increase the plate coupling
737 along the subduction fault at the scale of the forearc system [*Daly, 1989*]. The Late
738 Cretaceous-Early Eocene event can be also correlated with the collision of oceanic terranes in
739 the Ecuadorian margin [*Jaillard et al., 1995, 1997*] and Colombian margin [*Borrero et al.,*
740 2012]. The Latest Eocene to Oligocene-Miocene cooling event is associated with major
741 activity in the magmatic continental arc of northern Peru and southern Ecuador [*Schütte et al.,*
742 2010]. According to our sequential restoration of the forearc system we believe that the
743 flexure of the slab is modified during convergence rate acceleration (Figures 18a,c and 20).
744 Under this condition, the restoration shows that the upper part of the slab becomes shallower
745 while its deeper part becomes steeper as observed in analogs models of *Heuret et al. [2007]*
746 and *Guillaume et al. [2009]*. We propose that subsequent upper plate thrust stacking and
747 duplexing generate strong loading in the forearc system which in turn induce downward
748 flexure of the subducting oceanic plate. This explains the strong subsidence and sediment
749 trapping in the forearc system during Middle-Late Eocene and post-Oligocene periods
750 following convergence rate accelerations (Figures 18b,d, and 20).
751

752 Our proposed kinematic model shows that compressional features (thrust-related
753 structural highs) coexist with thin- and thick-skinned normal to strike-slip faults. The
754 direction of extension is parallels to the transport direction of the thrust system (except NE-
755 trending extensional faults in the Tumbes depocenter related to the extrusion of the North
756 Andean block). Surface and subsurface data, and the restoration of the Tumbes depocenter
757 show that variation of basin slope (related to imbricate growth) associated with high
758 sedimentation rates play an important role for shallow gravity-driven thin-skinned
759 deformations [*Mauduit and Brun, 1998*]. However, other major faults located at the rear of the
760 Amotape, Carpitás-Zorritos, and Banco Peru imbricates (Cuzco-Angolo, Carpitás-Trigal-
761 Tronco Mocho, and Banco Peru fault zones, respectively), connect at depth onto crustal
762 detachments or onto the subduction fault. Downdip variations of frictional properties along
763 the subduction interface may be influenced by the morphology of the subducting plate,
764 lithology, fluid pressure and temperature changes [*e.g., Zhao et al., 1986; Hyndman et al.,*
765 1995; *Kastner et al., 1998; Ikari et al. 2009; Schurr et al., 2012; Takahashi et al. 2013;*
766 *Namiki et al., 2014*]. The development of upper plate extensional faults and subsidence zones
767 as observed in the North Peruvian forearc system (Figure 18) may be also the consequence of
768 basal erosion of the upper plate along the subduction interface [*Von Huene and Lallemand,*
769 1990; *Von Huene et al., 2004; Sage et al., 2006*]. In context of high convergence rate as in
770 northern Peru, the trench sediments are less compacted and rapidly underplated under the
771 forearc system [*Le Pichon et al., 1993; Lallemand et al., 1994*]. Thus, the high pore-fluid
772 pressure along the subduction interface may contribute to decrease locally the plate coupling,
773 which in turn may favor the drag of upper plate material into the subduction channel, leading
774 to upper plate normal faulting and subsidence [*Von Huene et al., 2004*].

775 Onshore post-Oligocene rotations and inferred strike-slip component along the Banco
 776 Peru fault zone might be associated with oblique subduction context of the Northern Andes
 777 [Villegas-Lanza *et al.*, 2016] but also with collision of broad indentors immediately north of
 778 the study area along the Ecuadorian margin (oceanic terranes and Carnegie ridge) and
 779 northern escape of the North Andean block [*e.g.*, Daly, 1989; Witt and Bourgois, 2010].
 780 Strike-slip motion in context of oblique subduction may be an alternation to create apparent
 781 crustal normal faulting in forearc system [Takano *et al.*, 2013; Bourgois, 2013; Noda and
 782 Miyakawa, 2017], which would be consistent with inferred strike-slip motions, at least, in the
 783 Banco Peru fault zone.

784 The sequential restoration presented in this study does not reveal tectonic relationship
 785 between age variations of the subducting oceanic lithosphere [Sdrolias and Müller, 2006] and
 786 the evolution of the North Peruvian forearc system. As well, whatever the subduction age of
 787 the Inca Plateau (Early or Middle Miocene; Gutscher *et al.*, 1999b; Skinner and Clayton,
 788 2013) and its associated eastern Pliocene to present slab flattening beneath the arc [Espurt *et*
 789 *al.*, 2008], these processes seem to have no major impact on the structural architecture and
 790 evolution of the North Peruvian forearc system. However, the subduction of the trench-
 791 oblique, parallel-upper plate structural trend Sarmiento and Alvarado ridges might be
 792 associated with recent forearc uplift with perched marine terraces and Tablazos [Macharé and
 793 Ortlieb, 1994; Pedoja *et al.*, 2006; Darrioulat, 2011] together with moderate active
 794 deformation beneath the onshore domain [Villegas-Lanza *et al.*, 2016] as observed in the
 795 central Ecuador, central Peru and central Chile margins [*e.g.*, Laursen *et al.*, 2002; Saillard *et*
 796 *al.*, 2011; Collot *et al.*, 2017].

797 6.3 Influence of sedimentation and forearc tectonic

798 Sedimentation may have also strong influence on geometry and fault dynamics of
 799 forearc systems [*e.g.*, Fuller *et al.*, 2006; Simpson, 2010; Heuret *et al.*, 2012]. Since the Early
 800 Eocene, siliciclastic sediments eroded from the Northern Andes of Ecuador and Peru were
 801 transported by longitudinal and transverse drainages and deltas in the forearc zone [Séranne,
 802 1987; Carozzi and Palomino, 1993; Higley, 2004; Fildani *et al.*, 2008; Quispe Alcalá, 2010].
 803 As described above, our sequential model shows that thick sedimentary piles of the Talara and
 804 Tumbes depocenter are associated with deep seated normal to strike-slip faults. We suggest
 805 that the high sedimentation amounts (up to 11 km-thick) increases the vertical stress in these
 806 depocenters [Simpson, 2010]. In the case of the Talara-Lancones depocenter, basal drag may
 807 have initiated normal (to strike-slip?) faulting along the Tronco Mocho, Carpitás-Trigal and
 808 Cuzco-Angolo fault systems which have been controlled in a second time by large
 809 sedimentation rates during Middle-Late Eocene and post-Early Oligocene. In the case of the
 810 Tumbes depocenter, we propose that the Late Oligocene to present-day high sediment influx
 811 was sufficient to influence the apparent normal slip of the Banco Peru fault. Thus, this
 812 sedimentary load played a major role in the deformation of the Banco Peru, in probably
 813 controlling its trenchward displacement. This behavior may reflect spatial variations of
 814 frictional properties along the subduction with low friction beneath the Banco Peru. This
 815 interpretation is consistent with the present-day aseismic slip of the plate interface in northern
 816 Peru [Bourgois, 2013; Villegas-Lanza *et al.*, 2016] and any significant earthquake in this zone
 817 [Bilek, 2010].

818 6.4 Forearc/backarc system evolution and growth of the Northern Andes

819 Foreland systems record the large-scale interactions between tectonics, erosion and
 820 sedimentation [*e.g.*, Jordan, 1995; DeCelles and Giles, 1996; Horton, 1999]. Building of the
 821 Andean orogenic wedge since the Late Cretaceous led to large-scale orogenic loading control

822 on adjacent Cenozoic foreland basins [*Iaffaldano et al.*, 2006; *Roddaz et al.*, 2010]. As
 823 suggested by *Jaillard et al.* [1997], we propose that the collision of oceanic terranes in the
 824 Northern Andes accounts for additional deformations during Late Paleocene-Early Eocene.
 825 The regional unconformity overlain by the Early Eocene Mogollon-Salinas Formation maybe
 826 interpreted as an unloading stage of the orogenic wedge and westward distribution of
 827 thrusting into the forearc zone. The Middle-Late Eocene inner subsidence and large sediment
 828 influx in the North Peruvian forearc system may be also controlled by internal crustal stacking
 829 and associated loading of the Andean orogenic wedge as revealed by thrust-induced
 830 exhumation at ca. 45 Ma in the Western Cordillera of Ecuador [*Spikings et al.*, 2010].
 831 Ongoing Oligocene to Miocene orogenic building and magmatic arc activity [*Schütt et al.*,
 832 2010] are associated with high subsidence rates and thrust-induced exhumation into the
 833 forearc system. Middle-Late Miocene final thrust-related exhumation in the northern Peruvian
 834 margin coincides with thrust tectonic loading of the Eastern Cordillera, shortening transfer
 835 into the Peruvian Subandean zone [*Espurt et al.*, 2011; *Eude et al.*, 2015], onset of the main
 836 phase of Andean Plateau uplift and associated flexural subsidence in the Amazonian foreland
 837 basin [*Roddaz et al.*, 2010]. Modern relief development and west-directed drainage system
 838 provide a major sediment influx and overfill of the North Peruvian forearc system. This
 839 induces additional loading in the forearc system, which favors forward thrust propagation
 840 (Erdos et al., 2015).

841 **7 Conclusions**

842 The main conclusions of this study are summarized in the following five points.

843 (1) Surface and subsurface data and the construction of two ~200 km-long crustal-
 844 scale balanced cross sections show that the structure of the North Peruvian forearc system is
 845 dominated by an accretionary style through the Late Cretaceous to Cenozoic period with
 846 northwestward propagation of thrust-related structural highs involving basement, oceanic
 847 rocks and off-scraped sediments. The thrust-related structural highs bound thick thrust-top
 848 forearc depocenters deformed by crustal normal to strike-slip faults and thin-skinned
 849 gravitational instabilities.

850 (2) Apatite fission-track data, thermal modeling and geological data from the inner
 851 forearc system (Amotape High area) indicate two episodes of cooling/erosion, Late
 852 Cretaceous(?)–Early Eocene (~80–50 Ma) and Latest Eocene–Early Oligocene (36–27 Ma) to
 853 Middle Miocene, separated by a period of strong subsidence, burial and reheating during
 854 Middle-Late Eocene. These two cooling events recorded basement thrust exhumation and
 855 occurred approximately during periods of convergence rate acceleration.

856 (3) This study suggests that convergence rate acceleration leads to increase the plate
 857 coupling at the scale of the forearc system. Although the sequential restoration provides
 858 forearc shortening rate for only five periods, we show a correlation between uplift, shortening
 859 and plate convergence velocity between Late Cretaceous and ~5 Ma. Late Cretaceous–Early
 860 Oligocene shortening is accommodated by basement accretion of the Amotape and Carpitás
 861 thrust systems underneath the Lancones and Talara forearc depocenters, respectively. The
 862 growth of the frontal Banco Peru imbricate occurred during Oligocene–Miocene and
 863 structurally contributes to strong sedimentary accumulation in the Tumbes forearc depocenter.
 864 Post-Miocene to present-day uplift and frontal shortening in context of relatively lower
 865 convergence rate mostly result from the subduction of bathymetric asperities/ridges.

866 (4) The development of SE-facing crustal normal to strike-slip faults and large-scale
 867 subsidence zones during overall forearc system accretion might be the consequence of slab
 868 flexure, basal erosion along subduction plate interface, and/or strike-slip component in the

869 context of oblique subduction of the northern Peruvian margin. Strong sedimentation rate may
870 increase the apparent normal fault displacement and thrust propagation in the prism,
871 particularly in the case of the Tumbes forearc depocenter-Banco Peru system.

872 (5) The North Peruvian forearc system has recorded the building of the Northern
873 Andes and its associated orogenic loading evolution over the Cenozoic.

874 **Acknowledgments**

875 This work was conducted thanks to the Institut de Recherche pour le Développement
876 (IRD)–PERUPETRO S.A. research agreement. Financial support for field work and analysis
877 came from IRD (UR 234), CEREGE (internal research grant: Characterization and
878 quantification of the deformations in a complex compressional basin: the Tumbes-Talara
879 forearc basin, North Peru), and the Institut Carnot ISIFoR (Research project: Structural
880 modeling and petroleum simulations in complex zones: insight into the giant petroleum field
881 of the Nord Peruvian forearc). Midland Valley Inc. is acknowledged for providing academic
882 license of Move for structural modeling. We acknowledge the associate editor Augusto
883 Rapalini, Agustin Cardona and an anonymous reviewer for the constructive comments which
884 greatly helped us to improve our manuscript. Supporting data are included in supporting
885 information or available by contacting the corresponding author (espurt@cerege.fr).

886

Sample name/ Structural unit	Long. (m)	Lat. (m)	Elev. (masl)	Strat. age	Gr	Ns	ρ (cm ²)	$\sigma\rho$	P	σP	χ^2	Q(χ^2)	Pooled age (Ma)	Central age (Ma)	CP1 (Ma)	% grains in CP1	CP2 (Ma)	% grains in CP2	CP3 (Ma)	% grains in CP3	MTL (μ m)	Stdev (μ m)	Dpar (μ m)
1/Talara	514 429	9 542 461	175	Middle Eocene	38	835	1.7 10 ⁻⁴	1.2 10 ⁻⁷	1.499	9.8E10 ⁻³	157.6	0	40.1(-3.0,3.2)	43.2 \pm 3.7	28.8 \pm 1.9	38	50.7 \pm 2.7	56	120 \pm 19	7	12.49 \pm 0.14(202)	1.95	2.32
2/Talara	510 910	9 541 031	111	Early Eocene	38	494	9.7 10 ⁻⁵	4.7 10 ⁻⁷	1.463	9.8E10 ⁻³	48.8	0.1	42.1(-3.9,4.3)	46.8 \pm 3.0	38.8 \pm 2.7	47	57.1 \pm 6.8	53	-	-	12.31 \pm 0.13(200)	1.8	2.44
3/Talara	512 239	9 542 139	135	Middle Eocene	40	553	1.1 10 ⁻⁴	5.3 10 ⁻⁷	1.4866	9.8E10 ⁻³	57.1	0	40.6(-3.7,3.9)	45.1 \pm 2.7	36.2 \pm 2.6	43	54.1 \pm 6.1	57	-	-	12.83 \pm 0.39(202)	5.46	2.26
4/Talara	5150.32	9 541 539	186	Middle Eocene	40	1142	1.8 10 ⁻⁴	7.4 10 ⁻⁷	1.478	9.8E10 ⁻³	118.8	0	52.4(-3.5,3.7)	52.5 \pm 3.1	36.7 \pm 2.5	35	63.1 \pm 2.4	65	-	-	12.45 \pm 0.12(201)	1.64	2.22
5/Talara	542 492	9 566 482	129	Early Eocene	34	438	7.2 10 ⁻⁵	3.1 10 ⁻⁷	1.4636	9.8E10 ⁻³	60.1	0	49.8(-4.8,5.3)	52.1 \pm 3.7	37 \pm 18	9	50.5 \pm 5.1	83	116 \pm 23	8	13.01 \pm 0.12(205)	1.66	2.41
6/Amotape	543 166	9 553 245	319	Triassic (granite)	40	1479	7.7 10 ⁻⁴	1.8 10 ⁻⁶	1.5377	9.8E10 ⁻³	69.7	0	15.8(-0.9,1.0)	15.8 \pm 0.6	-	-	-	-	-	-	12.19 \pm 0.15(209)	2.14	1.89
7/Lancones	558 190	9 553 866	230	Late Cretaceous	40	1437	6.8 10 ⁻⁴	1.6 10 ⁻⁶	1.469	9.8E10 ⁻³	108	0	17.2(-1.0,1.1)	17.5 \pm 0.7	14.8 \pm 0.7	67	22.7 \pm 1.2	33	-	-	12.86 \pm 0.11(181)	1.46	1.88
8/Amotape	526 492	9 542 910	314	Early Eocene	40	334	1.0 10 ⁻⁴	5.3 10 ⁻⁷	1.4799	9.8E10 ⁻³	101.2	0	27.1(-2.9,3.3)	29.7 \pm 2.9	20.9 \pm 2.2	57	45.7 \pm 4.5	43	-	-	12.58 \pm 0.15(163)	1.94	2.43
9/Talara	519 306	9 539 698	210	Early Eocene	36	161	2.6 10 ⁻⁵	1.5 10 ⁻⁷	1.4621	9.8E10 ⁻³	26.8	0.8	51.63(-7.7,9.0)	56.1 \pm 4.4	-	-	-	-	-	-	12.47 \pm 0.15(128)	1.75	2.44

887 **Table 1.** Apatite fission-track data using laser ablation-inductively coupled plasma-mass spectrometry method. Gr–number of counted grains;
888 Ns–sum of spontaneous tracks; ρ –area of spontaneous track counting with its error ($\sigma\rho$); P–corrected $^{238}\text{U}/^{43}\text{Ca}$ isotopic ratio (10^{-3}) with its error
889 (σP); ICPMS Zeta factor is 8.2727 ± 0.1407 ; CP1-3–Component peak ages (1 to 3) from RadialPlotter [Vermeesch, 2009] (see supporting
890 information Figure S1); MTL–Mean track length (number of tracks); Dpar–mean maximum diameter of fission-track etch figures parallel to the
891 c-axis; Pooled ages are $\pm 95\%$ CI confidence interval; Central and peak ages are $\pm 1\sigma$; Coordinates are in UTM Zone 17S.

892 **Figure 1.** Geodynamic settings. (a): Physiographic map of the northern Peruvian-Ecuadorian
 893 Andes. The base map is produced using elevation data from NASA (National Aeronautics and
 894 Space Administration) 30 m ASTER (Advanced Spaceborne Thermal Emission and
 895 Reflection Radiometer) GDEM (Global Digital Elevation Model). Plate convergence vector
 896 and velocities (mm/yr) are from *Gripp and Gordon* [2002]. Mapping, vector and velocities
 897 (mm/yr) of the continental slivers are from *Villegas-Lanza et al.* [2016]. GR: Grivalja ridge.
 898 AR1-2: Alvarado ridges 1 and 2. SR: Sarmiento ridge. SB: Sechura basin. GB: Guayaquil
 899 basin. PH: Paíta High. IH: Illescas High. WC: Western Cordillera. HD: Huancabamba
 900 deflection (dashed white line). STF: Subandean thrust front. NAFB: Northern Andean
 901 foreland basin. (b): Onshore-offshore structural map of the study area showing major forearc
 902 depocenters (FD) and structural highs. Locations of cross sections A and B, seismic profiles
 903 and onshore wells (CORV40, DEL39, P. RED18) are shown. Red lines show faults. HF:
 904 Huaypirá fault. EFZ: La Encanada fault zone. CAF: Cuzco-Angolo fault. CFZ: Carpitás fault
 905 zone. TMFZ: Tronco Mocho fault zone. BPFZ: Banco Peru fault zone. Coordinate system is
 906 UTM zone 17S.

907 **Figure 2.** Synthetic stratigraphy, lithology and chart of the Cretaceous to Cenozoic series
 908 across the North Peruvian forearc system [*Jaillard et al.*, 1999; *Pozo*, 2002; *Valencia and*
 909 *Uyen*, 2002; *Fernández et al.*, 2005; *Fildani et al.*, 2008; *Vega*, 2009; *Hessler and Fildani*;
 910 2015]. Cretaceous-Cenozoic depocenters are separated by structural highs made of
 911 sedimentary, continental and oceanic materials. Major unconformities are shown. U1: Basal
 912 Cretaceous unconformity 1. U2: Late Cretaceous unconformity. U3: Early Eocene
 913 unconformity. U4: Late Eocene-Oligocene unconformity. U5: Middle Miocene unconformity.

914 **Figure 3.** Geologic map of the onshore study area showing onshore cross sections A and B,
 915 seismic reflection profiles and wells. This map is based on new field mapping and published
 916 maps of INGEMMET and petroleum companies. FD: Forearc depocenter. CFZ: Carpitás fault
 917 zone. TF: Trigal fault. CVF: Cabeza de Vaca fault. TMFZ: Tronco Mocho fault zone. CAF:
 918 Cuzco-Angolo fault. EFZ: La Encanada fault zone. Coordinate system is UTM zone 17S.

919 **Figure 4.** Geological field observations illustrating two major unconformities (U3 and U4) in
 920 the onshore domain. For locations, see Figures 1b, 3, 5 and 10. (a) Paleozoic metamorphic
 921 rocks of the Amotape High unconformably covered by strata of the Early Eocene Mogollon-
 922 Salinas Formation. (b) Pennsylvanian turbidites of the Chaleco de Paño Formation
 923 unconformably covered by strata of the Early Eocene Mogollon-Salinas Formation
 924 (southwestern edge of the Amotape High, High Talara River). (c) and (d) Subaerial erosional
 925 surface between basal marine Late Eocene Chira Formation and upper fluvial Latest Eocene-
 926 Oligocene series (Mirador, Plateritos and Mancora Formations). (e) Growth strata geometry in
 927 the Oligocene Plateritos sequences along the Bocapan River.

928 **Figure 5.** Surface cross sections A and B across the onshore domain of the Talara and
 929 Lancones forearc depocenters. For locations, see Figure 3. Locations of seismic profiles (L1,
 930 BPZ23-16 and PXII99-02) and wells are shown. Major unconformities (U1-5) are also
 931 indicated. ZH: Zorritos High. CH: Carpitás High. FD: Forearc Depocenter. TMFZ: Tronco
 932 Mocho fault zone. TF: Trigal fault. CAF: Cuzco-Angolo fault. EFZ: La Encanada fault zone.
 933 CFZ: Carpitás fault zone. CVF: Cabeza de Vaca fault.

934 **Figure 6.** Details of the NW-verging Jabonillos thrust fault zone through the Turonian
 935 Encuentros Formation in the Lancones depocenter. For location, see Figure 3.

936 **Figure 7.** Geological field observations illustrating the polyphased fault kinematics in the
 937 study area. For locations, see Figures 1b, 3 and 5. (a) Inversion and triangle zone in the Albian
 938 Pananga Formation in the northwestern Lancones depocenter. (b) Extensional reactivation of
 939 a fault-bend fold in the Early Eocene Mogollon-Salinas Formation in the Talara depocenter
 940 (northern Bocapan River, cross section A). (c) Thrust propagating with short-cut trajectory
 941 through normal fault in Middle Eocene Talara Formation in the Talara depocenter (northern
 942 Fernandez River). Numbers refer to fault sequence.

943 **Figure 8.** Structural interpretation of seismic profile PXII99-02 in the center part of the
 944 Lancones depocenter across the Gallinazos anticline. For location, see Figure 3. Faults are
 945 indicated by thick red lines. Note that some thrust faults connect with the Amotape Paleozoic
 946 basement. These faults may correspond to inherited normal fault active during the Early
 947 Cretaceous (e.g., Figure 7a). Shales of the Muerto Formation form a shallower thin-skin
 948 décollement level. Unconformity U1 is shown. TWT: two-way time.

949 **Figure 9.** Extensional faulting in the Eocene series of the Talara forearc depocenter between
 950 the Carpitás and Cabeza de Vaca faults, cross section B. For locations, see Figures 3, 5 and
 951 10). U4: Unconformity 4.

952 **Figure 10.** Structural interpretation of depth-converted seismic profile BPZ23-16 calibrated
 953 with wells and surface data across the Talara forearc depocenter between the Amotape High
 954 to the southeast and the Carpitás High to the northwest (cross section B). For location, see
 955 Figure 3. Faults are indicated by thick red lines. Eocene series are deformed by extensional
 956 faults. These faults branch at depth onto SE-dipping low-angle thrust faults within the
 957 Amotape Paleozoic basement. These thrust faults extend southeastward below the Amotape
 958 High. Unconformities U3 and U4 are shown. Locations of exploration wells and oil plays are
 959 also shown.

960 **Figure 11.** Geological field observations illustrating the gravitational instabilities in the shales
 961 of the Late Oligocene-Early Miocene Heath Formation, cross section A. (a): Bocapan River.
 962 (b) Animas River. For location, see Figures 3 and 5.

963 **Figure 12.** Structural interpretation of depth-converted seismic profile L1 across the Zorritos
 964 High calibrated with wells and surface data, cross section A. For location, see Figure 3. Faults
 965 are indicated by thick red lines. Note the extensional tectonic deforming Eocene-Early
 966 Miocene series corresponding to the Tronco Mocho fault zone. The normal faults show small
 967 inversion with short-cut geometries. Note also the unconformity U4 of the Oligocene
 968 Plateritos/Mancora Formations above the Early Eocene series and Amotape basement.
 969 Unconformities U3 and U5 are also shown. See details in the text.

970 **Figure 13.** Structural interpretation of the offshore domain of cross section B using depth-
 971 converted seismic profiles AIP92-15, L2, VMX09-23 and RIB93-1 across the Tumbes forearc
 972 depocenter (FD), Banco Peru and Trench-Slope Basin calibrated with the projected (pjt.)
 973 DEL39 well. For location, see Figure 1b. Small inversions and compressional structures are
 974 suspected on the seaward side of the Carpitás High. Onshore structure along seismic line
 975 BPZ23-16 of Figure 10 is also shown. Faults are indicated by thick red lines. Unconformities
 976 U3-5 are shown. BPFZ: Banco Peru fault zone. See details in the text.

977 **Figure 14.** Structural interpretation of the offshore domain of cross section A using depth-
 978 converted seismic profiles PC99-11, L3 and VMX09-01 across the Tumbes forearc
 979 depocenter (FD) calibrated with the DEL39 well. Note that the COR18 and P.RED18 wells

980 have been projected (pjt.). For location, see Figure 1b. Note the major compressional
 981 structures on the seaward side of the Zorritos High. Onshore structure along seismic Line 1 of
 982 Figure 12 is also shown. Faults are indicated by thick red lines. Unconformities U3-5 are
 983 shown. BPFZ: Banco Peru fault zone. See details in the text.

984 **Figure 15.** Apatite fission-track data (sample location and number; central and component
 985 peak ages in Ma; see Table 1) in the onshore study area (Talara, Amotape and Lancones
 986 units). FD: Forearc depocenter. TMFZ: Tronco Mocho fault zone. CFZ: Carpititas fault zone.
 987 TF: Trigal fault. CAF: Cuzco-Angolo fault. For legend of the sedimentary units, see Figure 3.

988 **Figure 16.** HeFTy inverse thermal modeling for samples 2, 6, 7 and 8 from the Talara,
 989 Amotape and Lancones units. The modeling together with geological data show time-
 990 temperature histories for two uplift episodes (Late Cretaceous(?)-Early Eocene and Late
 991 Eocene-Oligocene) separated by a major subsidence and burial/reheating period during
 992 Middle-Late Eocene. Light and dark grey fields represent acceptable and good model fits,
 993 respectively. The blue line represents the weighted mean path of the model. FD: Forearc
 994 depocenter.

995 **Figure 17.** Crustal-scale cross sections across the North Peruvian forearc system. For
 996 location, see Figure 1b. FD: Forearc depocenter. Write circles correspond to Mw>5 seismic
 997 events from the “Instituto Geofísico del Perú” catalog 2005-2013 (<http://www.igp.gob.pe>).
 998 Seismic events are projected along 100 km-wide corridors centered on the cross sections.
 999 Major normal fault systems are shown. Position of the apatite fission-track samples is also
 1000 shown (small black circles). CAF: Cuzco-Angolo fault. EFZ: La Encanada fault zone. CFZ:
 1001 Carpititas fault zone. TF: Trigal fault. TMFZ: Tronco Mocho fault zone. BPFZ: Banco Peru
 1002 fault zone. SR: Sarmiento ridge. AR1-2: Alvarado ridges 1 and 2.

1003 **Figure 18.** Crustal-scale sequential restoration of the North Peruvian forearc system along
 1004 cross section B. See Figure 1b for location and Figure 17 for legend of the sedimentary units.
 1005 Note that major thrust sheets are labelled (1 to 10). Position of the apatite fission-track
 1006 samples is also shown (small black circles). Vertical black arrows indicate downward flexure
 1007 of the slab. LD: Lancones depocenter. AH: Amotape High. TD: Talara depocenter. TUD:
 1008 Tumbes depocenter. BP: Banco Peru. CAF: Cuzco-Angolo fault. EFZ: La Encanada fault
 1009 zone. CFZ: Carpititas fault zone. BPFZ: Banco Peru fault zone. SR: Sarmiento ridge. AR1-2:
 1010 Alvarado ridges 1 and 2. AFT: Apatite fission-track. See details in the text.

1011 **Figure 19.** Restoration of the apatite fission-track samples at the end of the Middle-Late
 1012 subsidence in the Amotape High (Figures 18b). See details in the text. White bars represent
 1013 good model fits from the HeFTy inverse modeling of Figure 16. Dashed black line indicates
 1014 the ~110°C temperature closure of the apatite fission-track system according to a ~20°C/km
 1015 geothermal gradient and ~20°C surface temperature near the bottom of the sea. The
 1016 restoration is consistent with apatite fission-track and thermal modeling results: samples 6, 7
 1017 and 8 are reset whereas samples 1, 2, 3, 4, 5 and 9 are not or partially reset. Note the vertical
 1018 exaggeration. FD: Forearc depocenter.

1019 **Figure 20.** Comparison between convergence rate of the Nazca (Farallon)-South American
 1020 plate system [*Somoza and Ghidella, 2012*] and shortening rate in the North Peruvian forearc
 1021 system calculated from the sequentially balanced cross section B in Figure 18. In detail, the
 1022 increase of convergence rate at ~56-43 Ma and ~32-24 Ma is somewhat correlated with uplift
 1023 events in the inner forearc system while the following subsidence periods fit with stable or
 1024 decrease of plate convergence rate. Dashed grey lines shows mean convergence rate. (a-f):

1025 Restoration stages of Figure 18. FB: Farallon breakup. IP: Inca Plateau subduction. CR:
 1026 Carnegie ridge subduction. SR and AR: Subduction of the Sarmiento and Alvarado ridges.
 1027 Cooling and reheating periods of the apatite fission-track (AFT) system and major uplift and
 1028 subsidence (Subs.) periods are shown.

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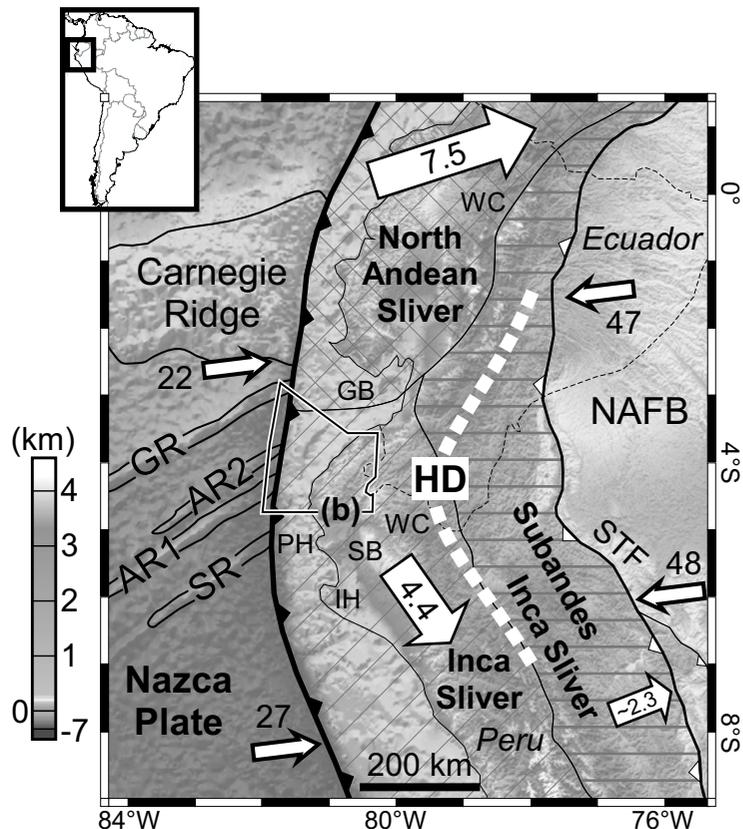
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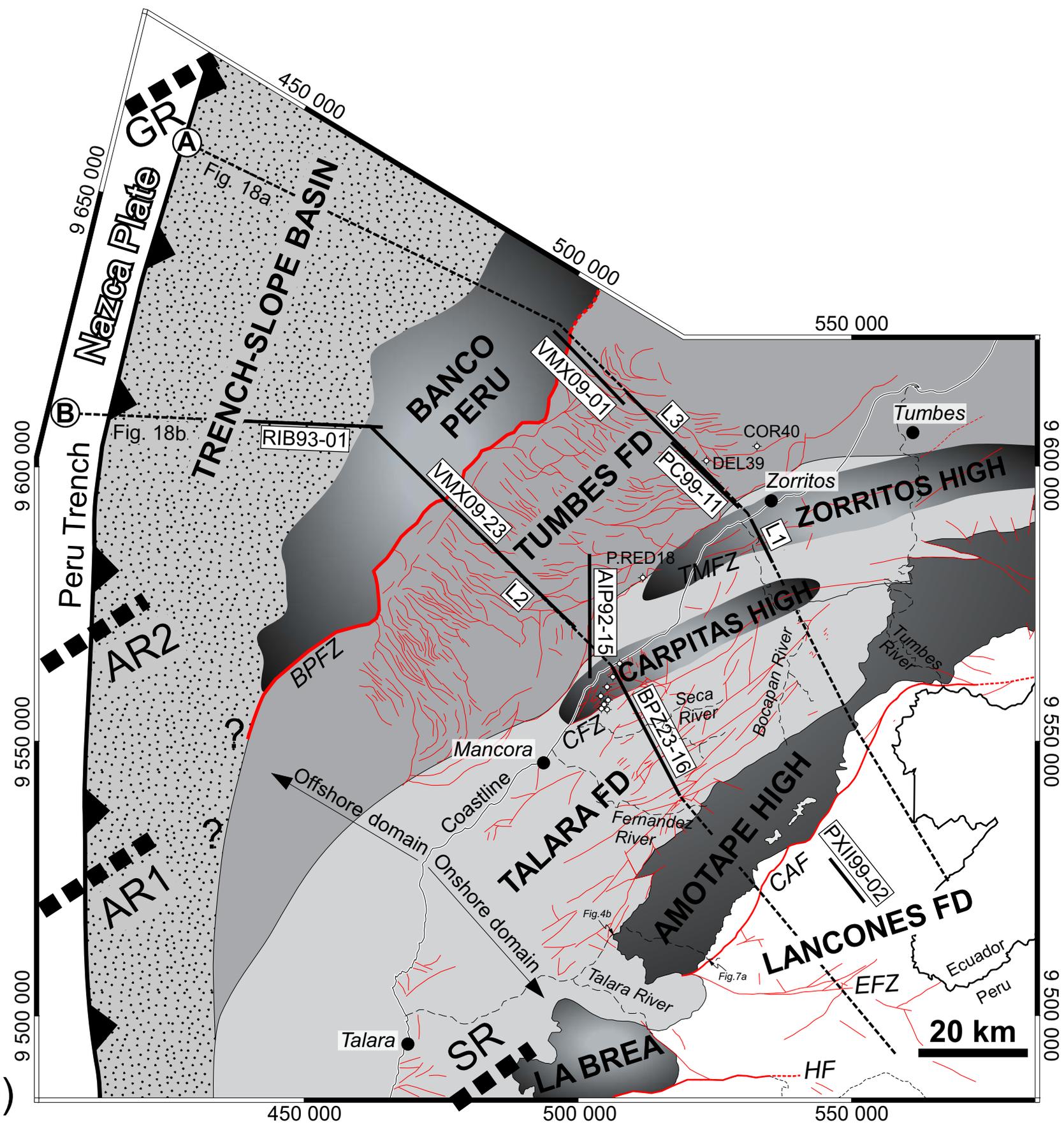
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1538 10,258.
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1541 Qinghai–Tibet Plateau tectonics, *Earth and Planetary Science Letters*, 243, 195–210,
1542 doi:10.1016/j.epsl.2005.11.033.

Figure 1.



(a)



(b)

Figure 2.

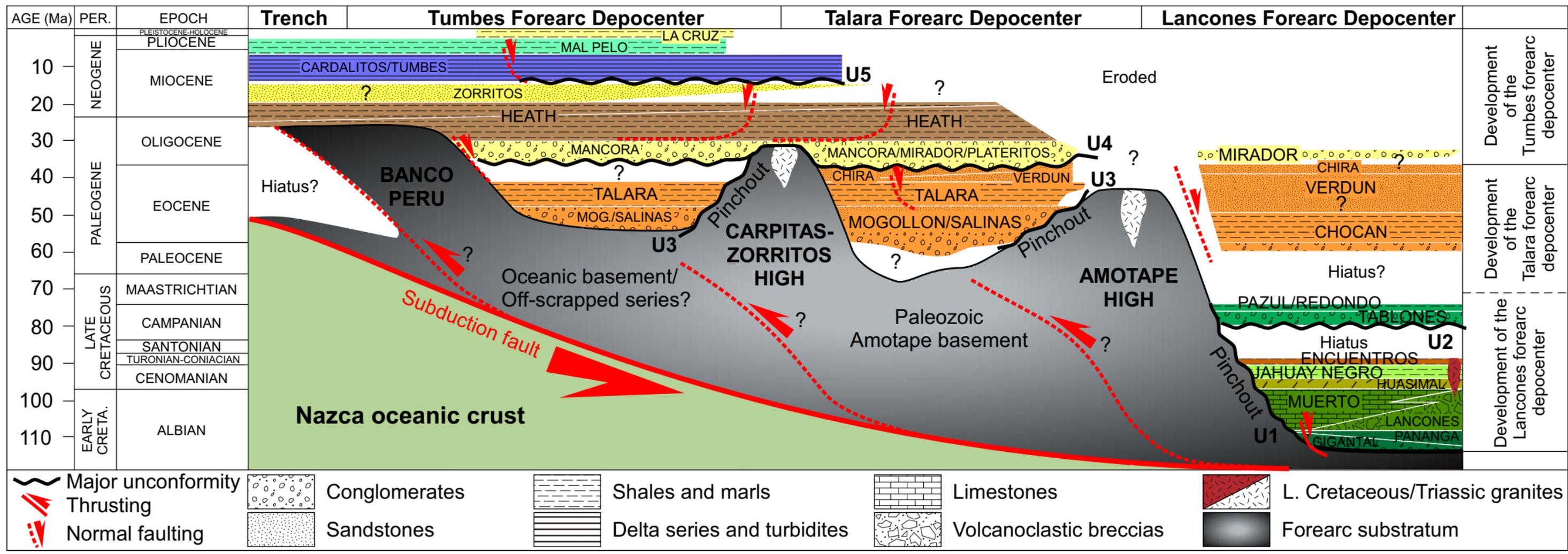
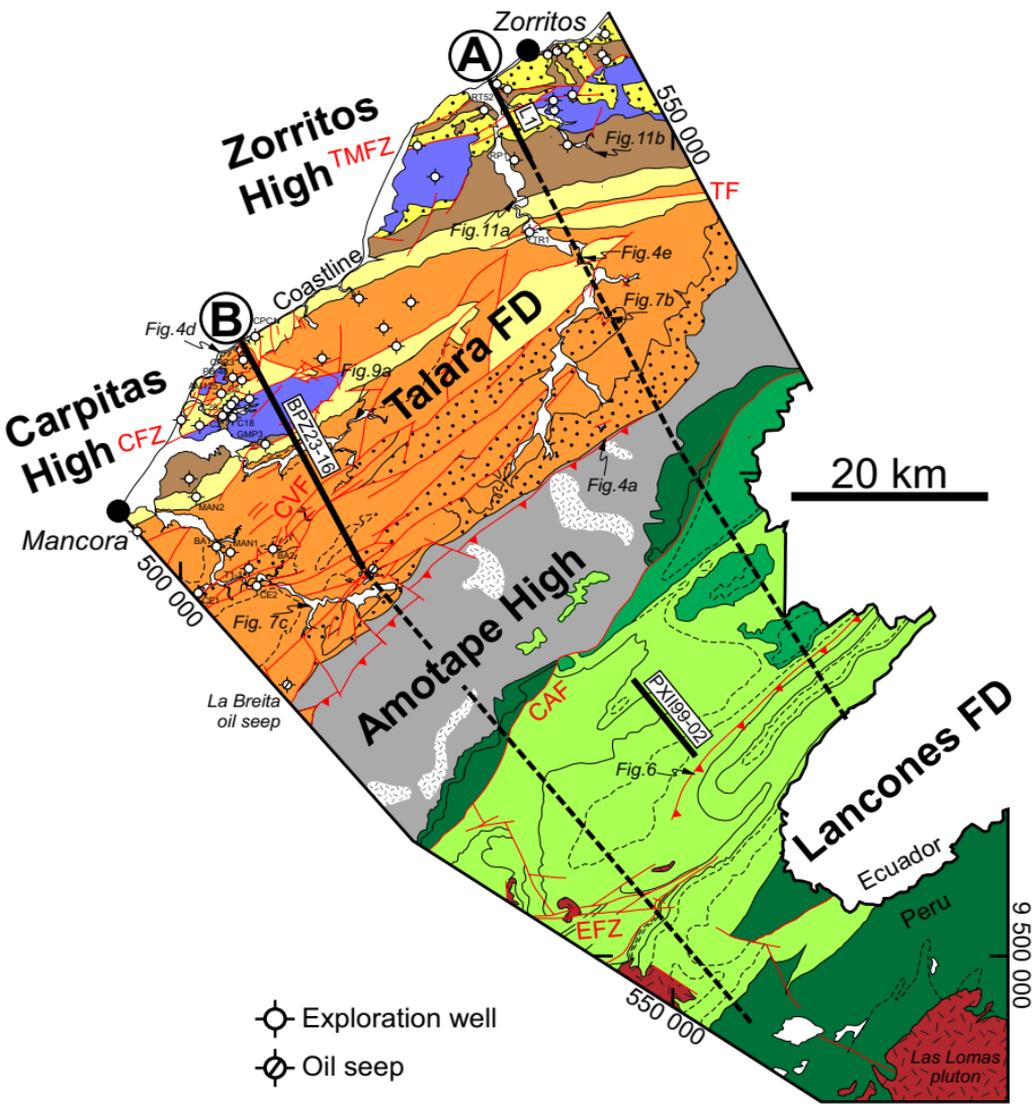


Figure 3.



⊕ Exploration well
 ⊙ Oil seep

- | | | |
|---|--------------------------------|------------------|
| □ Alluvial (Quaternary) | ■ Redondo/Tablones | Late Cretaceous |
| ■ Cardalitos (Middle Miocene) | ■ Encuentros Jahuay Negro | |
| ■ Zorritos (Early Miocene) | ■ Huasimal | Early Cretaceous |
| ■ Heath (L. Olig.-Early Miocene) | ■ Muerto/Lancones | |
| ■ Mir./Plat./Mancora (L. Eoc.-E. Olig.) | ■ Pananga/Gigantal | |
| ■ Talara/Verdun/Chira (Mid.-L. Eoc.) | ■ Granite (Triassic) | |
| ■ Mogollon-Salinas (Early Eocene) | ■ Amotape basement (Paleozoic) | |
| | ■ Intrusive | |

Figure 4.

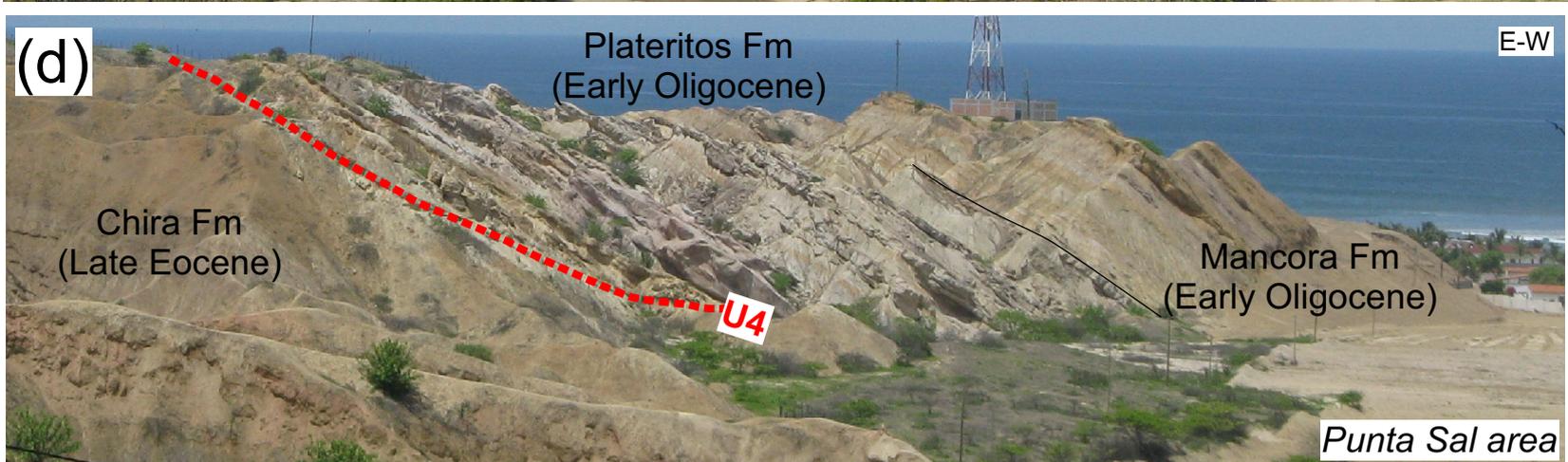
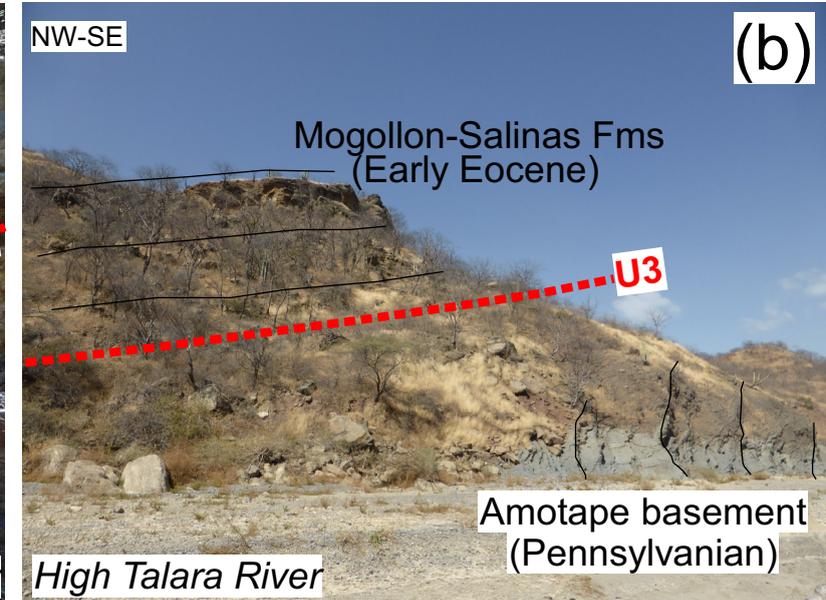
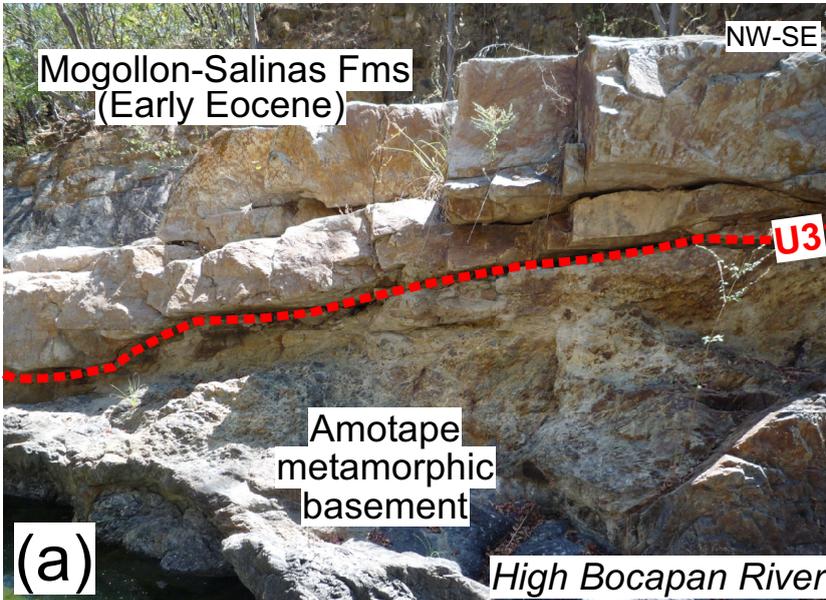


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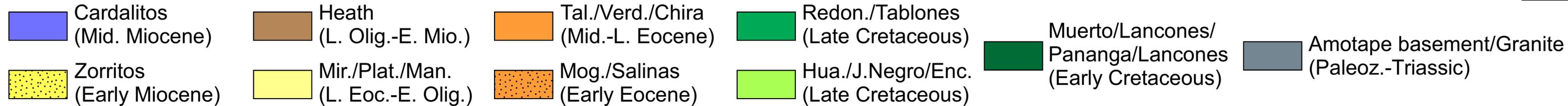
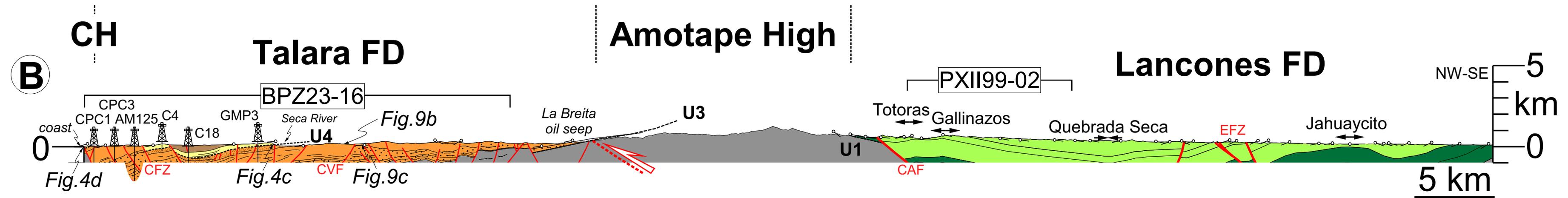
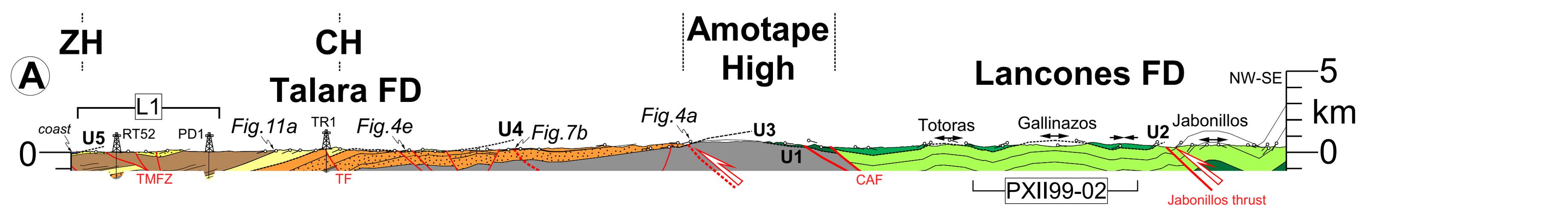


Figure 6.

NW-SE



NW-SE

Encuentros Fm
(Late Cretaceous)

Jabonillos thrust

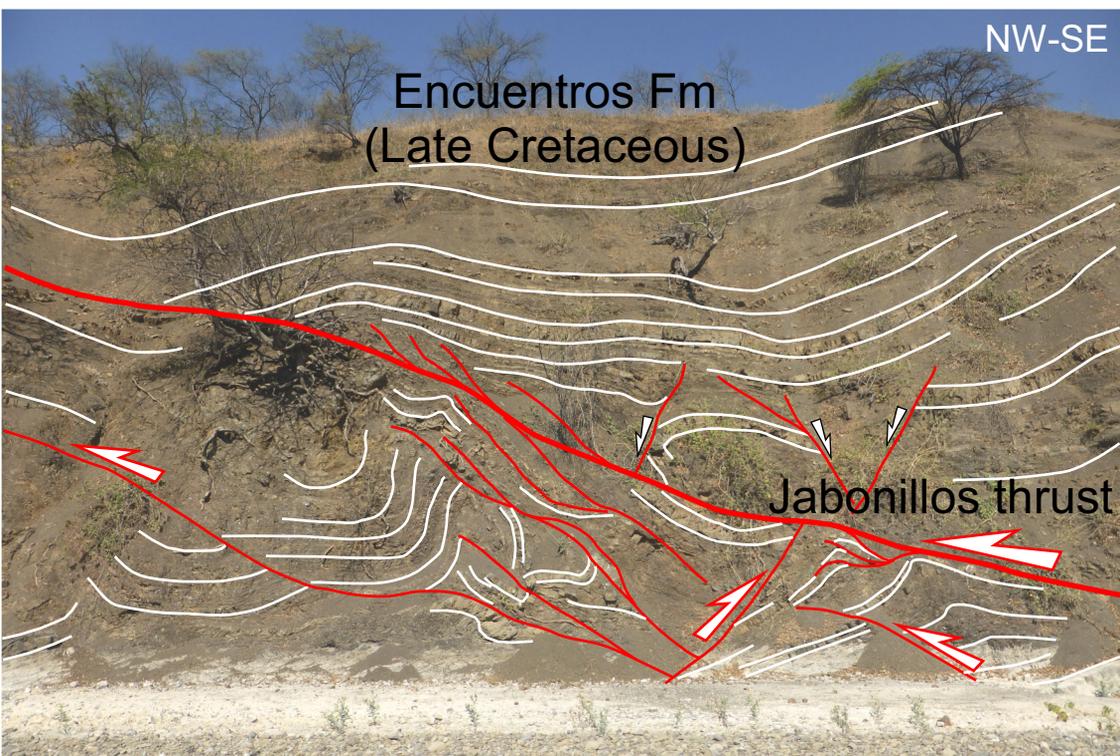


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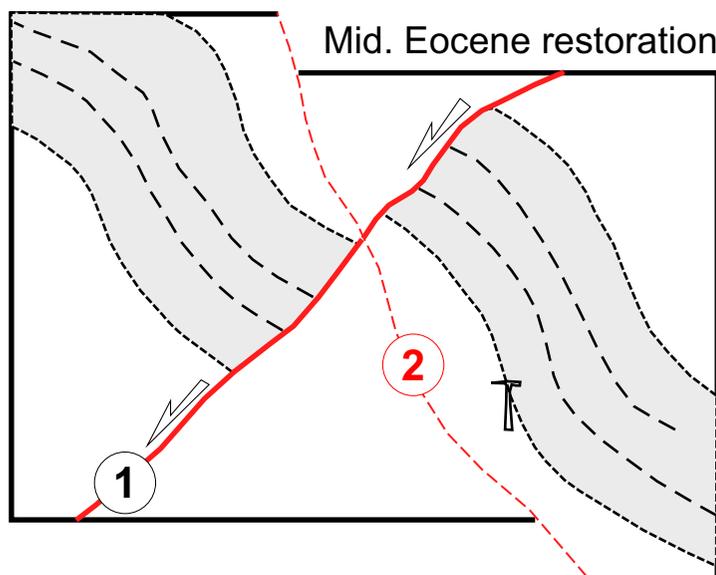
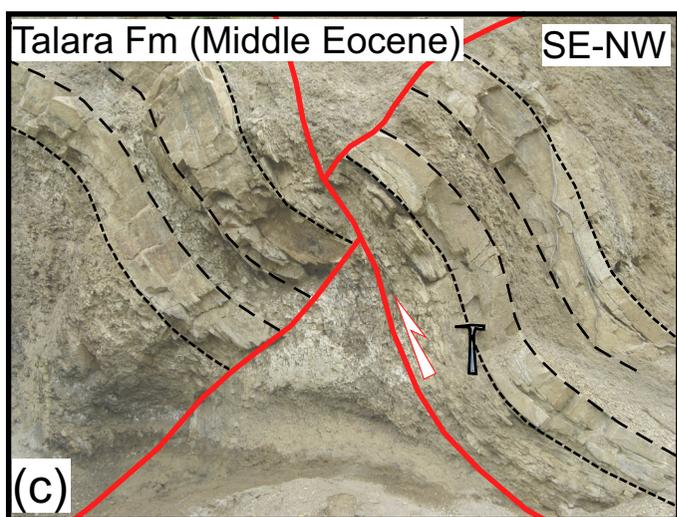
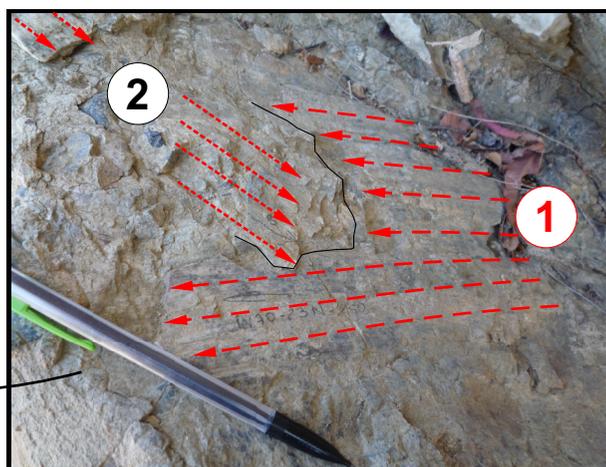
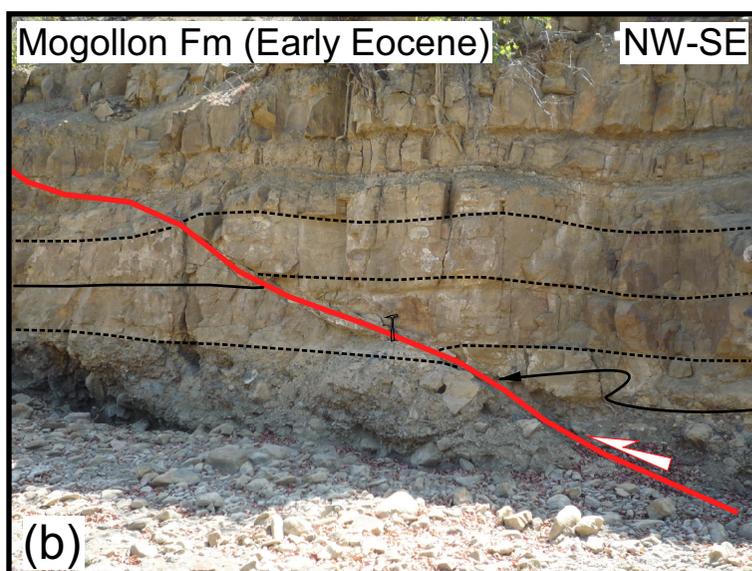
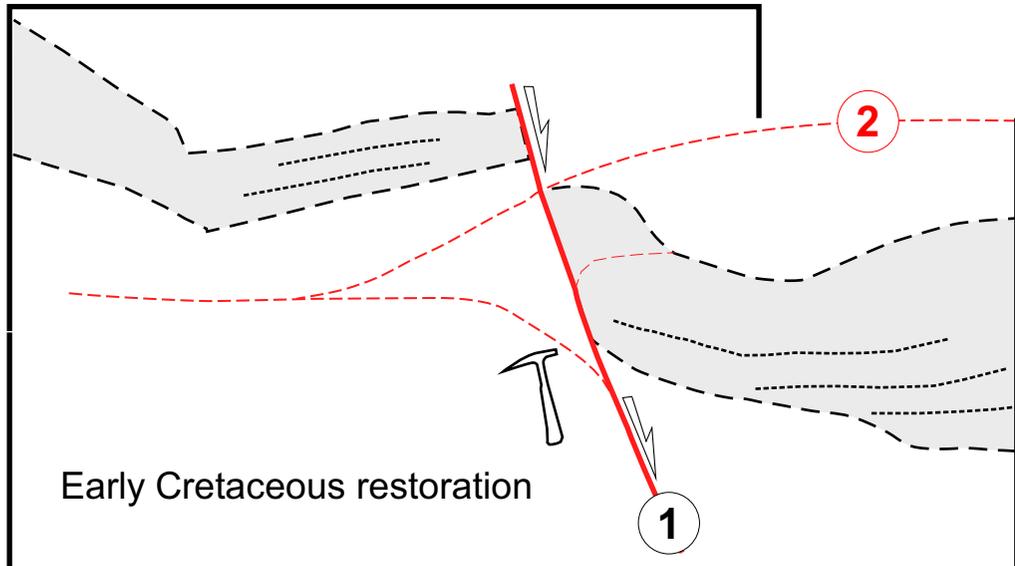
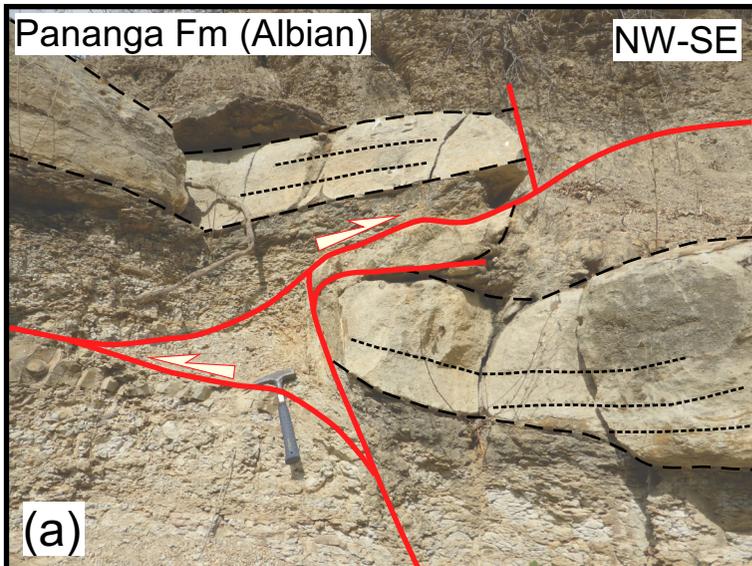
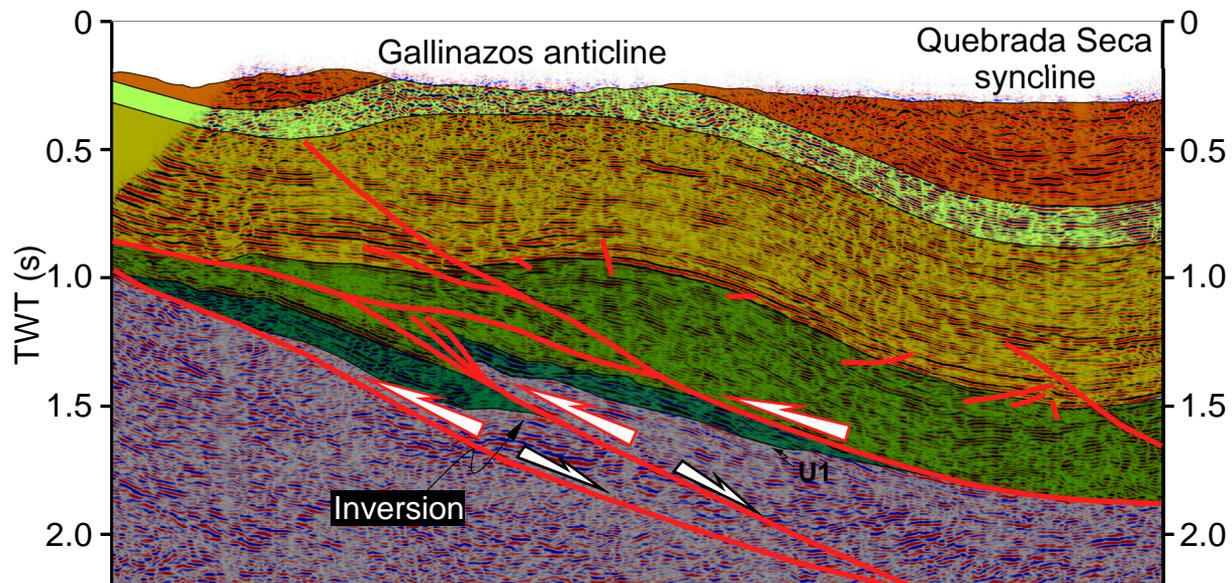
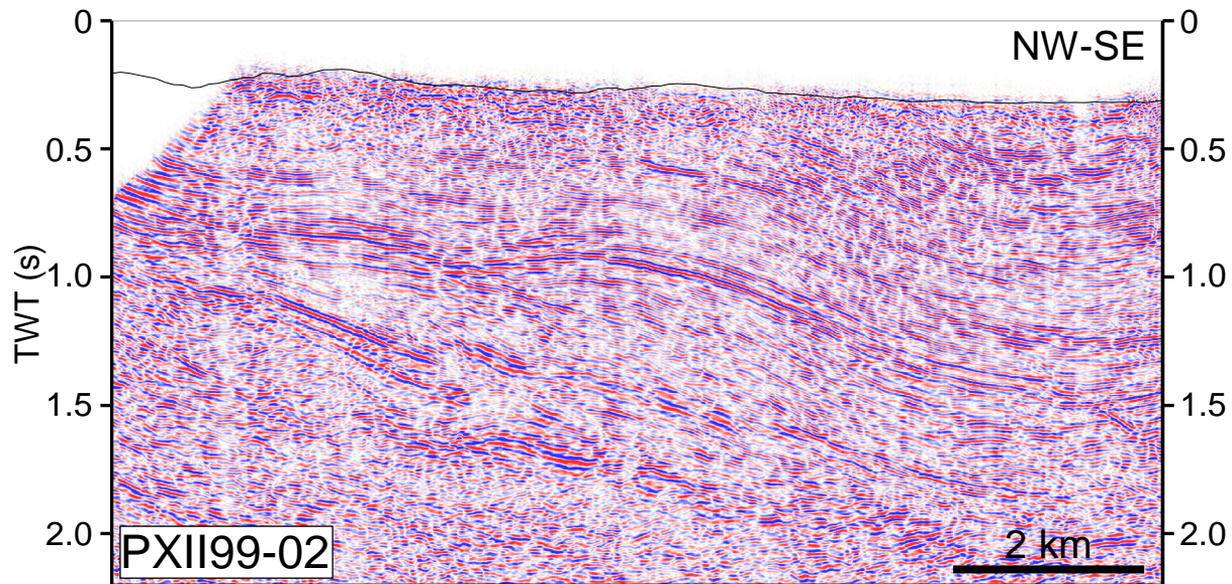


Figure 8.



Encuentros
(Late Cretaceous)

Jahuay Negro
(Late Cretaceous)

Huasimal
(Late Cretaceous)

Muerto/Lancones
(Early Cretaceous)

Pananga/Gigantal
(Early Cretaceous)

Amotape basement
(Paleoz.-Triassic)

Figure 9.

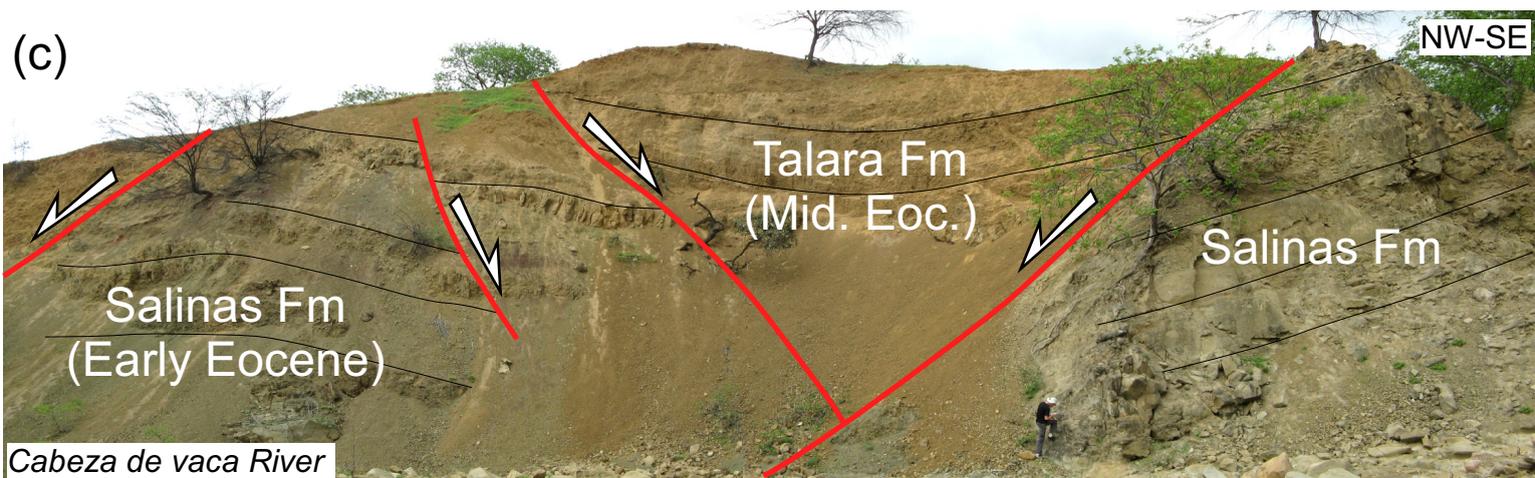


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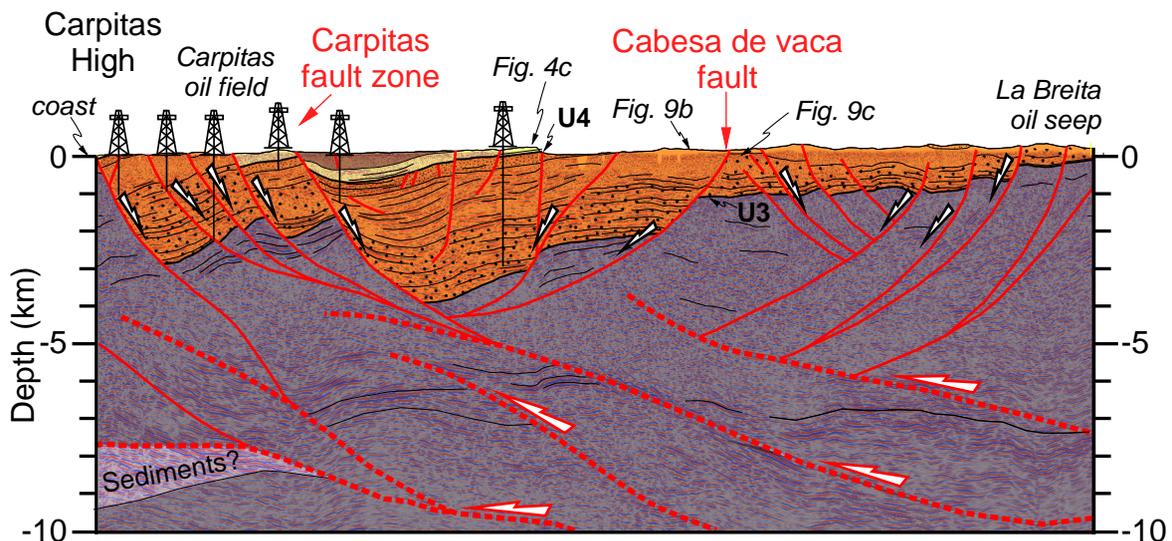
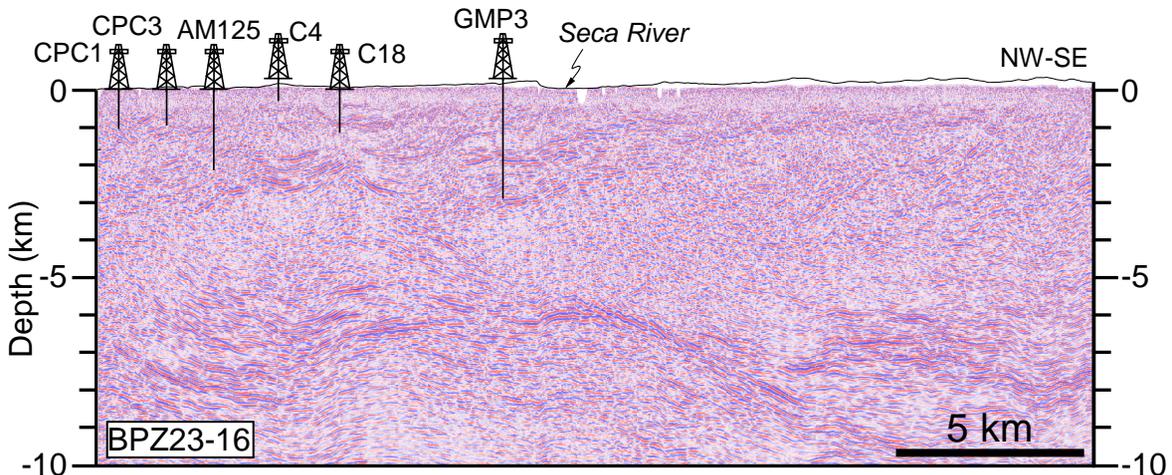
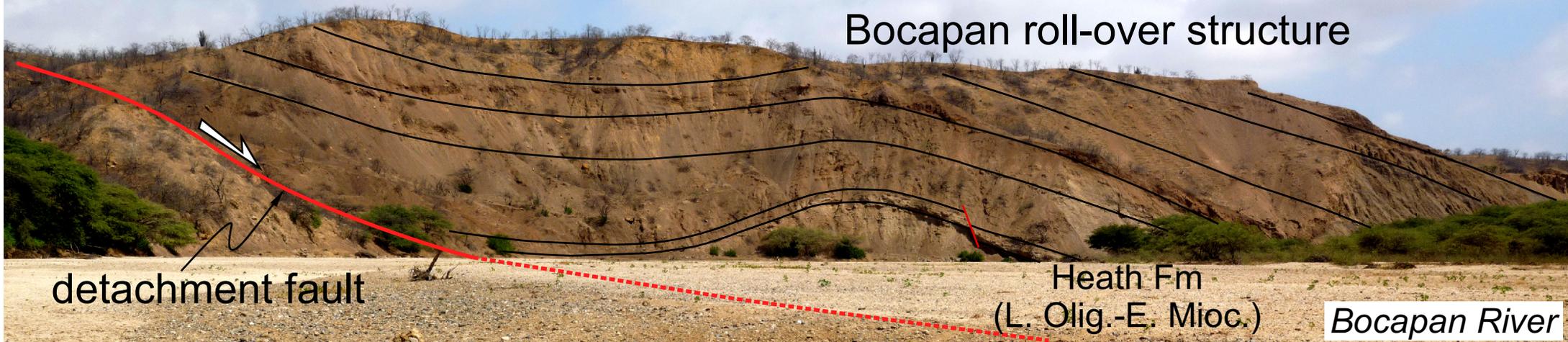
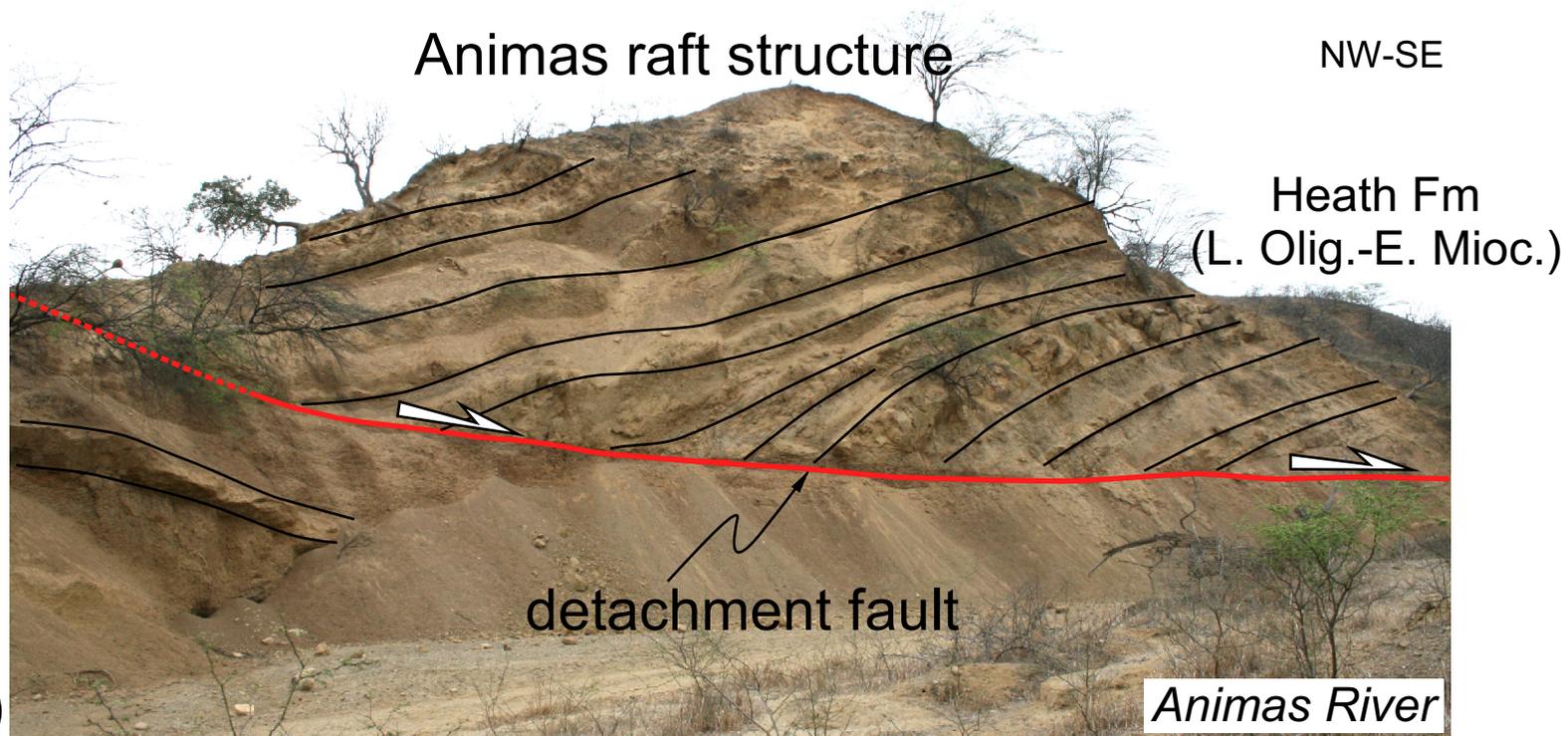


Figure 11.



(a)



(b)

Figure 12.

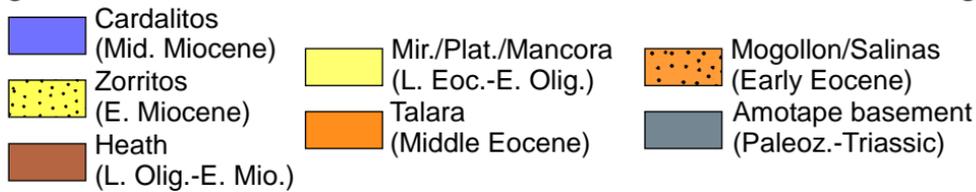
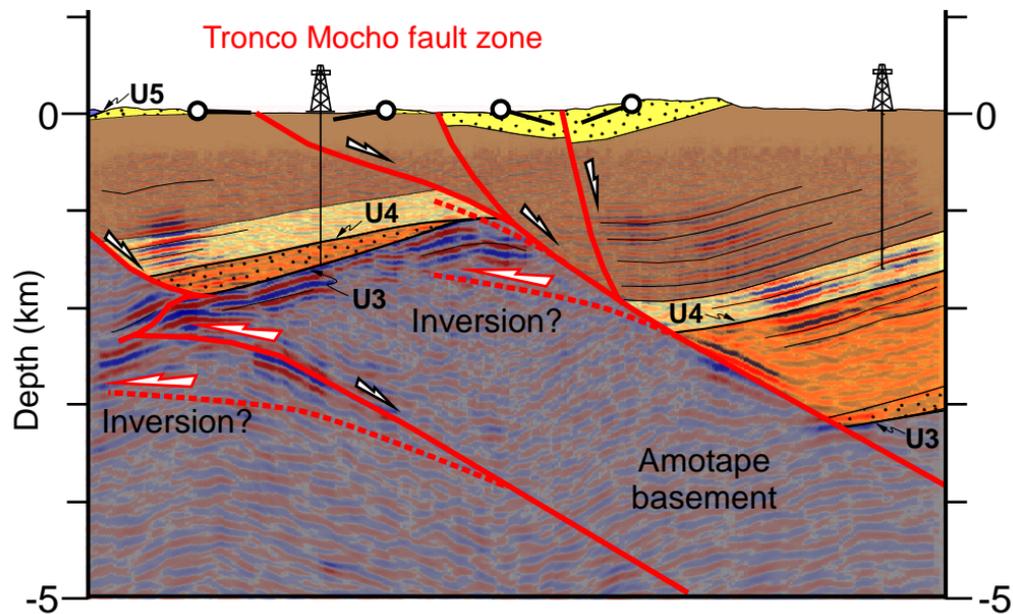
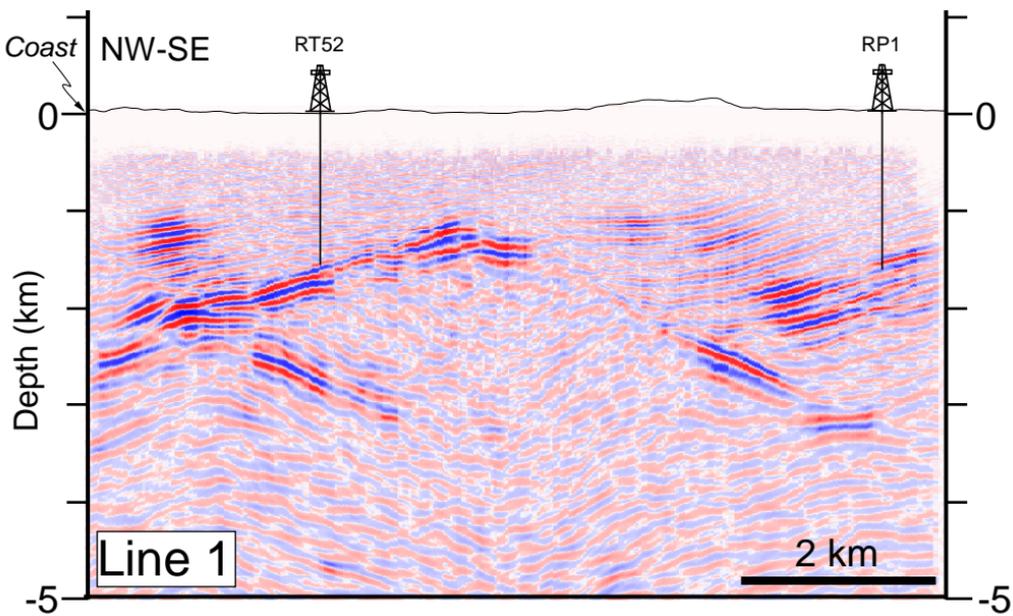


Figure 13.

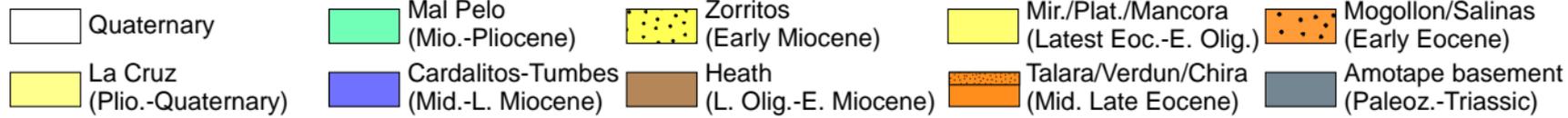
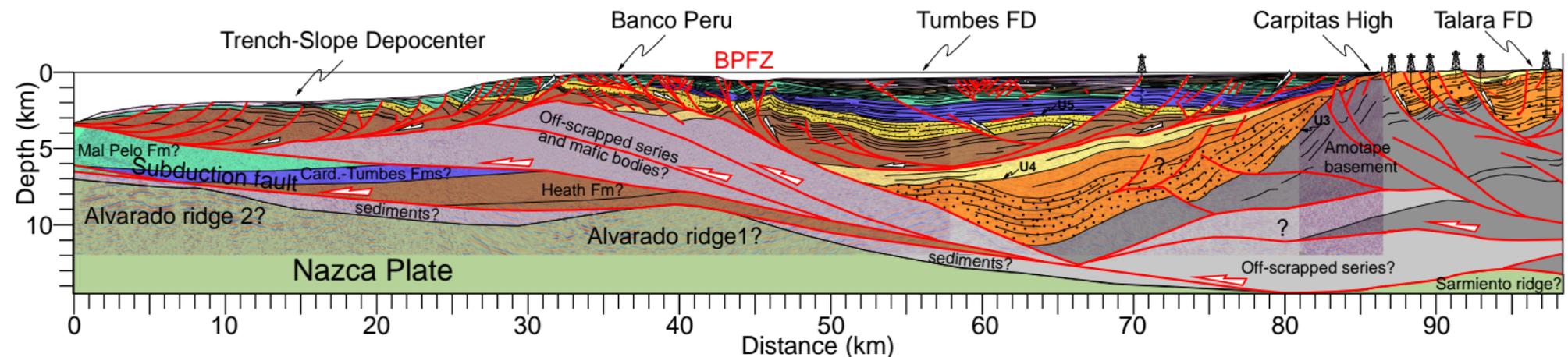
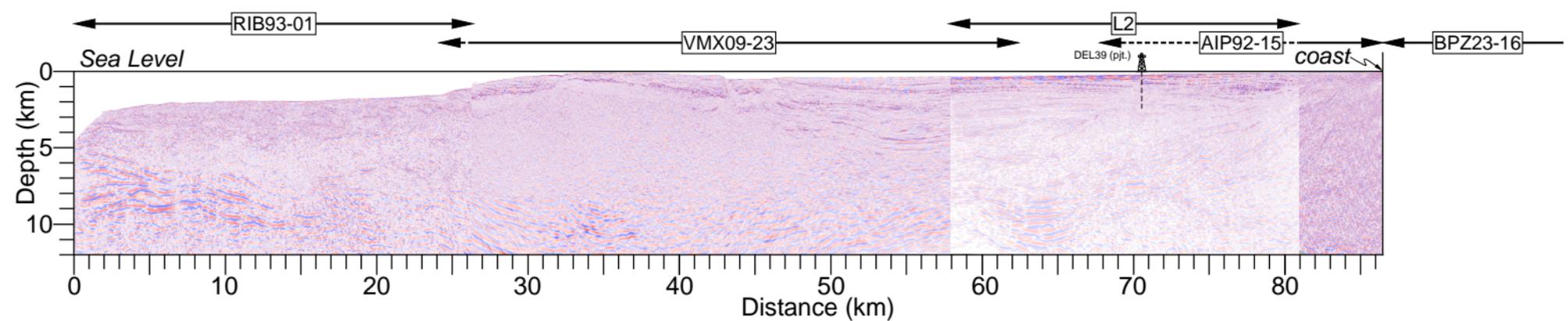
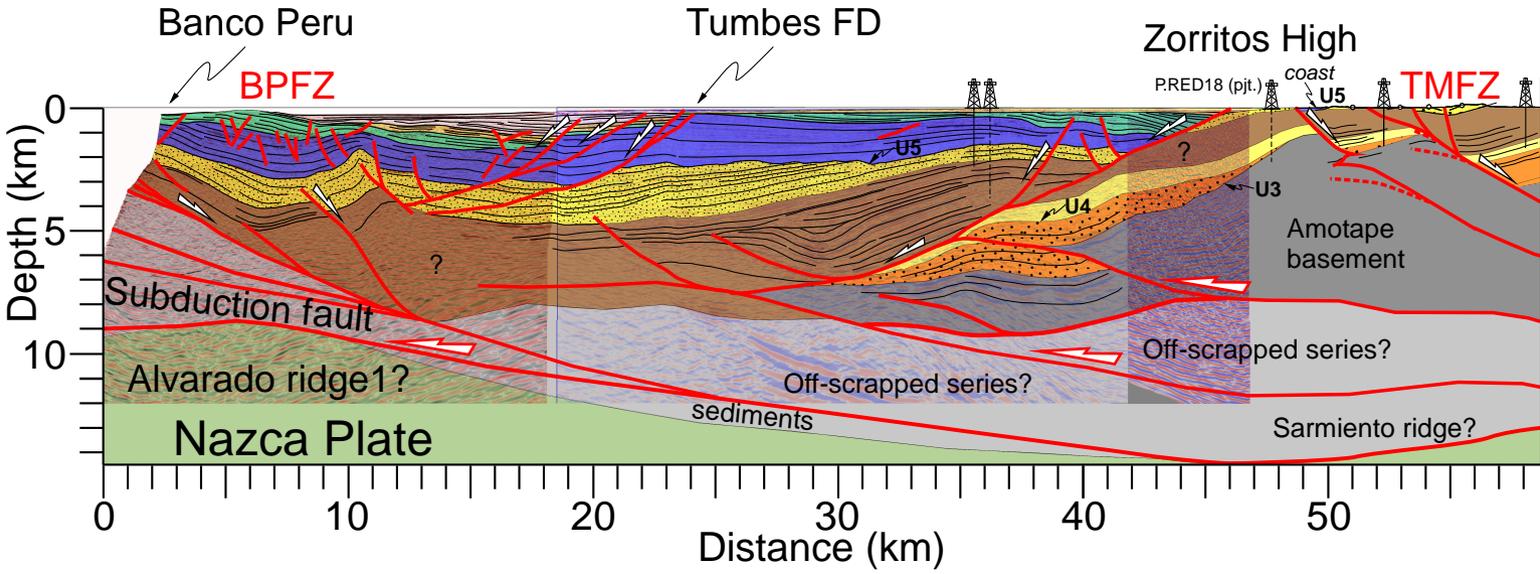
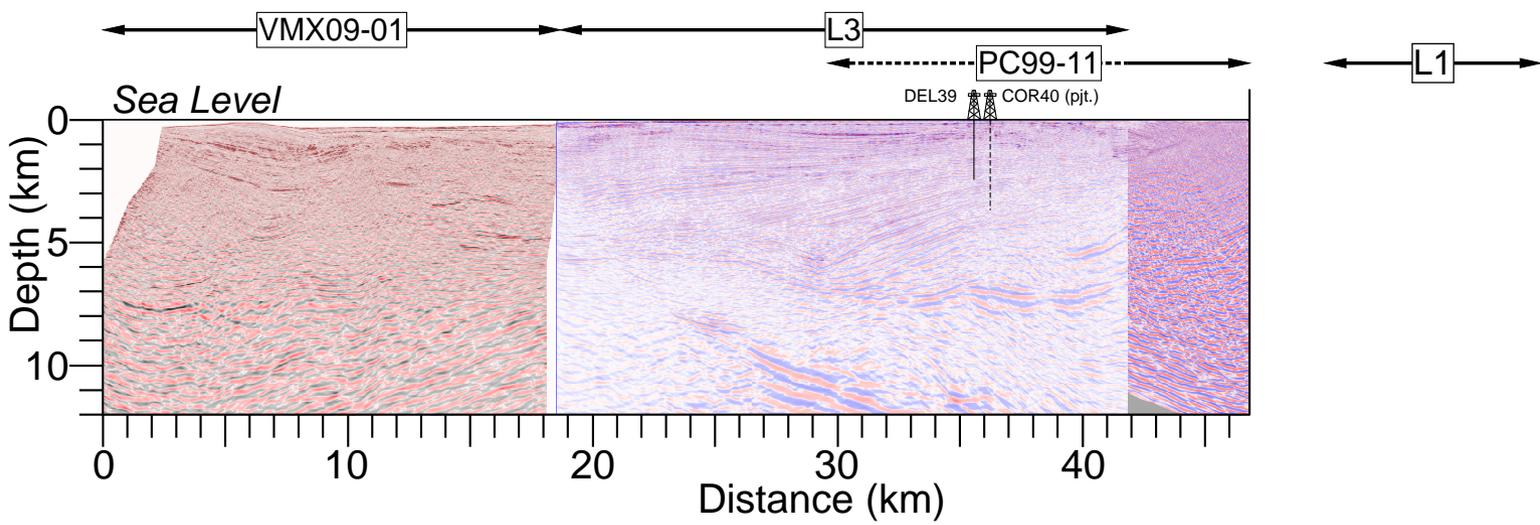


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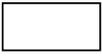
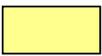
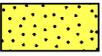
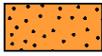
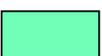
- | | | |
|--|---|---|
|  Quaternary |  Cardalitos-Tumbes (Mid.-Late Miocene) |  Mir./Plat./Mancora (Latest Eoc.-E. Olig.) |
|  La Cruz (Plio.-Quaternary) |  Zorritos (Early Miocene) |  Mogollon/Salinas (Early Eocene) |
|  Mal Pelo (Mio.-Pliocene) |  Heath (L. Olig.-E. Mio.) |  Amotape basement (Paleoz.-Triassic) |

Figure 15.

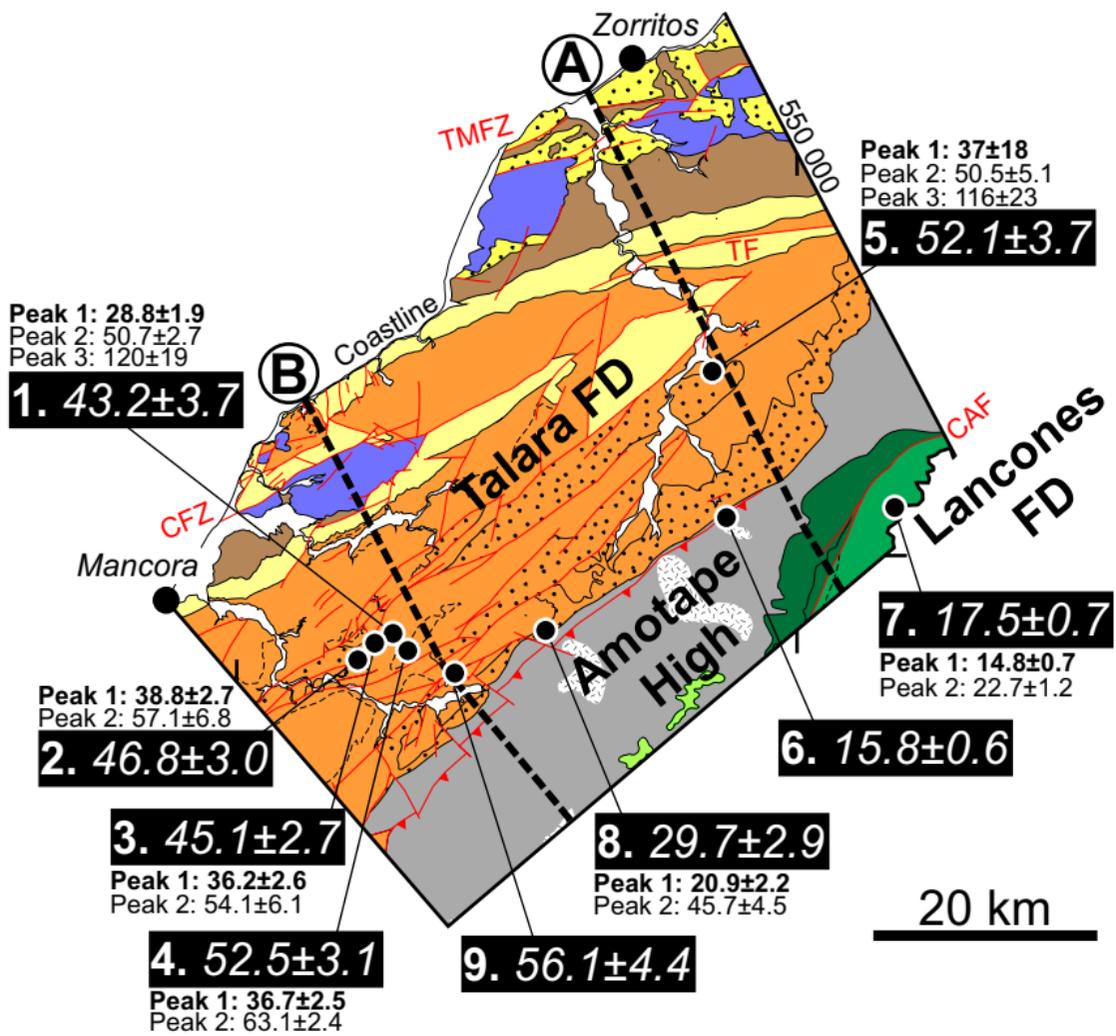


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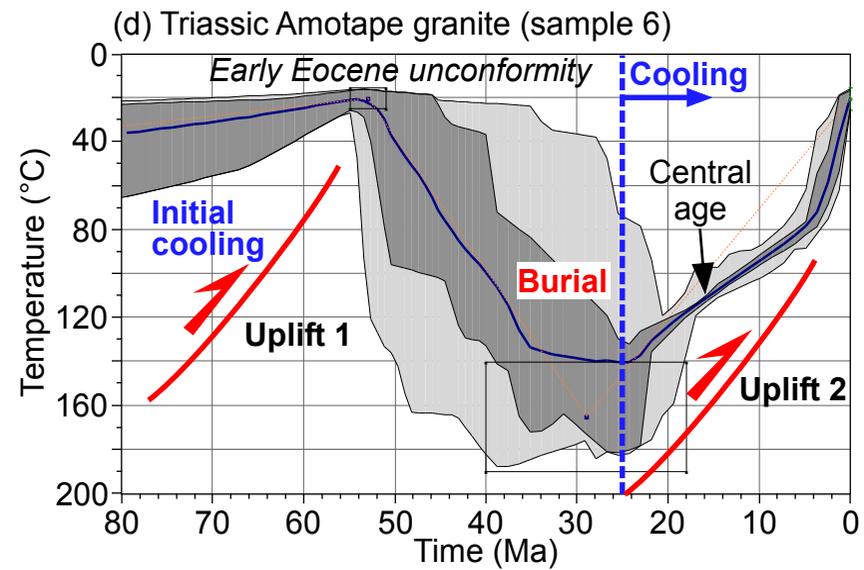
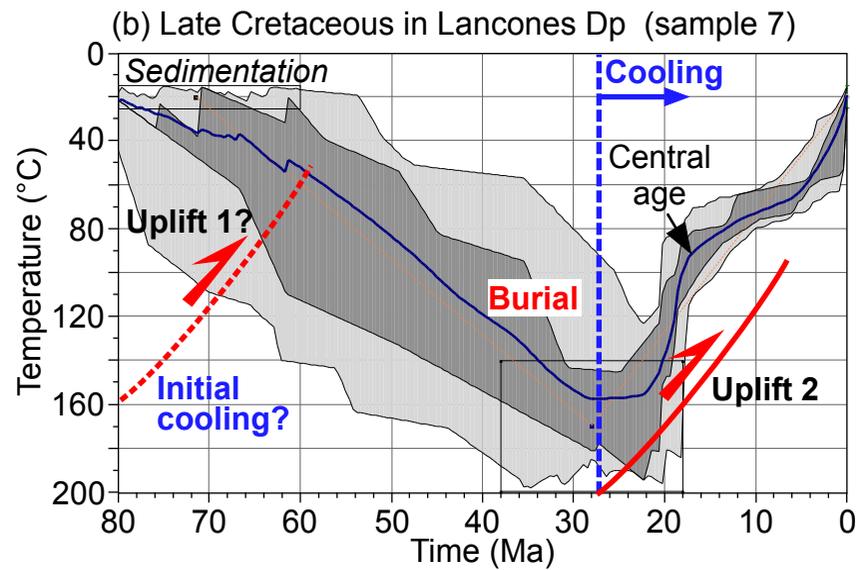
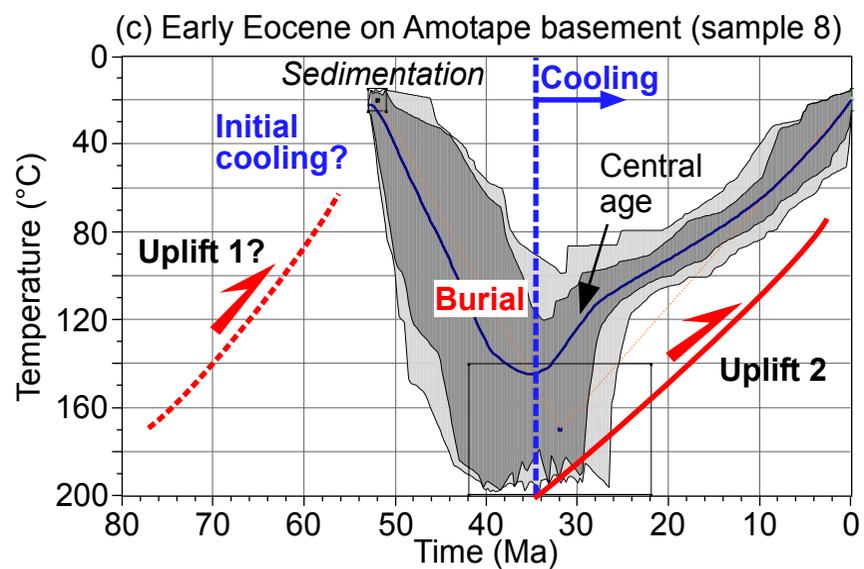
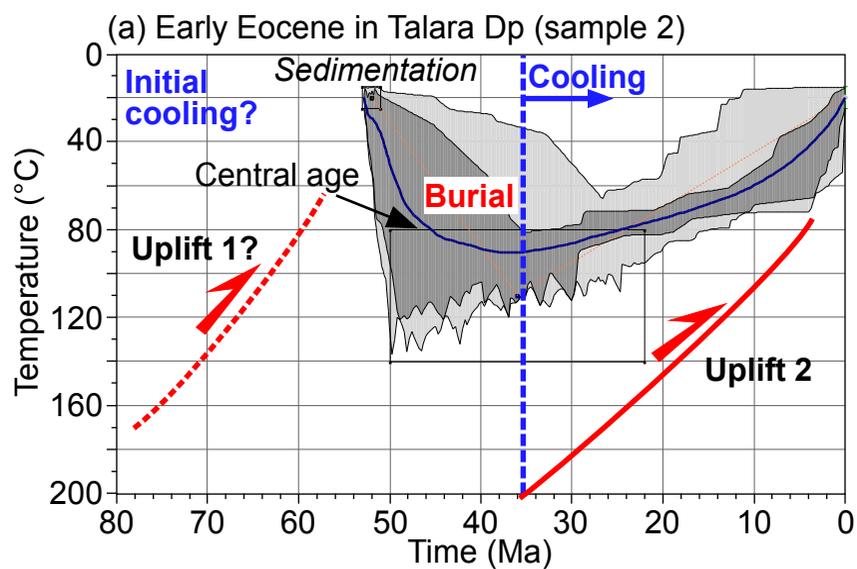


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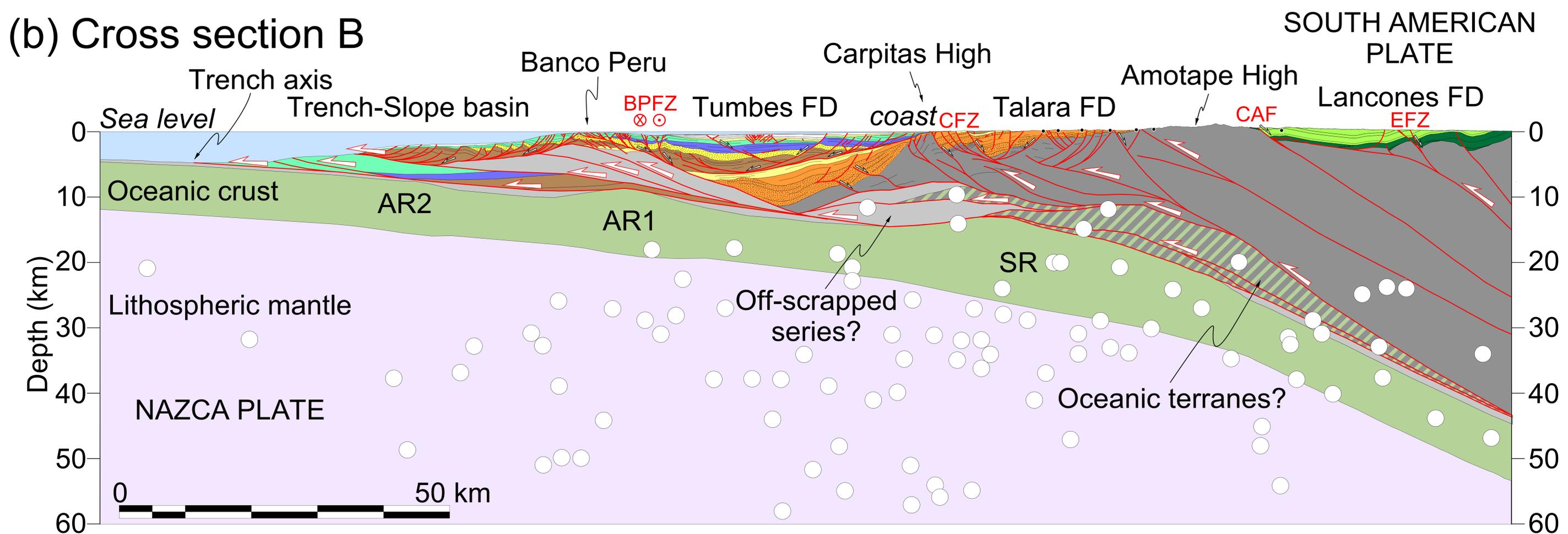
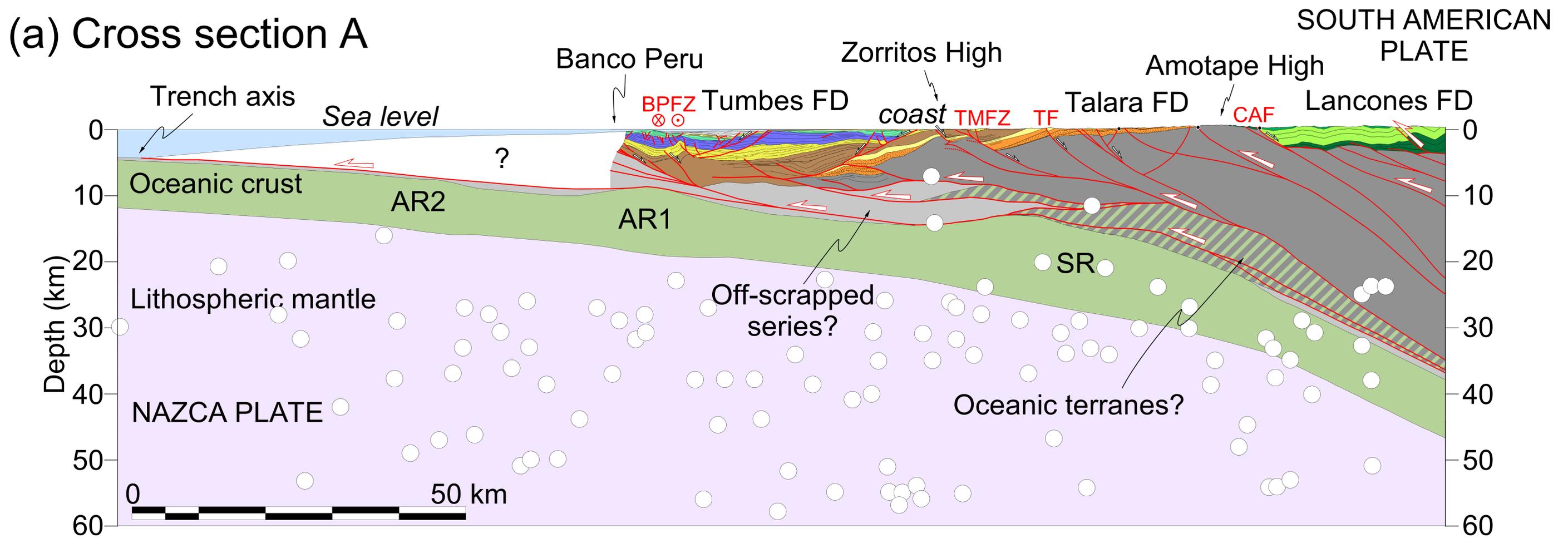


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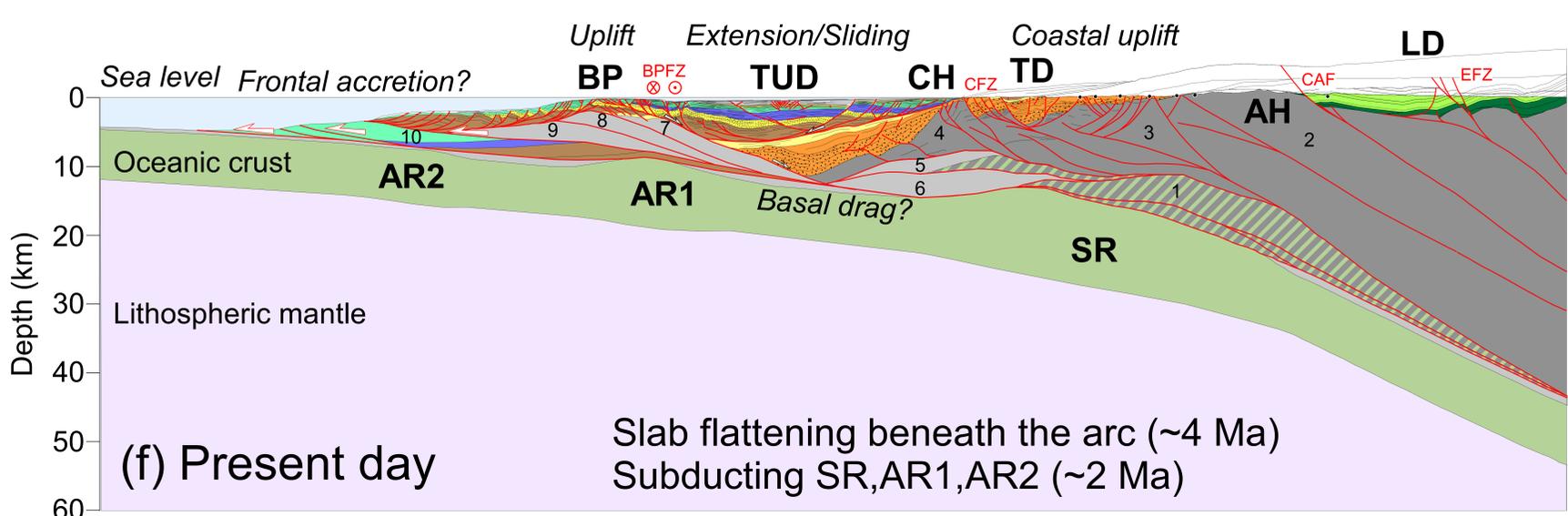
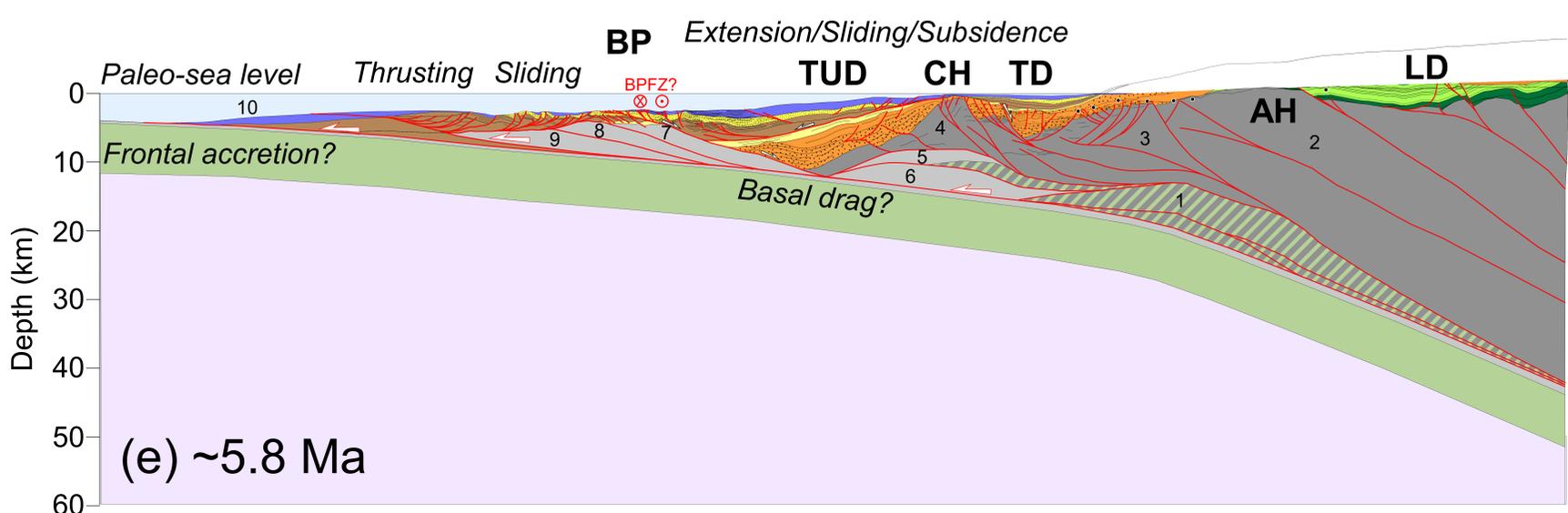
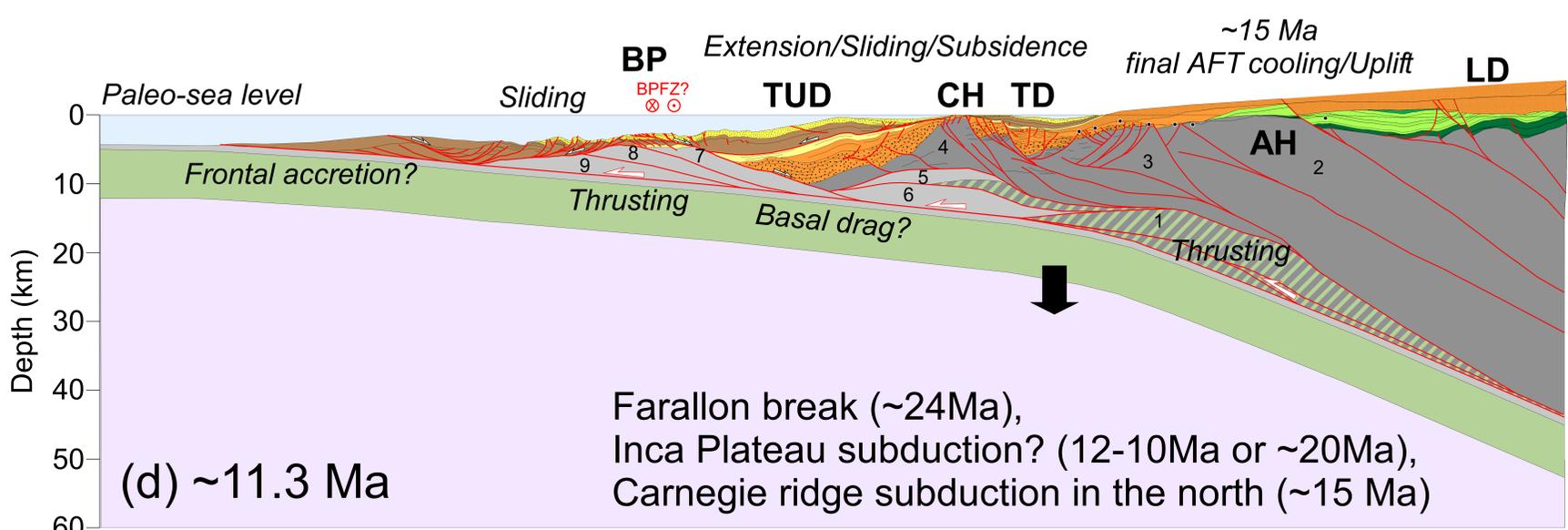
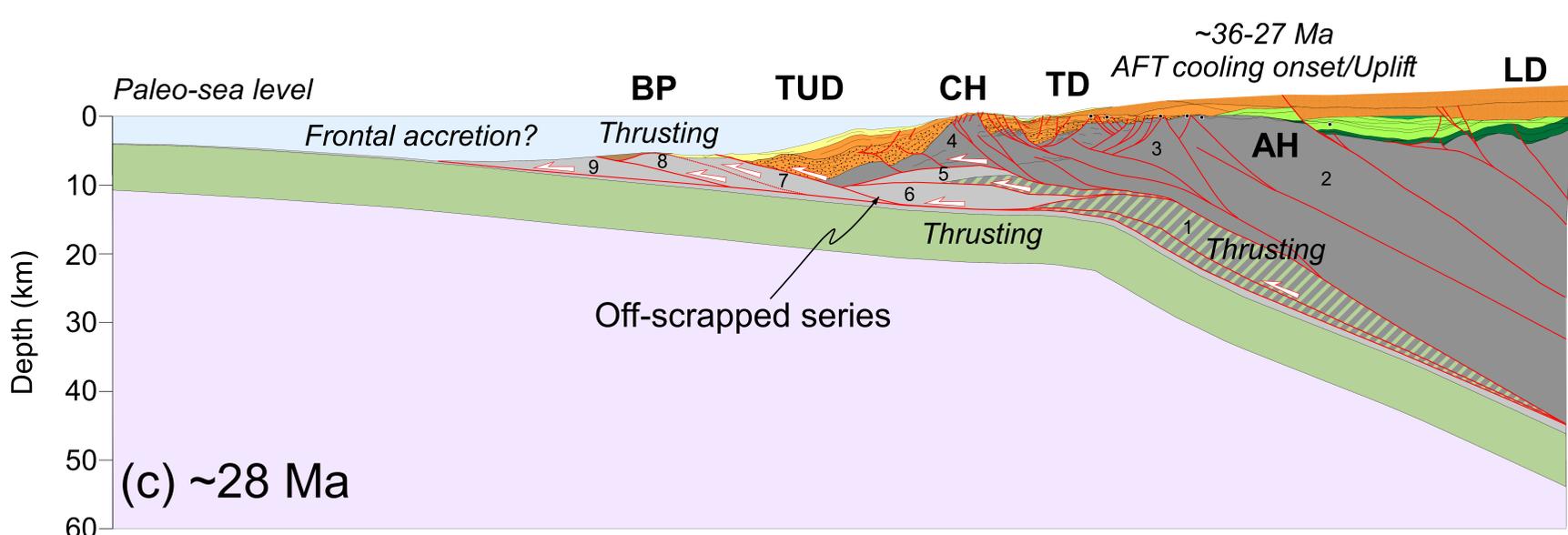
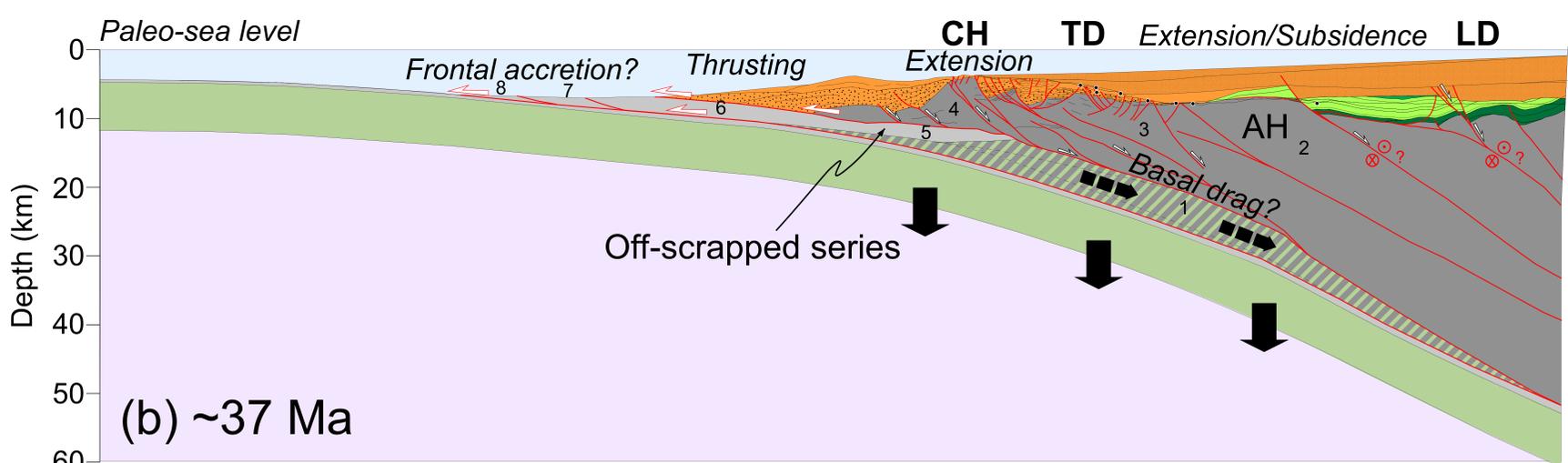
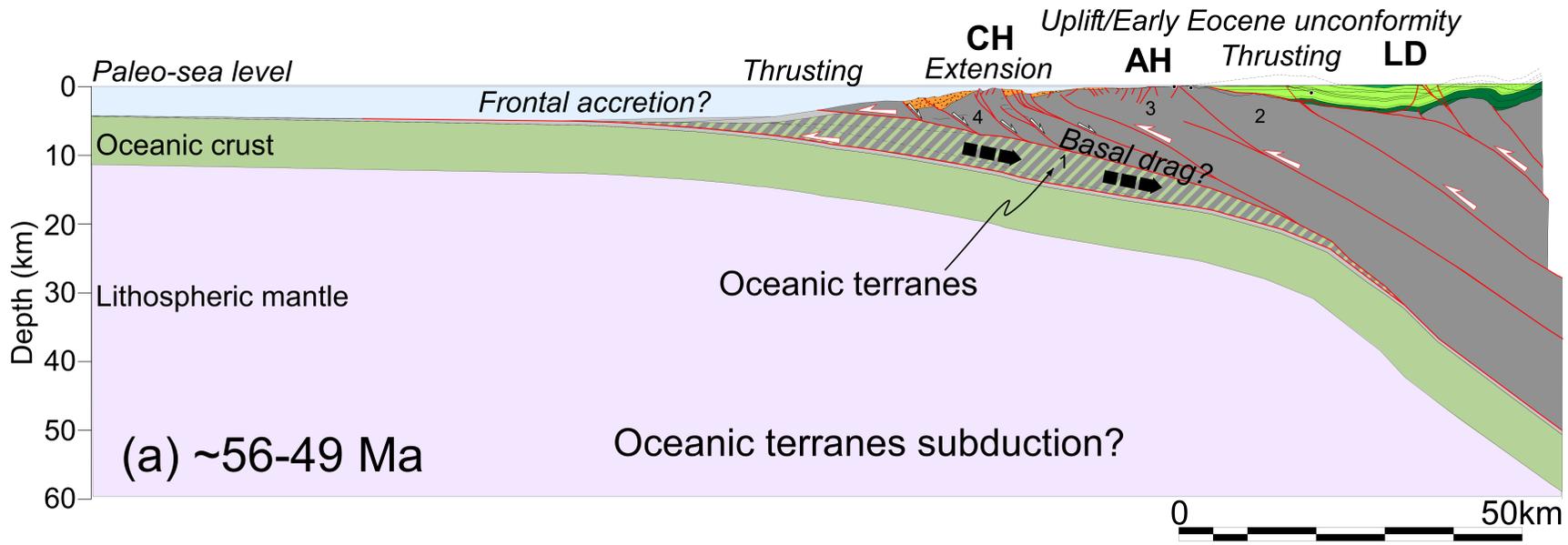


Figure 19.

Talara FD Amotape High Lancones FD

NW-SE

Sea bottom (~2°)

20

60

110

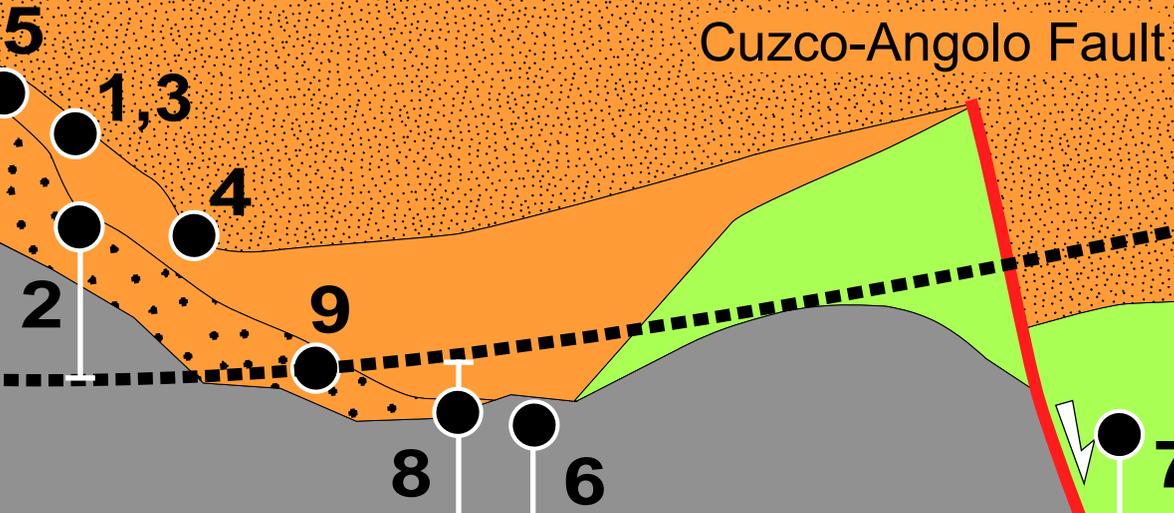
150

190

Temperature (°C)

0
-2
-4
-6
-8

Depth (km)



- Chira-Verdun (Middle-Late Eocene)
- Talara (Middle Eocene)
- Mogollon-Salinas (Early Eocene)
- Cretaceous
- Paleozoic-Triassic Amotape basement

Figure 20.

