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1 **Subsurface structure and stratigraphy of the northwest end of**  
2 **the Turkana Basin, Northern Kenya Rift, as revealed by**  
3 **magnetotellurics and gravity joint inversion**

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17

18 **ABSTRACT**

19 In order to understand the subsurface stratigraphy and structure of the northwest end of  
20 the Turkana Basin, Northern Kenya Rift, we used 2-D joint inversion of magnetotelluric  
21 (MT) and gravity data acquired along 3 profiles perpendicular to the main Murua Rith-  
22 Lapur Rift Border Fault. The regional geology is characterized by a basement of  
23 Precambrian age overlain by a  $\leq 500$ -m thick sandstone formation named the Lapur

24 Sandstone of upper Cretaceous-lower Eocene in age, covered by thick rhyolitic and basaltic  
25 lavas of late Eocene-middle Miocene age, known as the “Turkana Volcanics”. Final  
26 interpretation of the resistivity and density models, until 5 km depth, obtained by the joint  
27 inversion approach confirms the previous general knowledge about the half-graben  
28 geometry of the northern part of the Turkana Basin. The main Murua Rith-Lapur Rift  
29 Border Fault is well identified by both gravity and MT. At least, two other important  
30 secondary faults without surface expression are also identified. A new small half-graben  
31 basin, named the Kachoda Basin, parallel to the main Turkana Basin and filled by 1.5 km  
32 of sediments, has been also characterized. This study also highlights strong thickness  
33 variations of the three main geological units that could be expected in the subsurface of the  
34 Turkana Basin. For example, the sedimentary Nachukui and Kibish Formations reach up to  
35 >3 km in thickness at the eastern end of the north and central profiles. Lateral variations of  
36 the topography of the Precambrian basement are also evidenced. Conceptual geological  
37 models, which result from the combination of the obtained density and resistivity models as  
38 well as from geological and reflection seismic data, are proposed. In such an area of  
39 intensive and promising oil exploration, these models are essential in terms of identification  
40 of reservoirs, source rocks and trapping mechanisms.

41

42 **Keywords:**

43 Northern Kenya Rift, Turkana Basin, Kachoda Basin, Lapur Sandstone, “Turkana  
44 Volcanics”, Sub-basalt imaging, magnetotelluric, gravity, joint inversion.

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50 **1. Introduction**

51 The north-western part of the Kenya territory is characterized by a wide NW-SE  
52 oriented tectonic depression known as the Turkana Depression, located immediately to the  
53 southeast of the oil-rich rift basins of southern Sudan (Fig. 1a). This region has been the  
54 subject of a major interest for possible commercial hydrocarbon potential (Morley, 1999;  
55 Wescott et al., 1999; Tiercelin et al., 2004, 2012b). In the north-western part of the Turkana  
56 Depression near the borders of South Sudan, Uganda and Ethiopia, gravity data acquired in  
57 the 80s by the Amoco Kenya Petroleum Company (AKPC) revealed wide elongate  
58 anomalies suggesting the presence at depth of two deep, N-S oriented sedimentary basins  
59 named the Lotikipi Basin to the west, and the Gatome Basin to the east (Wescott et al.,  
60 1999) (Fig. 1a). Because of insufficient geophysical data and the lack of exploration wells,  
61 the stratigraphy of these basins remained largely unknown. Very little seismic reflection  
62 data was acquired in this area by AKPC (e.g. Wescott et al., 1999) and it showed very low  
63 vertical resolution caused by the presence in the shallow subsurface of a 3.5 km thick pile  
64 of basaltic and rhyolitic lavas of Late Eocene-Middle Miocene age known as the “Turkana  
65 Volcanics” (Bellieni et al., 1981; Zanettin et al., 1983; Morley et al., 1999; Tiercelin et al.,  
66 2012). In the eastern part of the Turkana Depression, Project PROBE (Dunkelman et al.,  
67 1988, 1989) and AKPC (e.g., Morley et al., 1992; Wescott et al., 1999) conducted intensive  
68 land and offshore Lake Turkana reflection seismic campaigns that aimed at understanding

69 the subsurface geology in areas with poor surface outcrop conditions. Interpretation of  
70 these data allowed for the determination of the deep structure and sedimentary infill of  
71 several N-S-trending half-grabens ranging in age from Paleogene to Plio-Pleistocene,  
72 known as the Lokichar (North and South), North Kerio, and Turkana Basins, respectively  
73 (Morley et al., 1999; Tiercelin et al., 2004; Talbot et al., 2004) (Fig. 1a). The Lokichar and  
74 Turkana Basins have been tested during the 90s by two deep exploration wells, operated by  
75 Shell Exploration and Production Kenya B.V.: the Loperot-1 well drilled in the Lokichar  
76 Basin, and the Eliye Springs-1 well drilled in the Turkana Basin (Fig. 1a). These two wells  
77 confirmed the existence of thick alternating packages of fluvial, fluvio-deltaic and  
78 lacustrine sediments, of Eocene-Middle Miocene age for the Lokichar Basin, and Plio-  
79 Pleistocene age for the Turkana Basin (Morley et al., 1992, 1999). The Loperot-1 well  
80 demonstrated the presence of thick, organic-rich shales and oil shows in sandstone units  
81 (Wescott et al., 1999). In the last 5 years, more than ten exploration wells have been drilled  
82 by a group of oil companies (Tullow Oil and Africa Oil Corp.) in the South Lokichar Basin.  
83 All these wells revealed the presence of a large number of net oil pays in two main high  
84 quality reservoir horizons, known as the Lokone Sandstone and the Auwerwer Sandstone  
85 (Africa Oil Corporation, 2011, 2014) (Fig. 1a).

86 In this work, we present the results of an MT and gravity joint inversion survey  
87 devoted to understand the stratigraphy and structure of subsurface terrains of the northwest  
88 end of the Turkana Basin, a sensitive area where outcrop data are limited and where seismic  
89 studies are either absent or encountered a sub-basalt imaging problem and are therefore  
90 unable to bring accurate subsurface information (Fig. 1a and b).

91

92

**Figure 1**

93

95 The roughly N-S-oriented Turkana Basin occupies the central-eastern part of the  
96 Turkana Depression between latitudes 4° and 4.5° N, and hosts the present-day Lake  
97 Turkana, which is the largest water body of the Eastern Branch of the East African  
98 Rift System (Fig. 1a and c). The Turkana Basin started to form around Middle  
99 Miocene (15-10 Ma) (Dunkelman et al., 1988, 1989; Morley et al., 1992; Dunkley et  
100 al., 1993; Morley et al., 1999). The northern half of the basin reveals a typical east-  
101 facing half-graben structure bounded by a set of N-S oriented normal faults  
102 morphologically marked by the main Murua Rith-Lapur (MRL) Border Fault  
103 escarpment (Fig. 2a). Geologically, the MRL Border Fault footwall and hanging wall  
104 displays a simple stratigraphic succession with, unconformable overlying a  
105 Precambrian basement mainly formed by migmatites and amphibolites (Walsh and  
106 Dodson, 1969) (Figs. 2a-c and 3a), an up to 500-m thick accumulation of  
107 conglomerates, sandstones, siltstones and mudstones named the Lapur Sandstone  
108 (Figs. 2a and b and 3a and b), thinning and disappearing toward the north at about  
109 4.45° N and toward the south at Keniroliom (04° 11'10" N, 35° 49' 41" E) (Thuo,  
110 2009; Tiercelin et al., 2012) (Fig. 1d). Overlying the Lapur Sandstone are the  
111 "Turkana Volcanics" that widely outcrop to the west, in the Gatome and Lotikipi  
112 regions, where they reach a maximum thickness of 3.5 km (Bellieni et al., 1981;  
113 Zanettin et al., 1983; Tiercelin et al., 2012a) (Figs. 1a, 2 and 3c). To the immediate  
114 west of the MRL escarpment is a small roughly N-S oriented, ~15 km wide, flat-  
115 bottomed valley bounded on both sides by basalts and rhyolites belonging to the  
116 "Turkana Volcanics", forming the eastern faulted flank of the Gatome Basin. This  
117 valley, known as the Kachoda Valley, opens towards the north into the Sanderson's

118 Gulf and the Todenyang Plain to the immediate west of the Omo River delta (Fig. 1c  
119 and d). Alluvial-type sediments of unknown age and thickness characterize the surface  
120 of this valley.

121

122 **Figures 2, 3 and 4**

123

124 To the east of the MRL Border Fault, the subsurface stratigraphy of the MRL  
125 hanging wall can be deduced from the interpretation of one W-E oriented, onshore  
126 reflection seismic line (TVK-10) acquired by AKPC in 1985 at 4.13°N, between the  
127 MRL escarpment and the Lake Turkana shoreline (Figs. 1d and 2c). Wescott and co-  
128 workers interpret this seismic line as showing a thick (up to 2 sec TWTT) pile of Late  
129 Miocene-Pliocene sedimentary rocks, conformably overlying the top of Middle  
130 Miocene volcanics belonging to the “Turkana Volcanics” unit (Wescott et al., 1999;  
131 Fig. 2). A recent interpretation of this TVK-10 seismic line (Tiercelin et al., 2012a)  
132 (Fig. 4) suggests the presence in the hanging wall of the MRL Border Fault, below the  
133 “Turkana Volcanics”, of a 300-m thick sedimentary package that could be interpreted  
134 as the Lapur Sandstone. The “Turkana Volcanics” are in turn overlain by thick (1.5  
135 sec TWTT) sediments forming the uppermost part of the infill of the Turkana Basin.  
136 Only the upper sedimentary deposits that characterize the hanging wall of the MRL  
137 Border Fault are known at the outcrop level. These deposits correspond to a  
138 southwest-dipping pile of fluvio-lacustrine sediments of Plio-Pleistocene age (dated  
139 between 4.2 and 0.7 Ma) known as the Nachukui Formation (Feibel et al., 1989) (Fig.  
140 3d). This ~740-m thick sediment accumulation is overlain at the northern end of the  
141 Turkana Basin by upper Pleistocene to Holocene sediments of fluvio-deltaic type, that  
142 possibly belong to the 100-m thick Kibish Formation, dated at about 0.2 Ma at its base



143 and outcropping largely at about  $5^{\circ} 25' N$  along the Omo River, nearby the Nkalabong  
144 Range (Brown and McDougall, 2011) (Fig. 1c). Offshore seismic reflection data  
145 obtained by the PROBE Project indicated for the Turkana Basin a 4-km thick  
146 sedimentary infill immediately overlying the thick pile of the “Turkana Volcanics”  
147 (Dunkelman et al., 1988, 1989). Near the southern end of the Turkana Basin, the Eliye  
148 Springs-1 exploration well penetrated 2964 m of fluvio-lacustrine sands and shales  
149 similar to surface outcrops lying to the north and possibly belonging to the Nachukui  
150 Formation (Fig. 1c).

151

### 152 **3. Magnetotelluric and gravity surveys**

153 The study area is mainly located on the western faulted side of the northern part of the  
154 Turkana Basin, between latitudes  $4.1305^{\circ}$  and  $4.4001^{\circ}$  N and longitudes  $35.5890^{\circ}$  and  
155  $35.9280^{\circ}$  E in WGS84 system (Fig. 1). Magnetotelluric and gravity data as well as  
156 complementary field observations were acquired during one field campaign conducted in  
157 August 2006 in cooperation with teams from two Kenyan companies, the Kenya Electricity  
158 Generating Company (KenGen) and the National Oil Corporation of Kenya (NOCK). We  
159 carried out a total of 27 magnetotelluric soundings along three W-E oriented profiles,  
160 almost perpendicular to the main N-S geological strike direction illustrated by the MRL  
161 Border Fault (Fig. 1b). The southern profile (P1) was superimposed on the trace of the W-E  
162 oriented TVK-10 seismic reflection line whose track was still clearly visible in the field  
163 (Fig. 1b and d and 2). The median profile (P2) followed the car track coming from the  
164 western shoreline of Lake Turkana through the Lowarengak village then the Lokitaung  
165 Gorge, crossing the MRL escarpment up to the township of Lokitaung (Fig. 1b and d and  
166 2). This profile extended 15 km further to the west, following a track running almost E-W,  
167 crossing through the Kachoda Valley (Fig. 1b and d and 2). To the north, the field survey

168 was limited at latitude  $4.40^{\circ}$  N because of the bad security conditions nearby the Sudan and  
169 Ethiopia borders. The northern profile (P3) extended toward the east in the area of the  
170 Lapur Peak, from the trace of the MRL Border Fault up to the shoreline of Lake Turkana  
171 (Figs. 1a, d and 2).

172 The MT sites were spaced at an average distance of about 1.5 km, with the exception of  
173 two stations on the median profile (between station 22 and station 23, and between station  
174 24 and station 10 situated in the narrow and deep Lokitaung Gorge (Fig. 1b). Here, the  
175 distance between the two stations was much larger as it was not always easy to find a  
176 suitable place to record the electrical component. Data were acquired using a Phoenix  
177 system provided by KenGen (Fig. 5c-e). The electric and magnetic fields were recorded in  
178 N-S and E-W perpendicular directions.

179 The gravity measurements were made using a Lacoste-Romberg gravimeter also  
180 provided by KenGen (Fig. 5a and b). Gravity was measured at 243 points along the three  
181 MT profiles (Fig. 1b). The measurement points were spaced at an average distance of 250  
182 m, with the exception of the Lokitaung Gorge where this distance was larger as a  
183 consequence of the morphology of the gorge. Nevertheless, its spatial resolution remained  
184 greater than the MT sites. The quality of both MT and gravity data was relatively good and  
185 the MT data showed little noise (see Fig. 6).

186  
187

#### Figures 5 and 6

### 188 4. Geophysical data processing

#### 189 4.1 MT processing

190 The magnetic and electric time series were processed robustly with the algorithm of  
191 Chave and Thomson (2004), covering the period range 0.02–450 s. Because of difficult  
192 field conditions and no remote reference (Goubau et al., 1978), data were carefully edited

193 and only time series of good quality were processed, reducing the number of robust  
194 estimates and increasing some of the error bars (Fig. 6). Overall, MT transfer functions are  
195 of fair to good quality. The complex conjugate directions of the tensor were computed  
196 (Counil et al., 1986) to study the dimensionality of the data. Both electric and magnetic  
197 directions are similar, an indication of a weak effect of local 3-D heterogeneities. Electric  
198 directions for all sites are shown in Fig. 7 at two periods. In general, they indicate a rough  
199 N-S strike direction for the transverse electric TE mode (e.g., Parker, 2011) on the central  
200 profile, although directions may vary locally, particularly within the Lokitaung Gorge.  
201 These directions indicate therefore only approximately a true 2-D strike. Nevertheless, the  
202 3-D modelling of the three profiles confirmed that a local 2-D approach is suitable for most  
203 of the sites for the first kilometres in the crust (Abdelfettah, 2009), with a main strike  
204 direction in agreement with the geological trend. The central profile has 2 stations (23 and  
205 24) within the Lokitaung Gorge (Fig. 1b and d), 5 stations on the western side of the  
206 Turkana Basin (from west to east: 10, 11, 25, 26 and 27), and 5 stations in the Kachoda  
207 Valley (from west to east: 18, 19, 20, 21 and 22). Two stations, 22 and 23, show moderate  
208 static shift (Groom et al., 1989; McNiece and Jones, 2001) in the transverse magnetic, TM  
209 mode in relation with the topography that was accounted for in the 2D modelling. The other  
210 profiles are located on the western side only of the Turkana Basin, from the trace of the  
211 MRL Border Fault to the west up to the Lake Turkana shoreline to the east. Because of the  
212 high conductivity ( $1 \Omega.m$ ) of the sedimentary infill of the Turkana Basin, no significant  
213 topography effect was observed in the other stations of the three profiles. Details of the MT  
214 study and modelling can be found in Abdelfettah (2009).

215

216

**Figures 7**

217 **4.2. Gravity processing**

218 The first correction performed on the acquired gravity data is the instrumental drift.

219 The second correction is the terrestrial tide, which is of small amplitude but was considered  
220 in order to make a complete data processing sequence. After these two corrections, the free  
221 air reduction was applied on the data to obtain the free air anomaly (Fig. 8), which is the  
222 final anomaly used for the inversion. Rather than calculating the complete Bouguer  
223 anomaly, we use the free air anomaly and included the topography (Fig. 1b) correction  
224 (plateau and terrain corrections) directly in the modelling process. The latter consists of  
225 reproducing the topography of the area and, calculating its gravity effect at the  
226 measurement sites using a digital terrain model (DTM) of the studied area (SRTM3, 2003).  
227 The average density of the topography terrains was estimated based on data from the  
228 literature (2,450 kg.m<sup>-3</sup>), and adjusted such that the Bouguer anomaly was de-correlated  
229 from the topography. The density value taken into account in the calculation of the gravity  
230 effect of the terrains is 2,450 kg.m<sup>-3</sup>. The gravity effect of Lake Turkana (water density  
231 1,000 kg.m<sup>-3</sup>) was also taken into account in the forward modelling.

232

233 **Figure 8**

234

## 235 **5. Joint inversion formulation**

### 236 *5.1. MT and gravity inversion method*

237 The forward solution for MT is obtained with a 2-D finite difference algorithm  
238 (Tarits, 1989). The objective function  $F(\mathbf{r})$  of MT combines the MT misfit and a  
239 regularisation term:

$$240 \quad \mathbf{F}(\mathbf{r}) = \sum_{i=1}^{nst} \sum_{j=1}^{np} \left\{ \left| \frac{Z_{ij}^{O TE} - Z_{ij}^C(r)^{TE}}{\sigma_{ij}^{TE}} \right|^2 + \left| \frac{Z_{ij}^{O TM} - Z_{ij}^C(r)^{TM}}{\sigma_{ij}^{TM}} \right|^2 \right\} + \lambda_r S_r^2 \quad (1)$$

241 where  $Z$  is the 2-D MT impedance. The indices O and C are respectively the observed

242 and calculated impedances for both transverse electric (TE) mode (the horizontal  
 243 electric field parallel to the strike) and transverse magnetic (TM) mode (the horizontal  
 244 magnetic field parallel to the strike) (e.g. Simpson et Bahr, 2005). The values  $nst$  and  
 245  $np$  are the number of sites and the number of periods respectively. The term  $\sigma$  is the  
 246 standard deviation for each mode. The smoothness function  $S_r$  is defined by

$$247 \quad S_r = \sum_{i=1}^{N-1} \sum_{j=i+1}^N (r_i - r_j)^2 \quad (2)$$

248 where  $N$  is the number of parameters,  $r$  the log-resistivity, and  $\lambda_r$  is a damping  
 249 coefficient. The 2-D model is bounded on both sides by one-dimensional (1-D)  
 250 structures. The layered 1-D earth model is extended about 3-4 skin depth for the  
 251 highest resistivity in both right and left sides to avoid the effect of our 2-D structures  
 252 (e.g. Doucet et Pham, 1984).

253 The gravity model response is calculated at the earth surface from the gravity  
 254 attraction generated by all rectangular prisms (e.g., Blakely, 1995). The objective  
 255 function  $F_G(d)$  for the gravity data is defined by

$$256 \quad F_G(d) = \sum_{i=1}^{N_g} \left( \frac{g_i^o - g_i^c(d)}{\sigma_{g_i}} \right)^2 + \lambda_r S_d^2 \quad (3)$$

257 where  $N_g$  is the number of data points,  $\sigma_g$  is the standard deviation of measured gravity  
 258 data.  $g^o$  and  $g^c$  are the observed and the computed gravity anomalies, respectively.  
 259 The gravity smoothness function  $S_d$  is computed using Eq. 2 where the parameter  $r$  is  
 260 now the density contrast.

261

## 262 5.2. Joint inversion formulation

263 Let a couple of model parameters  $r$  and  $d$ . We define a multiple objective function  
 264  $Q(r,d)$  of the form

266 The function  $\psi$  is a condition function (CF) coupling the parameter  $r$  and  $d$ . The CF  
267 may be included in the inversion as a deterministic relationship between parameters  
268 (e.g., Tiberi et al., 2003) or a geometrical constraint (e.g., Gallardo et Meju, 2007).  
269 Here we investigate a solution based on a CF combining geometrical constraint and a  
270 relationship between the parameters  $r$  and  $d$ . We named this CF a geometrical  
271 condition function (GCF). We use the GCF to build the starting model  $d_0 = \psi(r_0)$  from a  
272 model  $r_0$  obtained independently. This GCF assigns  $d_0$  values according to a given rule  
273 in regions or domains defined by the geometrical features extracted from the model  $r_0$ .  
274 Once the inversion started, the parameters are free to vary within the fixed domains  
275 and no longer guided by that rule.

### 276 **Figure 9**

277  
278 First we obtain a preliminary resistivity model (PRM)  $r_0$ . This was achieved with the  
279 minimisation of (Eq. 1). The geometrical features in model  $r_0$ , named domains,  
280 correspond to regions in the PRM where the resistivity values vary by less than one  
281 order of magnitude and to the regions delimited by strong resistivity contrasts. The  
282 density model  $d_0$  was set constant in these domains and defined according to low  
283 (high) resistivity correspond to low (high) density. The extreme values of low and high  
284 density are defined from geological knowledge or previous studies in the same area  
285 and from the surrounding, for instance  $2,750 \text{ kg.m}^{-3}$  for a Precambrian basement and  
286  $2,000 \text{ kg.m}^{-3}$  for Nachukui Formation. Then, the intermediate density values are  
287 obtained by linear relationship between density and  $\log_{10}$  resistivity values. With this  
288 starting density model, the gravity data were introduced in the inversion algorithm and

290 The minimisation routine used to achieve this work is based on a steepest descent  
291 technique derived from Beiner (1970) (see also Fischer and Lequang, 1981) and based  
292 on downhill simplex method (e.g., Press et al., 1992) and therefore may only find a  
293 relative minimum of the objective function. The derivatives of the function are not  
294 calculated, hence the function itself is called and all differences in the parameters  
295 space are stored until the descent is found. The algorithm calls once the forward MT  
296 and gravity solutions each iteration.

297 We run the first stage of the inversion (stage 1). During the minimisation of  $Q(r, d)$ ,  
298 density values were free to change but the PRM domains defined above are still  
299 enforced, that is the density remains constant within the domains. Once a relative  
300 minimum for  $Q$  is found, the conditions on the density model are changed. The density  
301 values could vary within a domain where it was previously constant and a second  
302 minimization (stage 2) is carried out.

303

304 In practice, in our MT and gravity formulation, we adopt a common inversion grid  
305 based on 2-D prisms to run the joint inversion (Fig. 9). The MT inversion grid is  
306 defined on the basis of the data distribution and the frequency range (e.g., Fig. 9). The  
307 gravity inversion grid is mapped on the MT inversion grid. Hence there is the same  
308 number  $N$  of density cells and resistivity cells (Fig. 9). Aforementioned, we run the  
309 joint inversion in two steps. First, the density values were grouped into large  
310 homogeneous domains (piece-wise) defined by the PRM so that the number of density  
311 values sought is a small number ( $< 20$  parameters) compared to  $N$ . The density values  
312 in this initial density model are determined by the GCF. Stage (1) constrains the  
313 gravity inversion with a fixed geometry obtained from the preliminary MT inversion.

314 In stage (2) we relax the constraint of fixed large domains of homogeneous density.

315 We let the density value to evolve in all cells within the domains so the number of

316 density values (N) required becomes equal to the number of resistivity values (N).

317 This last step is important to check whether the density model obtained at stage 1 is

318 robust, and to improve the final gravity and MT fits.

319

## 320 **6. Density and resistivity models**

321 Abdelfettah (2009) has tested the MT inversion and the MT-gravity joint inversion

322 techniques on synthetic models and on real data. For the Turkana Basin study (Abdelfettah

323 2009), resistivity and density models obtained from the joint inversion for the three profiles

324 are represented in Figs. 10, 11, 12 and 13 down to a depth of 5 km.

325 The resistivity models are characterized mainly by three major units (Figs. 10a, 11a, 12a

326 and 13a).

327 - A shallow conductive unit with resistivity values, less than 10  $\Omega$ .m;

328 - Resistive units with resistivity values higher than 100  $\Omega$ .m;

329 - Between these two units, a third unit with intermediate resistivity values between 10 and

330 100  $\Omega$ .m (Figs. 10a, 11a, 12a and 13a).

331

332

### **Figures 10, 11, 12, 13**

333

334 The density models obtained in this study (Figs. 10b, 11b, 12b and 13b) show that the

335 central and southern profiles have similar characteristics (with Figs. 11a, 12a and 13a). In

336 contrast, the northern profile (Fig. 10b) shows some differences in terms of thickness of the

337 observed geological units compared to the southern profiles, especially in the eastern part

338 near Lake Turkana shoreline. These differences may be partly attributed to the presence of

339 a local three-dimensional heterogeneity located at depth between this profile and the central



340 profile as revealed by a complementary 3D MT inversion (Abdelfettah, 2009; Fig. 4.10).

341 The central and southern profiles show a good correlation between the variation of  
342 resistivity and density values. Usually, a lower density corresponds to a conductive unit  
343 while a higher density corresponds to a resistive unit. The resistivity values and particularly  
344 high-density contrasts highlight the complex structures of the Turkana Basin and the  
345 Kachoda Valley, respectively.

346

## 347 **7. Subsurface structure of the Turkana Basin**

### 348 *7.1. Northern profile (P3)*

349 The resistivity model obtained for the northern profile (Fig. 10a) shows an upper limit  
350 (L1) between a very conductive geological unit ( $<10 \Omega.m$ ) and a more resistive zone where  
351 resistivity values vary between 10 and 50  $\Omega.m$ . This limit is located at a depth of 1.4-1.5  
352 km on the western part of the profile, under station 13 near the trace of the MRL Border  
353 Fault. This layer may be interpreted as the base of the known sedimentary unit the  
354 Nachukui Formation and its upper Pleistocene-Holocene coverage (Kibish Formation)  
355 (McDougall et al., 2005). This result may confirm the presence in this northern part of the  
356 Turkana Basin of a more significant sediment thickness than the one observed further south  
357 (740 m for the Nachukui Formation). However the L1 limit is not well defined in the  
358 density model which shows significant lateral variations seemingly controlled by faults.

359 We seem to observe the signature of faults in both the density and resistivity models. The  
360 major MRL Border Fault to the west end has a surface expression and is clearly expressed  
361 in the density model (Fig 10b). Two secondary faults: the FON Fault at the east of the  
362 profile between sites 13 and 14, and the F3N Fault between sites 16 and 17 seem identified  
363 in the resistivity model but are less clearly in the density model. The structures in the  
364 middle part of the profile in the density model could be interpreted as the signature of

366 The traces of these two last faults are not so clearly imaged in the resistivity model but  
367 seem constrained by the density distribution. The F0N and F3N faults as well as the F1N  
368 and F2N faults have no surface expression.

369 Towards the east, the limit (L1) appears at a shallow depth, 1.2-1.3 km under site 15,  
370 and reaches ~1 km depth midway between sites 16 and 17, at the eastern end of the profile  
371 when approaching the Lake Turkana shoreline. These variations in depth are also observed  
372 in the density model where the highest negative density contrasts thicken from East to  
373 West. This thickening is in agreement with the general dip to the west of the sedimentary  
374 beds of the Nachukui Formation as it is observed at the surface along the northwest  
375 shoreline of Lake Turkana. The fact that the resistivity distribution is not strongly marked  
376 by the FN1 and FN2 faults suggests that the material has no significant resistivity contrast.

377 At the eastern end of the profile, immediately east of the F3N, the (L1) limit is no longer  
378 visible, and the thickness of the identified sediments reaches a value of 2.5 km, but possibly  
379 higher. Another limit, named (L0), can be observed both in the density model and within  
380 the very conductive unit but poorly constrained by the data. If real, it could be interpreted  
381 as being the upper limit of a known large salt-water wedge (e.g. Johnson et al., 1987)  
382 associated to Lake Turkana (Fig.10).

383 A weakly defined second limit (L2) is suggested in the lower part of the fairly  
384 conductive package but again not well identified in the density model. Under site 13, (L2)  
385 occurs at a depth of ~2 km, and is found at a depth of ~1.8-1.9 km under site 16. To the  
386 east, (L2) is visible at a depth of ~1.4 km near the F3N Fault. From F3N toward the east,  
387 (L2) is no longer visible.

388  
389 In terms of lithostratigraphy, the layer between L1 and L2 could be interpreted as the

390 volcanic pile known as “Turkana Volcanics”. At the western end of the profile, near the  
391 MRL Border Fault, this layer shows a thickness of about 0.6-0.7 km under site 13 that  
392 remains relatively constant toward the east. Then, from site 16, it decreases toward the east  
393 until crossing F3N, and reaches a thickness of ~0.4-0.5 km between sites 16 and 17. The  
394 high resistivity value and no density contrast between sites 16 and 17 suggest intrusion of  
395 volcanics in the sediments which are not outcropping probably because recovered by the  
396 recent Pleistocene-Holocene coverage.

397 At a greater depth ( $\geq 2$  km), the model under station 13 and up to the western side of  
398 station 17 shows a high resistivity unit with values exceeding 100  $\Omega$ .m, excepted between  
399 sites 16 and 17 where the mean resistivity value is around 50  $\Omega$ .m. The top of this high  
400 resistivity unit corresponds to the limit (L2). Geologically, this unit would correspond to  
401 either the Lapur Sandstone or the Precambrian basement. The clear identification of the  
402 Lapur Sandstone, which is stratigraphically interbedded between the “Turkana Volcanics”  
403 and the Precambrian basement (Fig. 3c), is difficult because of the low resistivity contrast  
404 existing between the strongly consolidated sandstones and the overlying Precambrian  
405 basement (Fig. 3a), which both may have high resistivity values. In addition, the depth of  
406 investigation ( $>2$  km) and the relatively weak thickness of the Lapur Sandstone in the area  
407 of the northern profile, evaluated at 100-120 m at the Lapur Peak (Tiercelin et al., 2012)  
408 make their detection even more challenging. Under the Lapur Sandstone and/or  
409 Precambrian basement, another limit (L3) can be identified. This limit separates a resistive  
410 part (that corresponds to the basement and/or the Lapur Sandstone) and a conductive part,  
411 which could correspond to a zone of intense fracturing to explain the increase of the  
412 conductivity values.

413 The density model (Fig. 10b) shows only some vertical variations comparable to the  
414 resistivity variations, which can relate to the presence of the MRL Border Fault and the

415 other secondary faults, F1N, F2N and F3N present in the central and eastern part of the  
416 profile. The upper limit of the LS and/or the Precambrian basement, marked by the (L2)  
417 boundary appears relatively flat between sites 13 and 16, whereas it shows a slight dip to  
418 the west between sites 16 and 17, delimited by the faults F2N and F3N. Immediately east of  
419 site 17, this limit disappears. The thickness of the Lapur Sandstone seems relatively  
420 constant (~100 m) from west to east, and does not exceed 120 m in the northern part, as  
421 observed in the Lapur Peak cliffs (Figs. 2 and 3).

422 To the east of F3N, under the site 17 and eastward (Fig. 10a), the (L1) and (L2) limits  
423 previously described are no longer visible. Very weak resistivity values ( $<10 \Omega.m$ ) can be  
424 found from the surface down to a depth of 5 km. The density contrast is negative and does  
425 not exceed  $70 \text{ kg.m}^{-3}$ . One sub-horizontal density contrast limit, named (L0), is identified  
426 at ~1 km depth and may represent the upper limit of a wide salt-water wedge (Fig. 10).  
427 Although the MT data have been processed in 2-D, the rapid change in structures from  
428 profile P3 to P2 and the absence of the limits (L1-L2/L3) under site 17 and eastward could  
429 suggest the resistivity model in P3 is biased by lateral 3-D variations in depth. In fact, the  
430 data do not exhibit strong 3-D distortion as revealed in Figure 7 and in the 3-D inversion  
431 presented in Abdelfettah (2009).

432 These high conductivity and negative density contrasts could be the result of the presence at  
433 the northwest end of the Turkana Basin of an important thickness ( $>2.5 \text{ km}$ ) of sediments  
434 belonging to the Plio-Pleistocene/Holocene Nachukui and Kibish Formations, or even older  
435 sediments. This thickness value is of the same order than the thicknesses observed on the  
436 PROBE seismic lines as well as on the Eliye Springs-1 well. This significant sediment  
437 thickness could be explained as resulting of a major subsidence associated to a high  
438 sedimentation rate along the F3N Fault, which thus could be considered as the main border  
439 fault of the Turkana Basin activated during at least the Pliocene and Pleistocene/Holocene

441

442 *7.2. Central profile (P2)*

443 The central profile crosses from the east the littoral/alluvial plain forming the western  
444 side of the Turkana Basin, then the MRL Border Fault escarpment and the Lapur Range  
445 through the Lokitaung Gorge, and ends to the west on the western side of the Kachoda  
446 Valley (Fig. 1).

447 The density and resistivity models presented in Fig. 11a and 11b show similar features  
448 mainly a horizontal contrast defining the (L1-L3) limits. One major discrepancy between  
449 density and resistivity models is around the depth of the limit (L2), which is imaged by MT  
450 but not well resolved by gravity. The resistivity model shows a clear contrast whereas the  
451 recovered density model is more homogeneous. Perhaps in this area, the “Turkana  
452 Volcanics” are less fractured as in the other places (in northern profile?).

453 At least three secondary faults can be identified in this model (Fig. 11). The major MRL  
454 Border Fault is clearly visible at the western end of the profile. Between sites 11 and 25, the  
455 F1C Fault, and between sites 25 and 26, the F2C Fault, are identified and interpreted as the  
456 cause of the down lift of the three geological units identified in this location. A third fault,  
457 named F3C, is visible between sites 26 and 27. The F2C and F3C Faults can be correlated  
458 with the F2N and F3N faults identified in the northern profile (Fig. 10).

459

460 The density model obtained for the Turkana Basin for the central profile (P2) (Fig. 11b)  
461 shows almost similar structures as those observed in the resistivity model (Fig. 11a). A  
462 negative density contrast  $\sim 200 \text{ kg.m}^{-3}$  is visible in the eastern part from the surface down to  
463  $\sim 0.9 \text{ km}$  depth, and possibly represents the (L1) limit. The density values increase smoothly  
464 from this depth to reach a positive density contrast of  $\sim 200 \text{ kg.m}^{-3}$  at a depth of 1-1.1 km at

465 the centre-east of the profile (under site 26). This limit could be attributed to the (L2)  
466 boundary. A negative density contrast of  $50 \text{ kg.m}^{-3}$  can also be observed under sites 10 and  
467 11, that could correspond to a thin sedimentary layer (<150 m thick), the possible the (L1)  
468 limit. Below (L1), a positive density contrast of about  $150 \text{ kg.m}^{-3}$  is visible at a depth of  
469 ~1.2 km under site 11, and at ~1.7 km depth under site 10 (Fig. 11b). In terms of  
470 lithostratigraphy, the limit (L1) may correspond to the base of the Nachukui Formation at a  
471 depth of ~100-150 m under the sites 10 and 11, immediately east of MRL Border Fault  
472 (Fig. 11).

473 Four faults are well identified along the (P2) profile: the main MRL Border Fault, and  
474 three synthetic faults named F1C, F2C and F3C. At a distance of 7 km from the western  
475 end of the profile (between sites 11 and 25), the (L1) limit is found at a depth of ~0.5 km,  
476 immediately west of the F2C Fault. To the east and at a distance of ~5 km from the eastern  
477 end of the profile, the limit (L1) appears almost horizontal (under site 26) and reaches a  
478 depth of ~0.8 km immediately to the west of the F3C Fault. The (L2) limit, which is  
479 defined as the base of the “Turkana Volcanics”, is identified below (L1) at a depth of ~1.2  
480 km under site 26. It finally reaches a depth of ~2.2-2.3 km under site 27 near the Lake  
481 Turkana shoreline. The limit (L3) is partially visible below (L2), at the east end of the  
482 profile, at the depth of ~3.7-3.8 km under site 27.

483 The resistivity and density models obtained for this profile (Fig. 11) have different features  
484 in comparison to the northern profile. The conductive layer observed in the eastern half of  
485 the profile and interpreted as the Nachukui and Kibish Formations, is thinner than in the  
486 northern profile (1.3-1.4 km), (Fig. 11a). Under sites 10-11 and westward, this layer  
487 vanishes. Another difference with the northern profile can be observed at the eastern end of  
488 the central profile, from site 26 eastward to the lake shoreline (Fig. 11a), where the  
489 conductive layer continues monotonically toward the lake. Finally; the “Turkana

491

492 In some places, the intermediate density/resistivity values are not visible (e.g., Fig.  
493 11). This behaviour could be explained partly by the fact that large cooling structures such  
494 as columnar jointing, colonnades and tores affect the basaltic flows of the “Turkana  
495 Volcanics” (Fig. 3d). Several metres or tens of metres wide dykes and thick sills also  
496 intrude the “Turkana Volcanics” pile (Fig. 3f). Several metres thick beds of strongly  
497 brecciated lavas also separate the main massive lava flows. Such types of structures may  
498 induce discontinuities within the pile of lavas that may explain the relatively low average  
499 resistivity values

### 500 7.3. Southern profile (P1)

501 The resistivity and density models for the southern profile and their structural  
502 interpretation are presented in Figure 12. They reveal again an upper conductive and low  
503 density layer, here about 2 km thick over a more resistive and denser medium. The  
504 resistivity and density contrast values are on average less than for profile P2. The signature  
505 of three faults may be identified along the profile: the MRL Border Fault at the western end  
506 of the profile, the F2S Fault at the centre of the profile under the sites 04 and 06, and the  
507 F3S fault near the eastern end of the profile between sites 08 and 09.

508 The resistivity model suggests a limit (L1) at a depth of 1.7–1.8 km at the western end of  
509 the profile, below site 1 and site 2. This limit is interpreted as the base of the Nachukui  
510 Formation. Towards the East, this limit is shallower (at ~1.2–1.4 km depth) under sites 4  
511 and 5. The bottom of the upper low density layer is deeper than the limit L1 in the resistivity  
512 model (Fig 12ab) suggesting that this limit is probably deeper than indicated by the  
513 resistivity.

514 Under site 5 (Fig. 12a), a resistive heterogeneity, visible between ~100-150 m depth

515 down to 600-700 m depth within the Nachukui/Kibish Formations, has no signature in term  
516 of density contrast, which suggests that it is an artefact.

517 A possible interface (L2), supposed to be boundary between the “Turkana Volcanics”  
518 and the Lapur Sandstone and/or the Precambrian basement (Fig. 2c) is suggested in Figure  
519 12a while Figure 12b (the density model) suggests that this limit could be in fact L1. The  
520 resistive body beneath sites 6-9 has a density contrast slightly positive which would agree  
521 with either highly fractured volcanics or the Lapur sandstone or both. Eastward, this limit  
522 is not clearly identified in the resistivity model. Precambrian basement might form the base  
523 of the resistivity model, especially under sites 05 to 09.

524 Our interpretation suggests that the thickness of the Plio-Pleistocene/Holocene  
525 sediments in southern profile is larger than in profile P2. The depth of this limit between  
526 the sediments and the “Turkana Volcanics” decreases eastwards through a system of  
527 normal faults including the main MRL Border Fault and the F2S and F3S Faults. The  
528 chrono-stratigraphy visible at the MRL Border Fault suggests that volcanics overlying the  
529 Lapur Sandstone should be present but not distinct in our results (Fig. 12).

530 The significant thickness (2 km or more) of the Plio-Pleistocene/Holocene sediments, as  
531 suggested by the seismic interpretation, is clearly revealed in both resistivity and density  
532 models immediately to the east of the F3S Fault, and can be extended offshore Lake  
533 Turkana as observed in northern profile (Fig. 10). This interpretation is close to that  
534 proposed by Tiercelin et al. (2012a; Fig. 15, p. 62) achieved on the TVK-10 seismic line,  
535 which suggests the presence in the MRL hanging wall of an important pile of sediments,  
536 probably underlain by the “Turkana Volcanics”, and a sediment package including the  
537 Lapur Sandstone.

538

539 **8. Subsurface structure of the Kachoda Valley**



540 The resistivity and the density sections for the Kachoda Valley (Figs. 1b and d) are  
541 presented in Figure 13. The models are more complex and on average more resistive and  
542 dense than for profiles P1-P3. In Figure 13a, we identify the possible signature of several  
543 faults. On the West side of the profile, we defined F1W between sites 18 and 19; and F2W ,  
544 located under site 20 and which may reach a depth of >5 km. In the center of the profile,  
545 F3W between sites 21 and 22 is uncertain. To the East, F4W is beneath site 23 and F5W  
546 beneath site 24, also reaching a depth >5 km.

547

548 To the West, between sites 18 and 19 from the surface to ~1.5 km we observe an upper  
549 conductor over a resistive bedrock. We interpret this limit (named L1') as the base of the  
550 surface sediments probably intermingled with dikes and sills (because of the positive  
551 density contrast) overlying the "Turkana Volcanics". The sediment layer thins eastward and  
552 reaches 1 km depth under site 20. W. The resistivity values from surface down to (L1')  
553 limit do not exceed 10  $\Omega$ .m (Fig. 13). Below the (L1') limit, the resistivity values range  
554 between 20 and 70-80  $\Omega$ .m. We hypothesize that the limit (L2) marking the transition  
555 between the "Turkana Volcanics" and the Lapur Sandstone and/or the Precambrian  
556 basement, is identified under limit (L1'), This limit (L2) seems identifiable in both  
557 resistivity and density models between the Lokitaung Gorge and the eastern end of the  
558 Kachoda Basin (beneath sites 21 and 22, Fig 13a).

559 The stratigraphic contact between the Lapur Sandstone and the "Turkana Volcanics"  
560 outcrop on the right bank of the Lokitaung Gorge immediately west of station 24 at lat. 04°  
561 16' 04" N and long. 35° 47' 34" E (Figs. 2c, 13c). Thus station 24 is located directly on the  
562 Lapur Sandstone while station 23 is located on the overlying "Turkana Volcanics". From  
563 the resistivity model (Fig. 13a), the resistivity values beneath these sites are greater than 50  
564  $\Omega$ .m while the density contrast is slightly negative. This observation outlines the difficulty

565 in distinguishing the Precambrian basement from the Lapur Sandstone, as both formations

566 are characterized by high resistivity values.

567

568 This profile is very heterogeneous. The structures seem controlled by the faults  
569 identified in Figure 13a. In particular, the 1.5-1.6 km thick sediment infill of the Kachoda  
570 basin can be compared to a part of the Plio-Pleistocene/Holocene sediment infill existing in  
571 the nearby Turkana Basin.

572

### 573 **9. Subsurface geological models**

574 From the density and resistivity models obtained in this study as well as the available  
575 information as outcrops and known chrono-stratigraphical data, we propose a series of  
576 conceptual geological models along the three profiles of the Turkana Basin and the  
577 Kachoda Basin (Figs. 10d-13d and 14).

578

579

#### **Figure 14**

580

581 The proposed geological model for the northern profile is illustrated on Fig. 10d. As  
582 identified by the density and the resistivity models, and by geological data collected at the  
583 outcrop level in the Lapur Range, the main MRL Border Fault is clearly located and its dip  
584 is confirmed. Two other faults, F0N and F3N, are suggested in the western and eastern  
585 parts of the profile, as well two other faults, F1N and F2N, located in the central part of the  
586 profile. These faults have no surface expression and thus may be considered as inactive  
587 today. The main MRL Border Fault bounds the Plio-Pleistocene and Holocene sediment  
588 infill of the Turkana Basin to the west, i.e. the Nachukui and Kibish Formations. This  
589 sediment infill (corresponding to the lowest resistivity and density contrasts) does not

590 exceed a total thickness of ~1.5 km at the western end of the profile and decreases in  
591 thickness to about 1 km toward the east, at 2.5 km to the west of the Lake Turkana  
592 shoreline, on the western side of the F3N Fault. To the east of the F3N Fault, towards Lake  
593 Turkana, the thickness of these sediments reaches up to 3-5 km. Below these Plio-  
594 Pleistocene/Holocene (and possibly older?) sediments should lie the “Turkana Volcanics”  
595 unit. However, the density model does not show values in agreement with volcanics unless  
596 the later are strongly fractured or very thin. According to field observations (Tiercelin et al.,  
597 2012a), the “Turkana Volcanics” should be underlain in the area of the Lapur Peak by a  
598 maximum of 0.100-120 m of Lapur Sandstone (Figs. 2a and 3a). The thickness of the Lapur  
599 Sandstone may vary accordingly to the topography of the top of the basement. The  
600 basement should lie below the Lapur Sandstone and from the MRL Border Fault. The low  
601 density observed in the whole section excepted at the westernmost side suggests however  
602 that the material below Plio-Pleistocene and Holocene sediment could be sediments rather  
603 than Turkana volcanics. The thickness of the sediments is similar to the thicknesses  
604 observed on the PROBE seismic lines as well as on the Eliye Springs-1 well. This  
605 significant sediment thickness could be explained as the result of a major subsidence  
606 associated to a high sedimentation rate along the F3N Fault, which thus could be  
607 considered as the main border fault of the Turkana Basin activated during at least the  
608 Pliocene and Pleistocene/Holocene periods, compared with the main MRL Border Fault  
609 and the other secondary faults. Alternatively, the northern profile stands near the  
610 acknowledged interfering rifts between the Miocene to actual rift and older rift system  
611 running from the Anza into the Muglad-Melut systems (Fig.1). Accumulation of Pliocene  
612 and Pleistocene/Holocene sediments over cretaceous-holocene units could explain both the  
613 resistivity and density distribution beneath sites 13-17 (Figure 10ab). This interpretation is  
614 supported by recent gravity and magnetic surveys carried out over the Turkana Depression

616 On the eastern part of the profile, close to the Lake Turkana shoreline, the resistivity  
617 and density models do not show clear vertical contrast that could be used to distinguish  
618 sediments from the volcanic rocks, or any other interface below, to the exception of the  
619 limit (L0), which is characterized by a clear contrast in the density model, with nevertheless  
620 a poor contrast in terms of resistivity. This limit could correspond to a wide saline water  
621 intrusion (e.g. Johnson et al., 1987), which is limited to the west by the F3N Fault. In this  
622 part of the profile, more than 3 km of Plio-Pleistocene/Holocene (or older?) sediments  
623 identified.

624 At the bottom of the models we identified two structures (A and B) in Figs. 10a-b at the  
625 depth of 3-4 km and 2-3 km, respectively. These structures are limited in space, conductive  
626 and low density. Partial fusion of the basement is unlikely because it is shallow and the  
627 density is small (negative contrast of  $120 \text{ kg m}^{-3}$  for B and  $180 \text{ kg m}^{-3}$  for A). If the  
628 hypothesis of sediment accumulation through the conjunction of the EAR and Anza rift in  
629 the Turkana depression is correct, these structures could be small-scale depocenters. Their  
630 signature is similar to gravity and resistivity structures for depocenters observed in other  
631 regions but deeper (e.g. Hautot et al., 2007).

632 The proposed geological model for the central profile (P2 and Kachoda) is presented in  
633 Figs. 11d, 13d and 14. East of the escarpment toward Lake Turkana, The MRL Border  
634 Fault seems to have a clear signature in both the resistivity and density models. A major  
635 west-dipping structure (between sites 11 and 25) can be observed also in both models East  
636 of the MRL Border Fault. The resistivity and density values obtained for this structure are  
637 similar to those for the MRL fault region. The resistive body (beneath sites 10 and 11)  
638 outcrops is from the "Turkana Volcanics" unit (Tiercelin et al. 2012a). Thus, this structure  
639 could be interpreted as a large volcanic intrusion, possibly a wide volcanic dyke or a large

640 sill, both structures being well represented in the area of the Lapur Range (Fig. 3f)  
641 (Tiercelin et al., 2012a) (Fig. 11d). East F2C (Figure 11a), the resistivity and density  
642 models support the stratigraphic sequence observed on the escarpment (Figure 2b) unlike  
643 for the northern profile. We observe a variation in thickness of the Plio-  
644 Pleistocene/Holocene sediments and the “Turkana Volcanics” from ~0.5-0.6 km to ~0.8 k  
645 for the Plio-Pleistocene/Holocene sediments then remains relatively constant eastward of  
646 F3C. The thickness of the “Turkana Volcanics” unit varies from ~0.5-1.5 km. A maximum  
647 thickness of ~500 m of Lapur Sandstone could be present downward from the (L2), with  
648 the same dip as the “Turkana Volcanics” (Fig. 11d), but cannot be clearly imaged in this  
649 study.

650 The Kachoda Basin is well identified at the western end of the central profile (Figs. 13d  
651 and 14). The upper part of the basin infill is characterized by sediments with a maximum  
652 thickness of ~1.5-1.6 km (possibly the same sediments as those of Turkana Basin?). Below  
653 this pile of sediments is a package of “Turkana Volcanics”, the thickness of which remains  
654 uncertain because the (L2) limit is not precisely defined in this part of the model. However,  
655 a thickness value of >2 km is expected under the sites 21 and 22. Under the “Turkana  
656 Volcanics”, a maximum thickness of ~0.5 km can be expected for the Lapur Sandstone  
657 under site 24 and immediately to the west, as it is in the area of the Lokitaung Gorge (Thuo,  
658 2009; Tiercelin et al., 2012a) (Fig. 2b). If the Lapur Sandstone exists in the subsurface of  
659 the Kachoda Basin, it will show lateral variations of thickness according to the changing  
660 morphology (of topographic or tectonic origin) of the top of the basement. Between the  
661 Turkana and Kachoda Basins, no obvious geological interpretation can really be provided.  
662 A strong thinning of the Lapur Sandstone can be envisaged below the Kachoda Basin. In  
663 the nearby Gatome half-graben (Fig. 1a), the presence of Cretaceous?-Paleogene sediments  
664 is suggested by seismic reflection data but cannot be related directly to the Lapur Sandstone

666 The proposed geological model of the southern profile (Fig 12d and 14) presents a  
667 stratigraphy similar to the central profile with a thicker Plio-Pleistocene/Holocene sediment  
668 cover (2-2.5 km). (Fig. 12d) The thickness value of the “Turkana Volcanics” is difficult to  
669 assess because neither the resistivity or the density model show clear transitions between  
670 the volcanics, a possible Lapur sandstone layer and the

671 The conceptual geological model presented in Fig. 14, mainly for the southern profile, is  
672 generally in agreement with the recent re-interpretation of the TVK-10 seismic line  
673 (Tiercelin et al., 2012; Fig. 15) in terms of geometries, depths and thicknesses of the Plio-  
674 Pleistocene/Holocene sediments, the “Turkana Volcanics”, Lapur Sandstone and  
675 Precambrian basement.

676 The rapid structural changes in the resistivity and density models from the central profile  
677 to the northern profile is supported by the recent gravity and magnetic surveys carried out  
678 over the whole Turkana depression region (Hutchinson et al., 2010). The density model  
679 suggests that the imaged substratum is filled by sediments down to at least 5 km. The  
680 resistivity model completes the picture with a clear limit between highly conductive Plio-  
681 Pleistocene/Holocene sediments and more resistive, probably older (cretaceous-holocene?)  
682 sediments maybe to be related to the Gatome Cretaceous?-Paleogene sediments.

683

#### 684 **10. Hydrocarbon implications**

685 Following our study in the northwest part of the Turkana Basin, the highest potential  
686 area in terms of oil exploration can be found in the northern profile, along the shoreline of  
687 Lake Turkana, where the presence of ~3-5 km of sediments of Plio-Pleistocene age topping  
688 probably older sediment is imaged. This thick sedimentary pile may contain alternating  
689 sequences of potential source rocks and reservoirs, as it is the case in the oil-rich Lake

690 Albert Basin in the western branch of the EARS. Also, in the nearby South Omo Block in  
691 Southern Ethiopia, the Sabisa-1 well (~10 km immediately north of Turkana Lake) recently  
692 drilled by Tullow Oil and Africa Oil Corporation reached a total depth of 1810 metres and  
693 encountered “reservoir quality sands, oil shows and heavy gas shows indicating an oil  
694 prone source rock and a thick shale section”. Below the recent ~2km sediment  
695 accumulation in the North Turkana Basin the locally thick pile of “Turkana Volcanics” if  
696 present seems very thin but still could act as a seal for the underlying Lapur Sandstone,  
697 which demonstrates good reservoir qualities based on results of porosity measurements (3-  
698 25%) (Thuo, 2009). The interfering rifts of the Turkana depression (Hutshinson et al. 2010)  
699 may be at the origin of a thick pile of possibly creataceous-holocene sediments. Thus,  
700 considering the regional oil potential, e.g. the nearby South Sudan oil fields, and the  
701 promising South Lokichar Basin, the North Turkana area appears as a region of major  
702 interest for oil and gas exploration in the Eastern Branch of the EARS.

703 More effort must be devoted combining seismic and non-seismic techniques to get more  
704 information about the existence in the Turkana region of good quality reservoirs and  
705 trapping mechanisms as well the identification of mature source rocks necessary to support  
706 a working petroleum system.

707

## 708 **11. Conclusions**

709 The major results of this study in terms of subsurface structure and stratigraphy of the  
710 North Turkana Basin can be summarized as follows:

711 1) The resistivity and density models provided by MT and gravity joint inversion have  
712 clearly confirmed the half-graben geometry of the northwest end of the Turkana Basin, with  
713 the identification, in addition to the main MRL Border Fault, of three main synthetic faults  
714 (F1, F2 and F3) which today have no surface expression. Taking into account the thick

715 sediment accumulation (>3 km) in their respective hanging walls, the F3 Fault and the  
716 MRL Border Fault can be considered as being the main border faults of the North Turkana  
717 Basin at least for the Mio-Pliocene period for the MRL Fault, and for the Plio-Pleistocene  
718 period for the F3 Fault. This may suggest a migration of rift tectonics from west to east  
719 since Middle Miocene (initiation of the MRL Border Fault).

720 2) Characterization of a newly defined half-graben basin located to the immediate west of  
721 the Turkana Basin, named the Kachoda Basin, in terms of structure and subsurface  
722 stratigraphy. The main conclusion for the Kachoda half-graben is the presence within the  
723 basin of a 1.5 km thick pile of sediments that may represent a stratigraphic equivalent of the  
724 Plio-Pleistocene/Holocene Nachukui and Kibish Formations, both deposited in the nearby  
725 Turkana Basin. The Kachoda sedimentary infill may relate to a suite of major transgressive  
726 phases of Lake Turkana within the Kachoda Basin during the Plio-Pleistocene or even older  
727 periods. Underlying these sediments, a maximum of 1.5 km of volcanic rocks belonging to  
728 the “Turkana Volcanics” has been identified.

729 3) Important lateral variations in the thickness of the “Turkana Volcanics” from west to east  
730 and from south to north along the three profiles are also clearly evidenced.

731 4) The stratigraphic contact (L2) between the “Turkana Volcanics” and the underlying  
732 Lapur Sandstone and/or Precambrian basement is partly identified in the different profiles.  
733 The presence of the Lapur Sandstone in the Turkana Basin, and in the Kachoda Basin,  
734 nevertheless, remains unresolved because the difficulty to separate the geophysical  
735 response of the Precambrian basement and Lapur Sandstone.

736 5) Strong lateral variations in thickness of the Plio-Pleistocene and Holocene sediment and  
737 possibly older sediments to the North infill of the Turkana Basin (the Nachukui/Kibish  
738 Formations), from west to east and from south to north. From 1.5 km at the west end of the  
739 northern profile to >3 km at its east end, in the hanging wall of the F3C Fault, almost



741 6) Additionally, the proposed models also help to resolve ambiguities met in previous  
742 interpretations. In particular, the reflection seismic method previously used in the Lotikipi,  
743 Gatome, Turkana and Lokichar Basins has demonstrated difficulty in determining the  
744 thickness of volcanic rocks below a thick sediment pile, as well as imaging the stratigraphy  
745 and structures below thick piles of volcanic rocks (the well-known sub-basalt imaging  
746 problem, e.g. Ziolkowski et al., 2003) (e. g., Wescott et al., 1999; Tiercelin et al., 2012a).

747

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768

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873

874 **List of figures**

875 **Fig. 1.** (a) Schematic map showing the distribution of Cretaceous–Paleogene to  
876 Neogene rift basins in southern Sudan, southern Ethiopia and northern, central and  
877 eastern Kenya. Intense oil exploration is presently conducted in all these regions. In  
878 the Northern Kenya Rift, several N-S-trending sedimentary basins of Cretaceous?-  
879 Paleogene to Plio-Pleistocene age - the Lotikipi, Gatome, Lokichar (North and South),

880 North Kerio and Turkana Basins have been identified using gravity and seismic  
881 reflection methods. In the Lokichar Basin, in addition to the Loperot-1 well (drilled in  
882 1992), and the Ngamia-1 well (drilled in 2010) (indicated by a black dot and a black  
883 star, respectively), several other highly promising exploration wells have been drilled  
884 recently in the South Lokichar Basin (modified from Ebinger and Ibrahim, 1995;  
885 Morley et al., 1999; Wescott et al., 1999; Tiercelin et al., 2004; Africa Oil  
886 Corporation, 2011, 2014). The white box/black arrow indicates the study area. (b)  
887 Block-diagram of the study area, showing the MT and gravity measurement sites  
888 along the three profiles P1 (southern), P2 (central) and P3 (northern). SRTM30  
889 (Shuttle Radar Topography Mission of 30 m resolution) is used as a topography model  
890 and the vertical exaggeration is about 9 times (900 %). The numbers refer to the MT  
891 stations. (c) Regional map of the Lake Turkana Basin, showing outcrop areas of the  
892 Plio-Pleistocene "Omo Group" deposits, that include the Nachukui Formation in the  
893 northwest part of the Turkana Basin. The sediments of the Kibish Formation type-  
894 section outcrop further north, on the right bank of the Omo River. The 2.9-km deep  
895 Eliye Springs-1 well is indicated east of the town of Lodwar by a small rig. Older  
896 sedimentary deposits (Paleogene to Pliocene) outcrop at the southwest end of the  
897 Turkana Basin (redrawn from Feibel et al., 1989; Morley et al., 1999; McDougall et  
898 al., 2005). (d) Topographic map (scale 1:250,000) of the northwest part of the Turkana  
899 Basin, showing the Kachoda Valley, the Lapur Range and the Murua Rith Hills that  
900 bound the northwestern half of the Turkana Basin (i.e. the Murua Rith-Lapur Rift  
901 Border Fault). Geological/geophysical cross-sections, seismic lines and geographic  
902 sites cited in the text are indicated (from East African Topographic Map, 1972).

903

904 **Fig. 2.** Interpretative geological cross-sections perpendicular to the western, N-S-

905 trending faulted side of the North Turkana Basin, based on the geological map  
906 established by Walsh and Dodson (1969), seismic lines interpretations (Wescott et al.,  
907 1999; Tiercelin et al., 2012a) and fieldwork. The three geophysical profiles are  
908 superimposed on these geological cross-sections, respectively: the southern profile P1  
909 (which is also superimposed to the trace of the TVK-10 seismic line acquired by the  
910 Amoco Company), the central profile P2, and the northern profile P3. For the southern  
911 profile, the interpretation of the TVK-10 seismic line in the hanging wall of the MRL  
912 Border Fault is deduced from Wescott et al. (1999). On the 3 geological cross-  
913 sections, the continuous grey line represents the geophysical profiles, and the x-axis  
914 represents the distance (km) from the western shore of Lake Turkana. The dashed  
915 boxes delineate the study areas where the conceptual geological models (see Fig. 12)  
916 will be considered.

917  
918 **Fig. 3.** (a) General view from the east (Todenyang Plain) of the 1600 m high Lapur  
919 Range, showing the Lapur Sandstone (LS) overlying the Precambrian basement  
920 (marked by the yellow bold dashed line) between 04°20' and 04°35' N. In the region  
921 of the Lapur Peak (Figs. 1d and 2a), the Lapur Sandstone is about 100-120 m thick and  
922 forms the upper part of the Lapur Range, which corresponds to the Murua Rith-Lapur  
923 Border Fault escarpment that bounds the Turkana rift basin to the northwest. On the  
924 photo, the trace of the MRL Border Fault is marked by a yellow dashed line. The two  
925 peaks that dominate the LS cliff on the far horizon correspond to outcrops of lavas  
926 belonging to the « Turkana Volcanics » (TV), overlying the Lapur Sandstone. See Fig.  
927 1b and d for the location of the P3 profile across the Todenyang Plain. (b) View of the  
928 middle and upper parts of the Lapur Sandstone to the immediate north of the  
929 Lokitaung Gorge, at about 15 km south of Lapur Peak (see Fig. 2a and b). In this area,



930 the Lapur Sandstone is 500 m thick and overlies the Precambrian basement that  
931 outcrops a few kilometres to the north (see (a), yellow bold dashed line). (c) Detailed  
932 view of the stratigraphic contact (indicated by the yellow dashed line) between upper  
933 beds of the Lapur Sandstone and the lowermost flows of the “Turkana Volcanics”,  
934 visible on the right bank of the Lokitaung Gorge at 04°16' 04" N; 35°47' 34" E (LG;  
935 see Figs. 1d and 2b for location). (d) Fluvio-deltaic sediments belonging to the Plio-  
936 Pleistocene Nachukui Formation that forms a large part of the infill of the North  
937 Turkana Basin. (e), (f) Large cooling structures such as columnar jointing (e) and tores  
938 (f) are well developed within the basaltic flows of the “Turkana Volcanics”, and may  
939 explain the observed low average resistivity values. (g) Wide volcanic dykes and thick  
940 sills are abundant in the area of the P2 and P3 profiles (Lokitaung Gorge, Kerral area  
941 and north of Lapur Peak) and in the Keniroliom area south of the P1 profile (Fig. 1d).  
942 The (f) picture presents a view of a 10-m wide N60°-trending tephritic dyke  
943 crosscutting the upper beds of the Lapur Sandstone in the Kerral area (see location  
944 Fig. 1d). This dyke (marked by the black boulders on the photo) is dated  $27.03 \pm 0.57$   
945 Ma (from Tiercelin et al., 2012a). Larger dykes (up to 70 m) are known in the northern  
946 part of the Turkana Basin as well as in Southern Ethiopia (Ebinger et al., 2000).

947  
948 **Fig. 4.** Re-interpretation of the TVK-10 seismic line (from Tiercelin et al., 2012a),  
949 presenting the possible presence in the hanging wall of the MRL Border Fault, below  
950 the “Turkana Volcanics” (marked at top by a bold dashed line and at base by a dotted  
951 line), of a 300-m thick sedimentary package that can be interpreted as the Lapur  
952 Sandstone (marked at base by a dashed/dotted line). The “Turkana Volcanics” are in  
953 turn overlain by hundreds of metres of fluvio-lacustrine sediments of Plio-Pleistocene  
954 age forming the uppermost part of the infill of the Turkana Basin (i.e. the Nachukui

956 **Fig. 5.** MT and gravity field experiments showing the used materials to record datas.  
957 a) and b) gravity data acquisition using Lacoste-Romberg gravimeter. c) Phoenix  
958 datalogger used to record MT time series. d) and e) showed coil used to record  
959 magnetic field and probe used to record electrical field, respectively.

960

961 **Fig. 6.** Resistivity and phase fits recovered from magnetotelluric measurements.  
962 Symbols stand for the observed data and continuous lines for model. (a) Apparent  
963 resistivity and (b) phase fit for MT sites for the three profiles responses, where a good  
964 fit was obtained between observed and computed apparent resistivities and phases,  
965 especially in the small periods where the information for shallow subsurface  
966 concerning this study could be obtained. Red and blue colours represent the TM and  
967 TE modes, respectively. The error bars are the 68 % confidence interval.

968

969 **Fig. 7.** Maximum electrical field direction (MED) at each site at the period  $T=0.5$  s  
970 (yellow) and 50 s (red). The width of the pie wedge is two standard deviations. The  
971 length of the pie wedge is a function of the ratio between the maximum and minimum  
972 impedance tensor. Larger values indicate well-defined maximum electrical field  
973 direction. SRTM 30 m (Shuttle Radar Topography Mission, 30 m of resolution) is  
974 used in the background.

975

976 **Fig. 8.** Gravity data fit. Symbols stand for the observed data and continuous lines for  
977 model responses. Free air anomalies obtained for the northern, central and southern  
978 profiles.

979

980 **Fig. 9.** Model parameterisation and geometrical constraint defined by the GCF. The  
981 resistivity parameters are grouped in a limited number of domains (here 3 domains).  
982 The horizontal and vertical lines represent the 2-D grid. The parameters  $mr_{ij}$  and  $md_k$   
983 are the resistivity of the  $ij^{\text{th}}$  block and the density value of  $k^{\text{th}}$  domain, respectively.

984

985 **Fig. 10.** (a) Resistivity model, and (b) density model obtained by MT and gravity joint  
986 inversion for the northern profile (P3) (Fig. 1b). The dashed lines represent the major  
987 resistivity and density contrasts or uncertain fault extensions. (c) the major resistivity  
988 and density visible in the obtained results as well as major faults. (d) The final  
989 conceptual geological model proposed for this profile.

990

991 **Fig. 11.** (a) Resistivity model and (b) density model obtained by MT and gravity joint  
992 inversion for the segment of the central profile located in the Turkana Basin (eastern  
993 part of Profile 2 on Fig. 1b). The dashed lines represent the major resistivity and  
994 density contrasts or uncertain fault extensions (c). This held to the final conceptual  
995 geological model showed in (d).

996

997 **Fig. 12.** (a) Resistivity model, and (b) density model obtained by MT and gravity joint  
998 inversion for the southern profile (P1) (Fig. 1b). The dashed lines represent the major  
999 resistivity and density contrasts or uncertain fault extensions. (c) the major resistivity  
1000 and density visible in the obtained results as well as major faults. (d) The final  
1001 conceptual geological model proposed for this profile.

1002

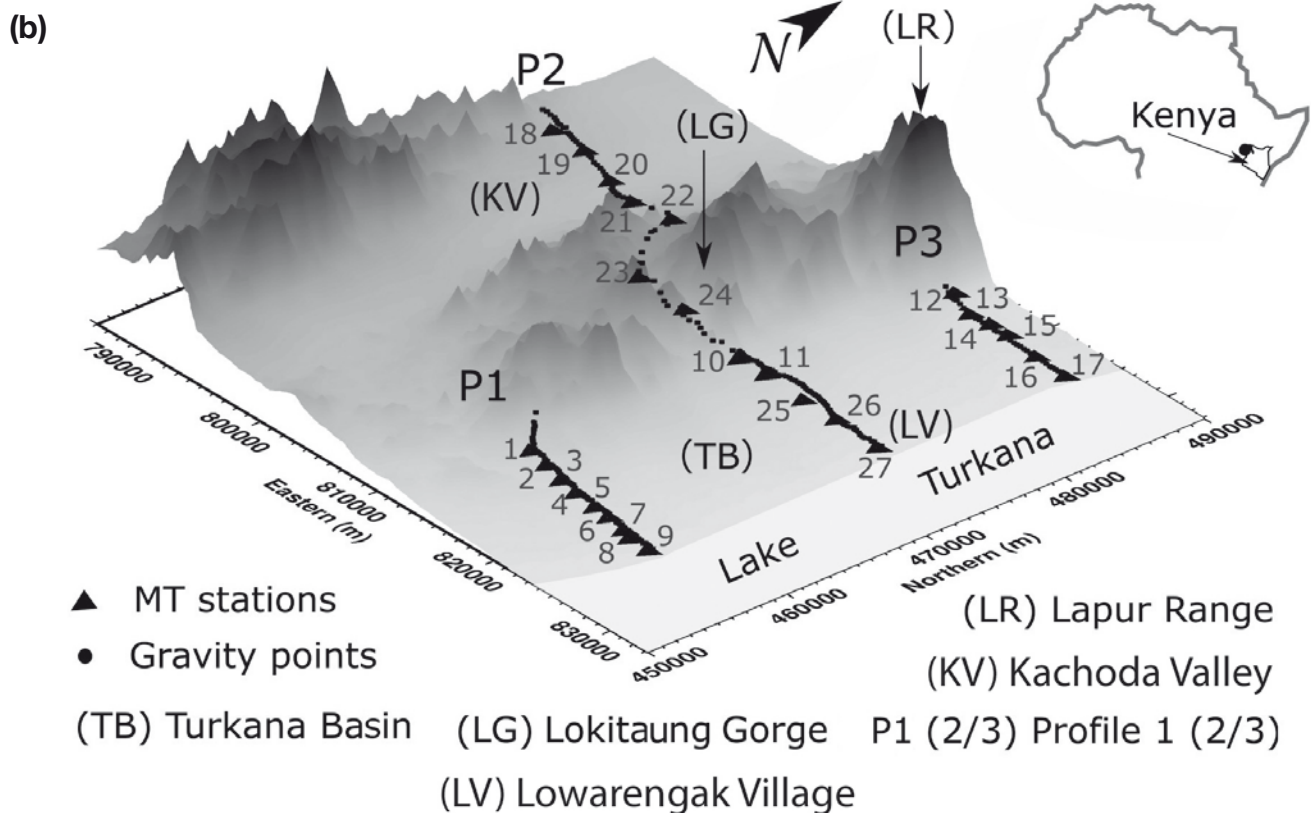
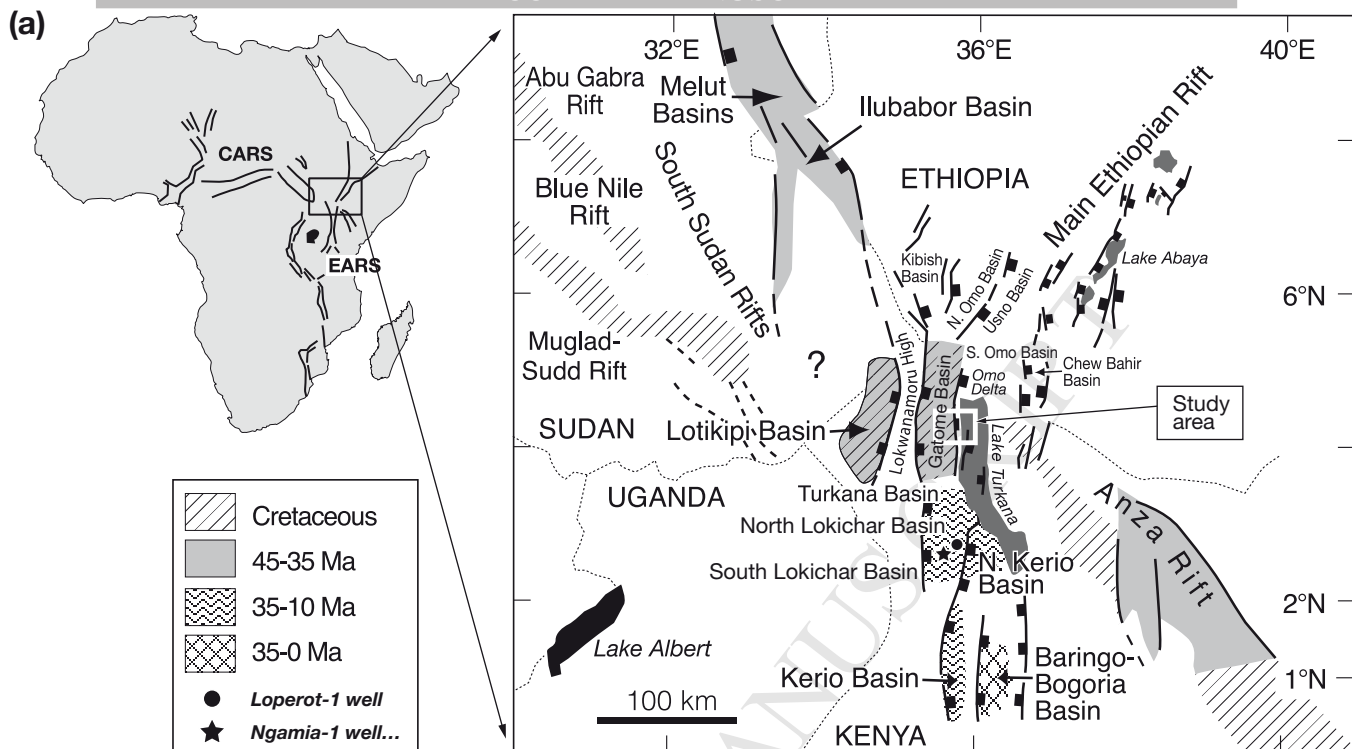
1003 **Fig. 13.** (a) Resistivity model, and (b) density model obtained by MT and gravity joint  
1004 inversion for the central profile (P2) in the Kachoda Basin (western part of the profile;

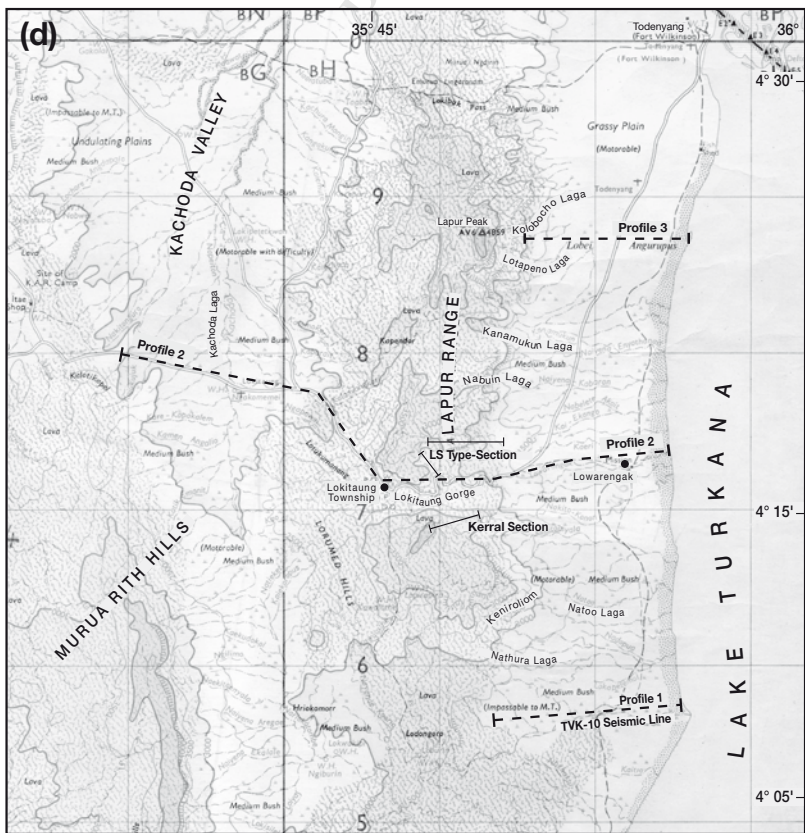
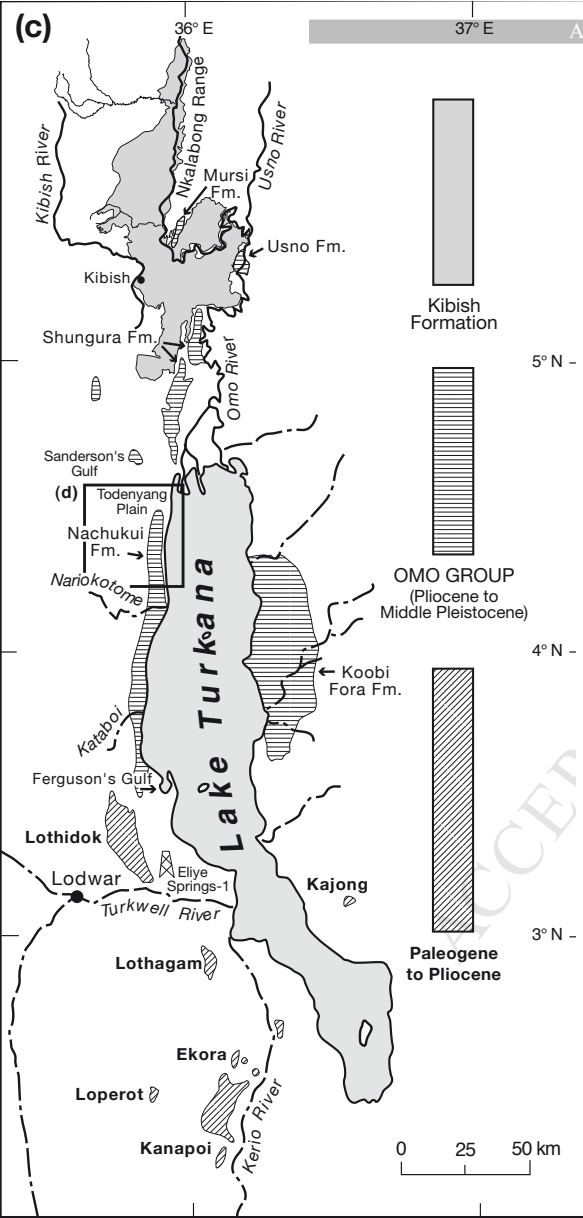
1005 Fig. 1b). The dashed lines represent the major resistivity and density contrasts or  
1006 uncertain fault extension. (c) the major resistivity and density visible in the obtained  
1007 results as well as major faults. (d) The final conceptual geological model proposed for  
1008 this profile.

1009

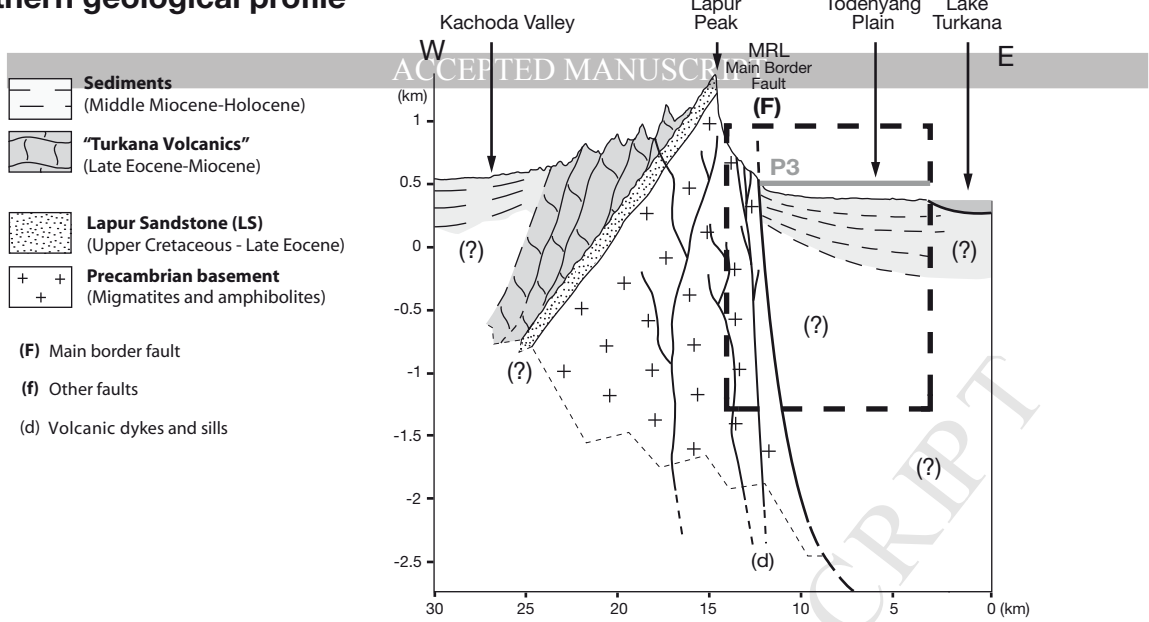
1010 **Fig. 14.** Conceptual geological models proposed for the central profile including both  
1011 Turkana and Kachoda basins. These conceptual models are derived using resistivity  
1012 and density models obtained in this study, as well as the available geological  
1013 knowledge provided mainly from the fieldwork.

1014

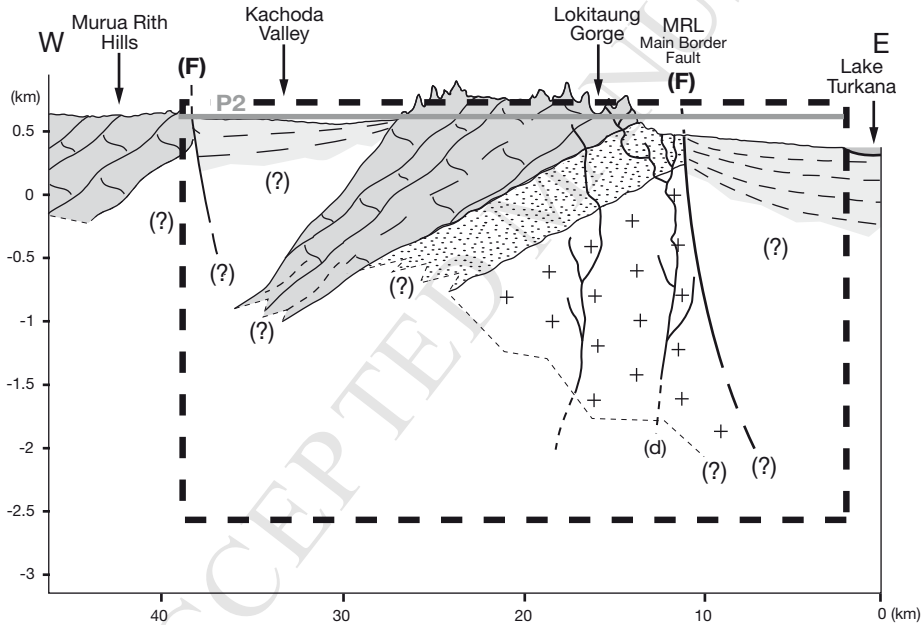




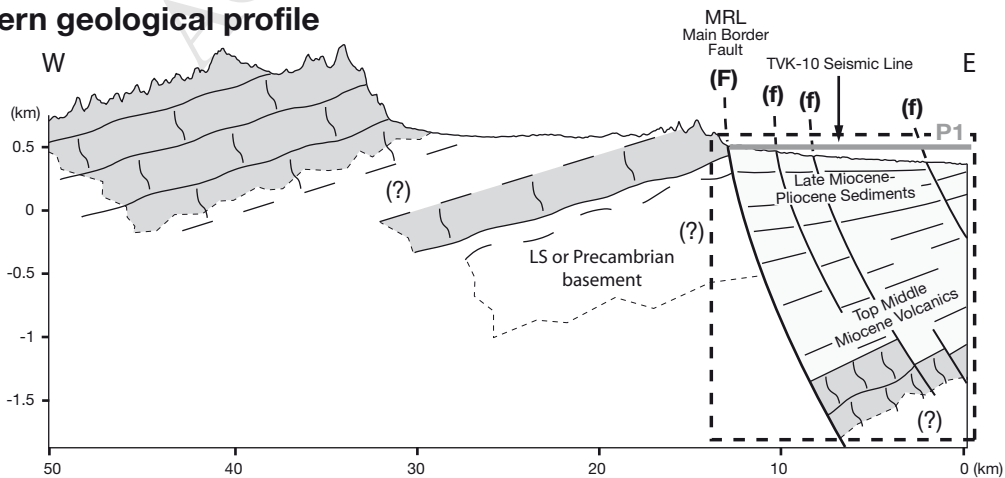
### (a) Northern geological profile

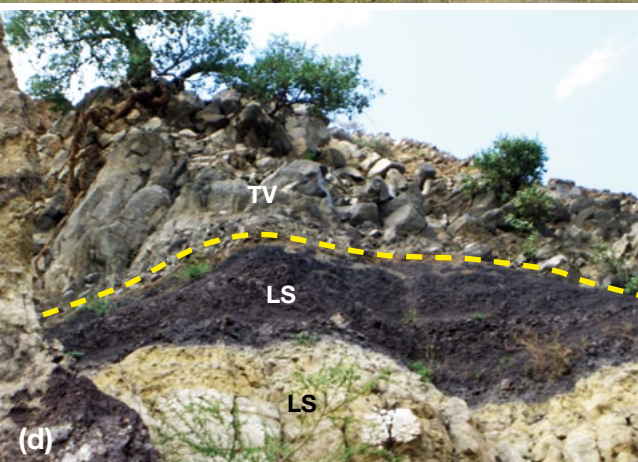
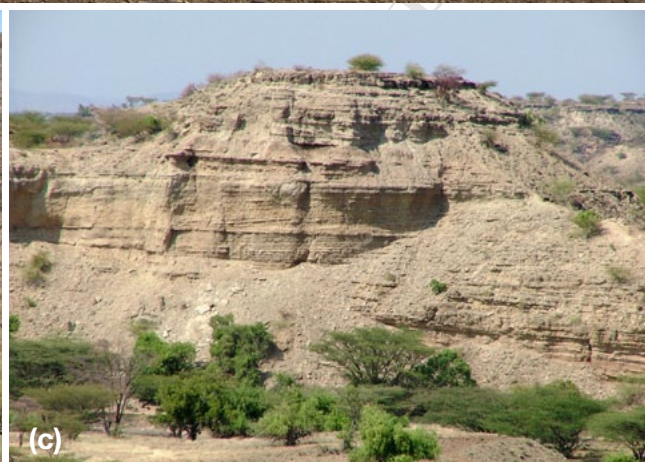
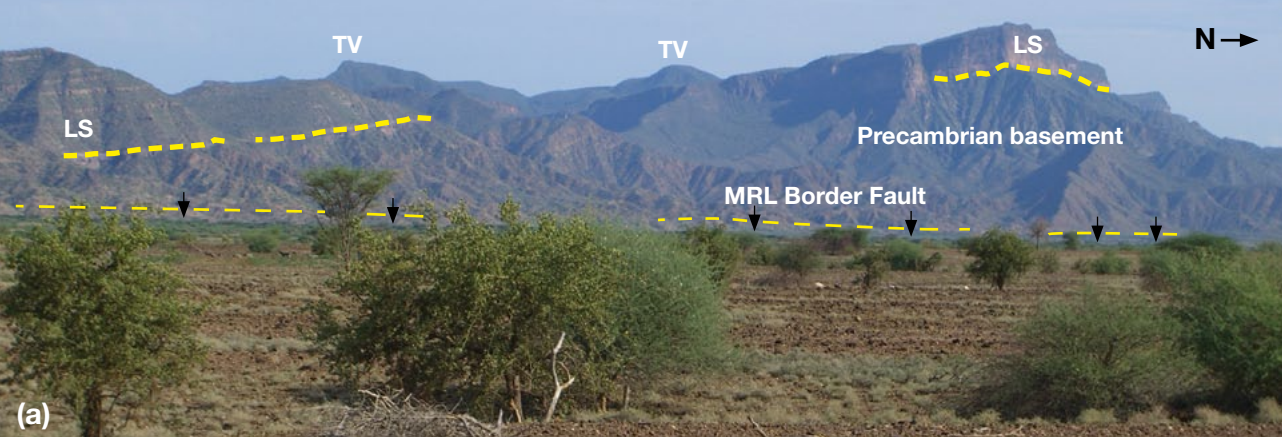


### (b) Central geological profile

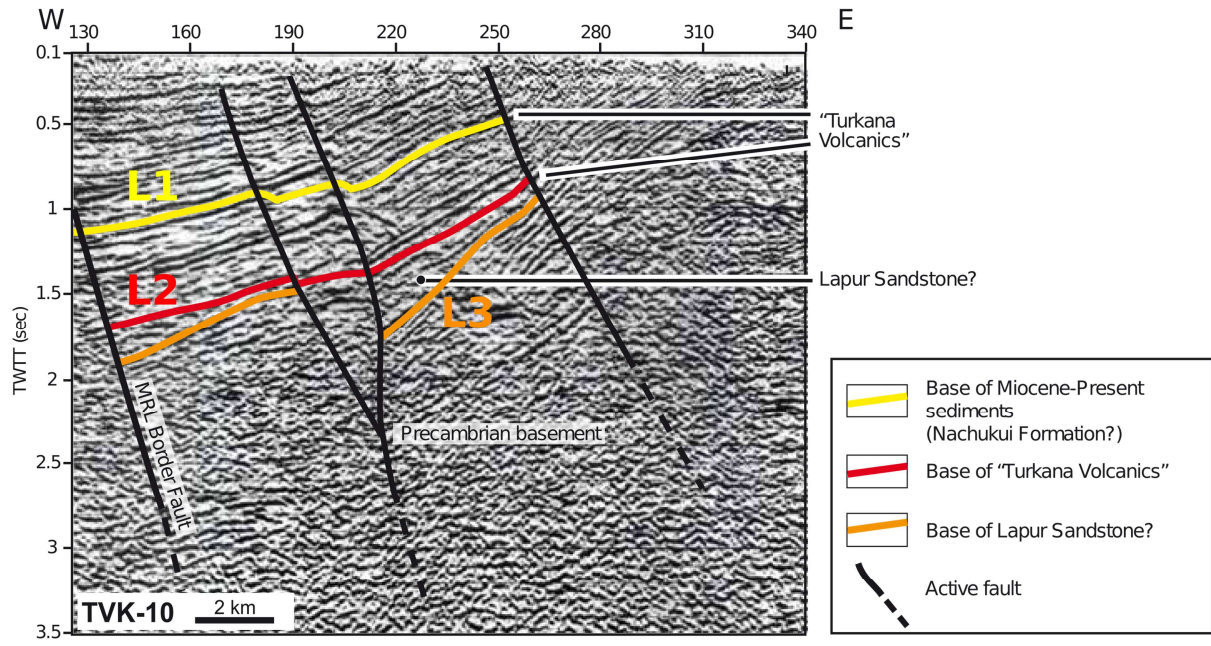


### (c) Southern geological profile

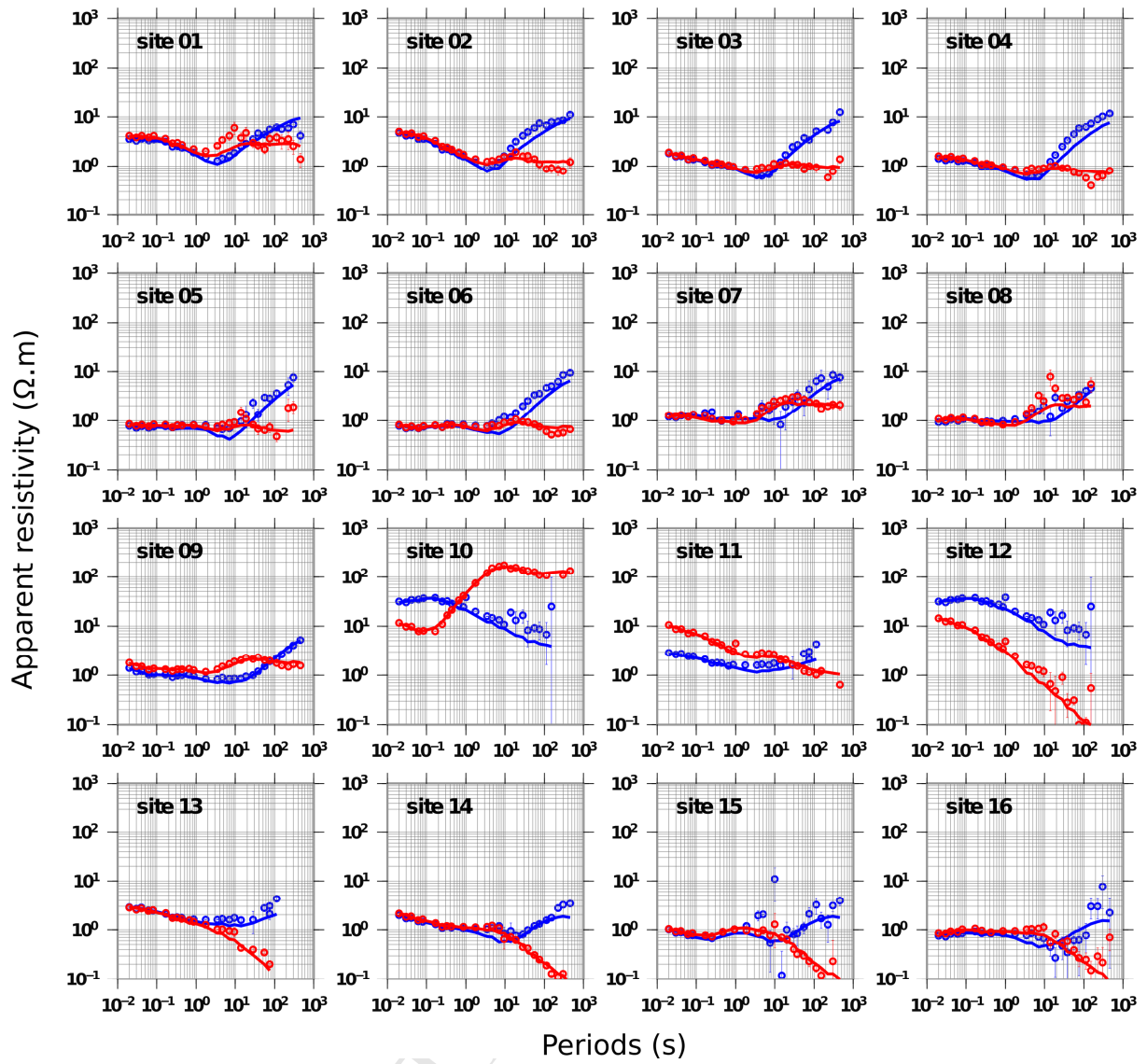


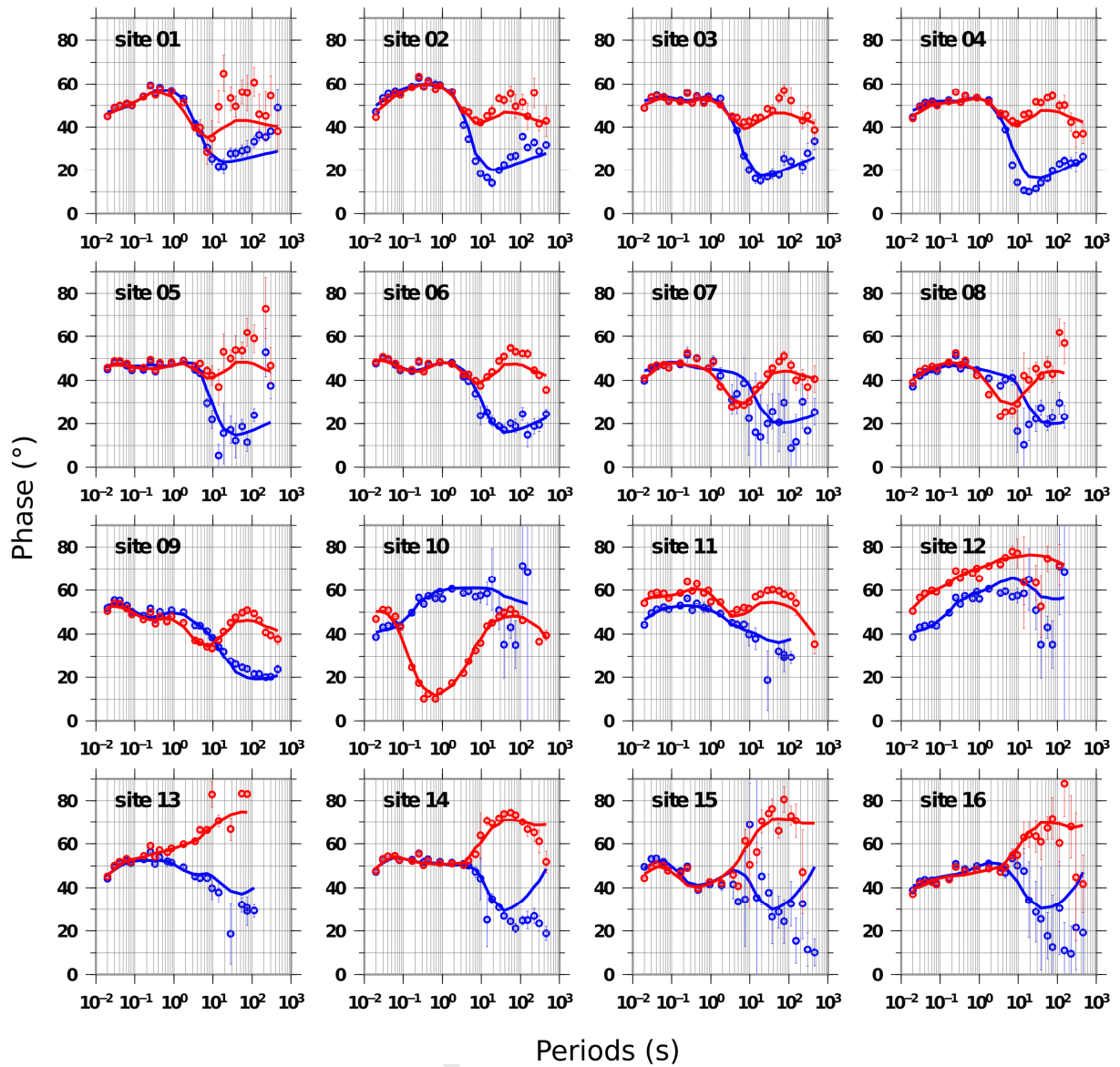


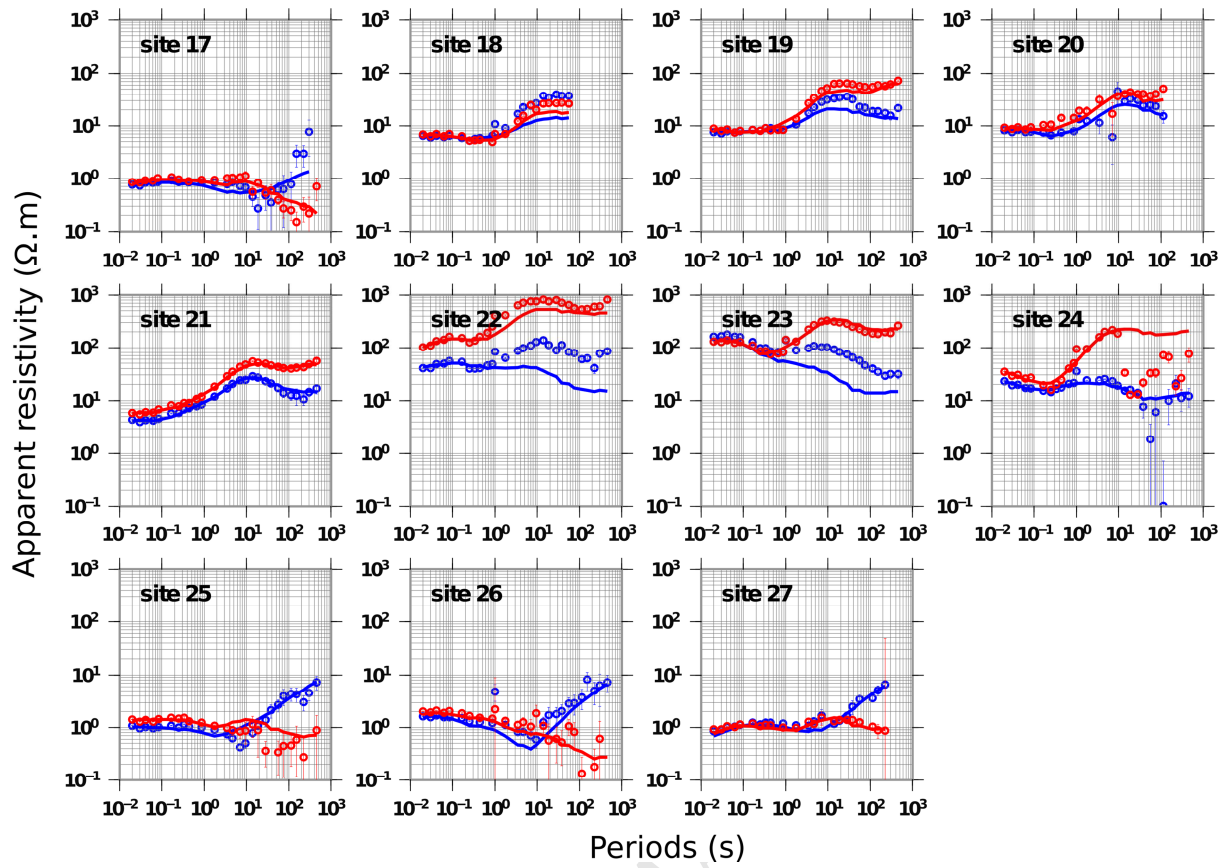


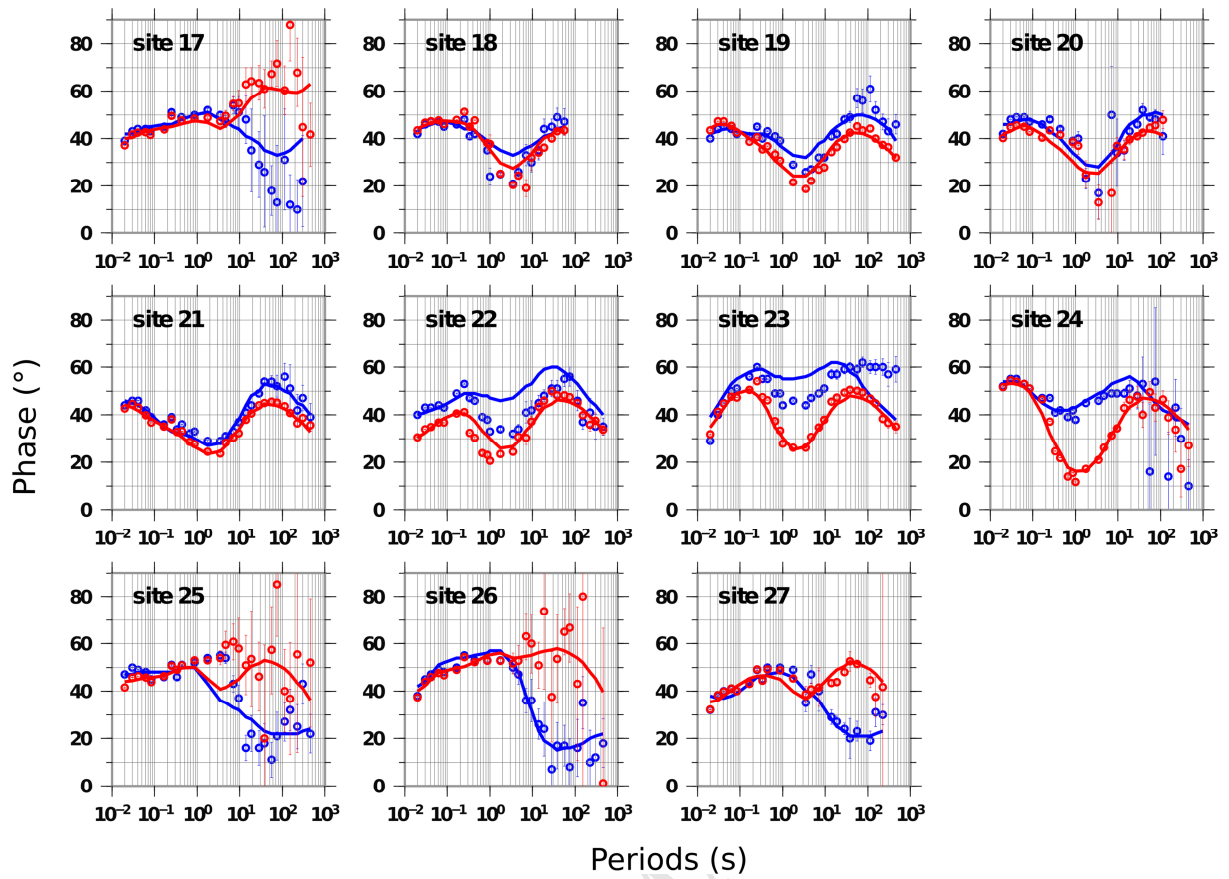


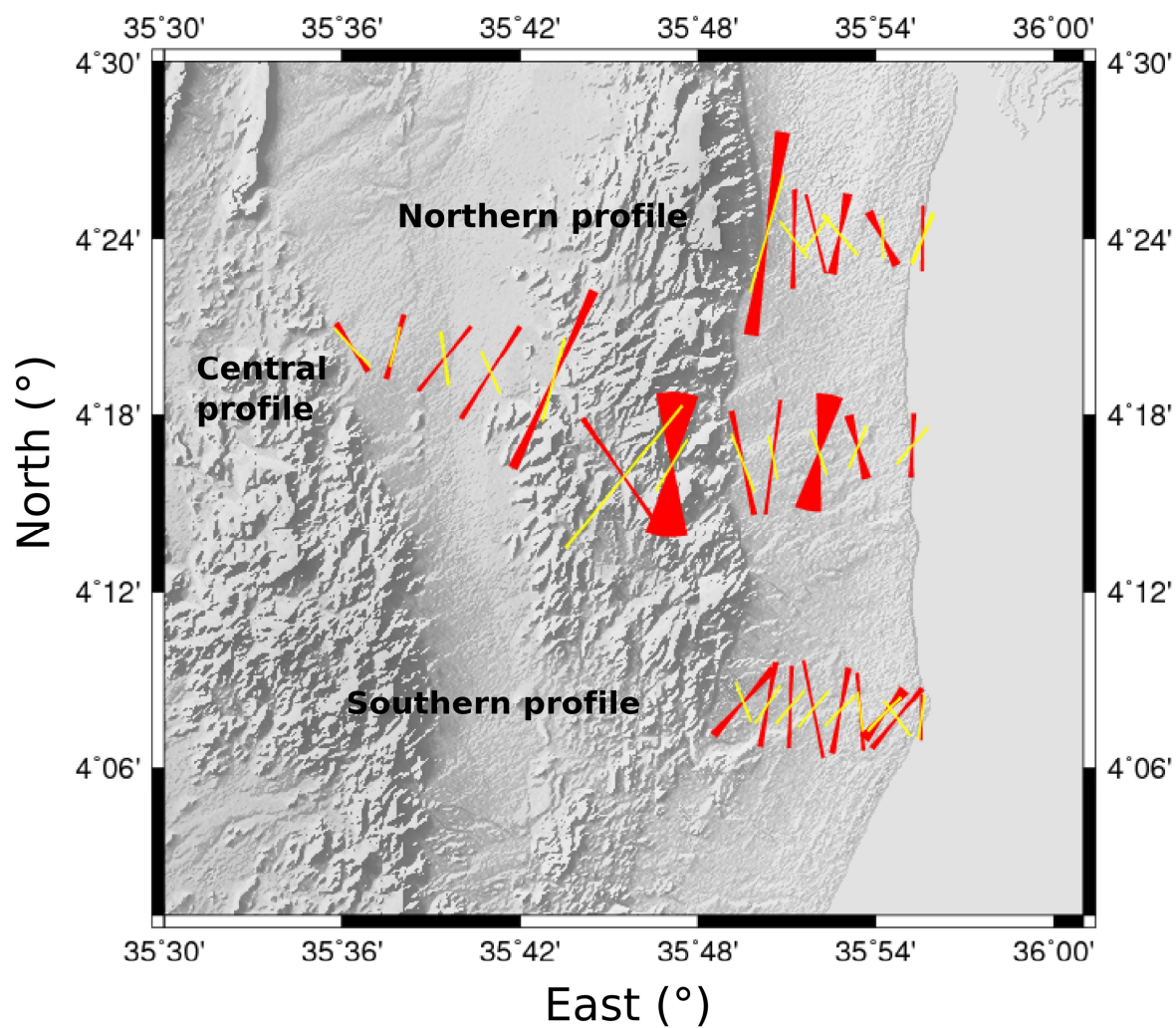






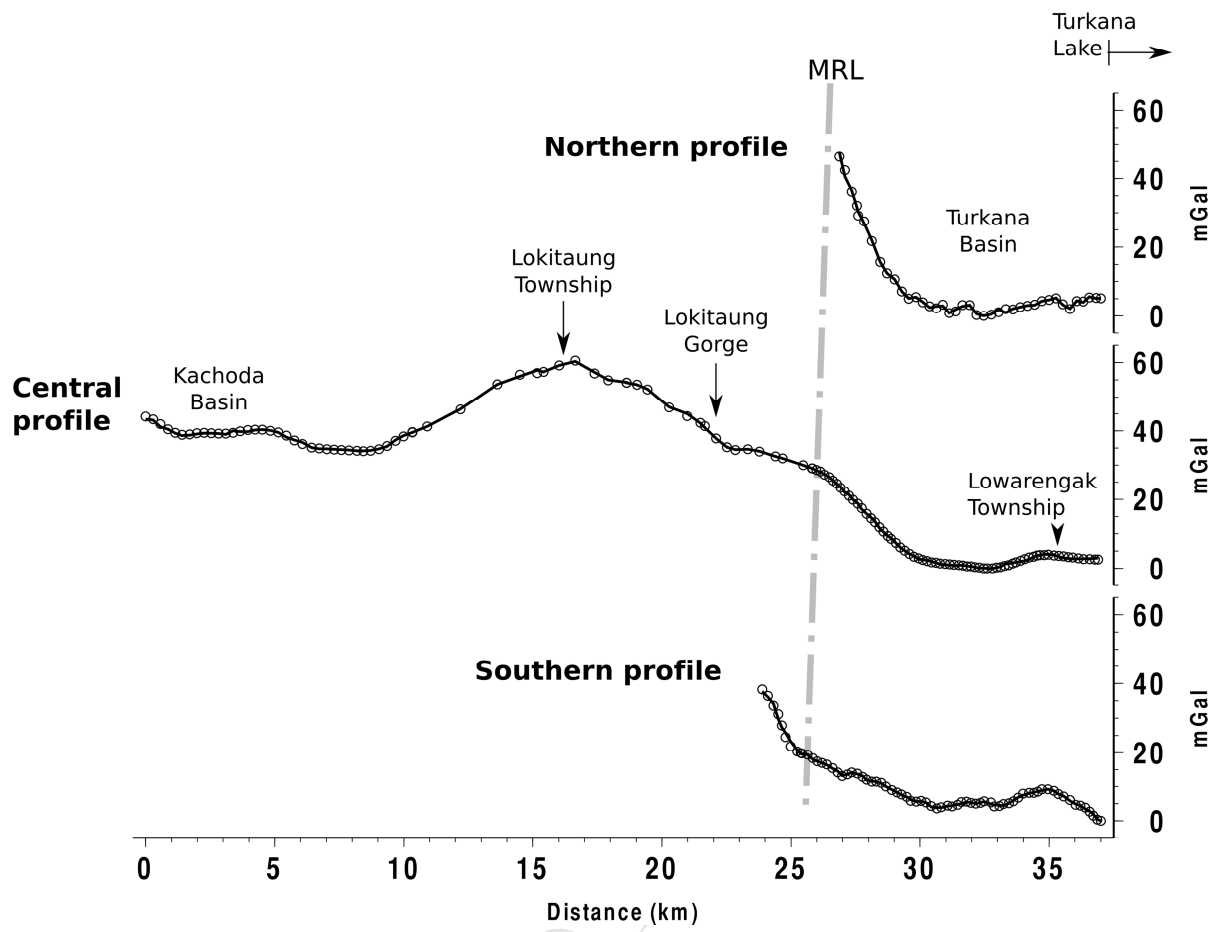




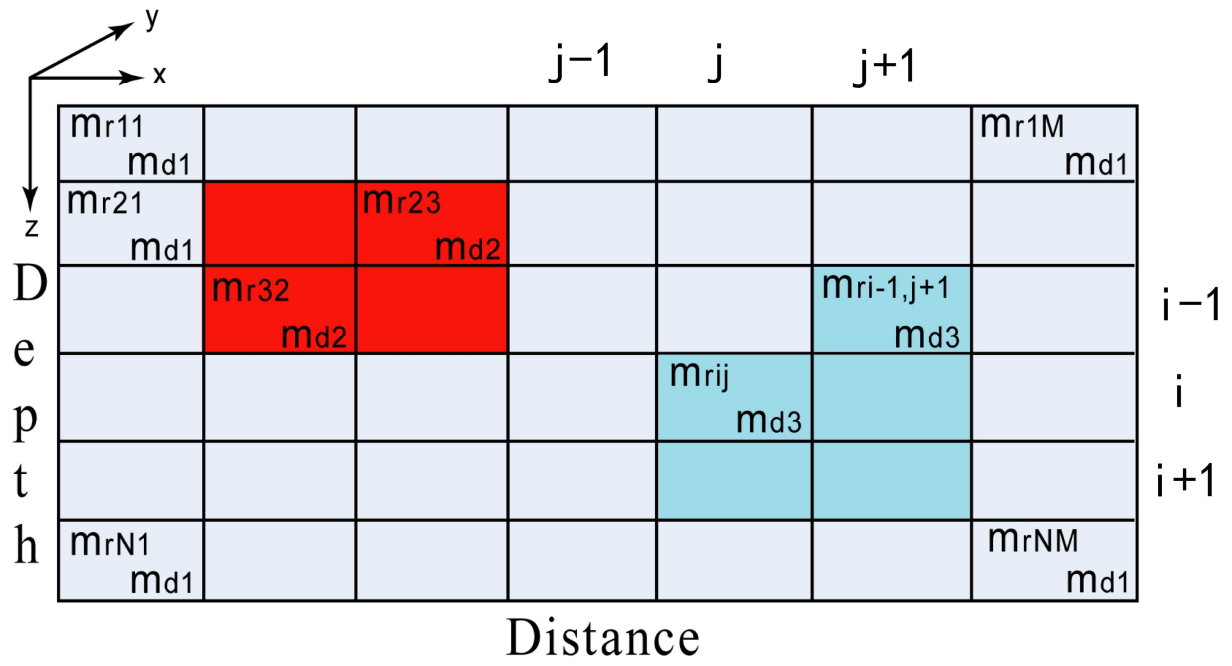


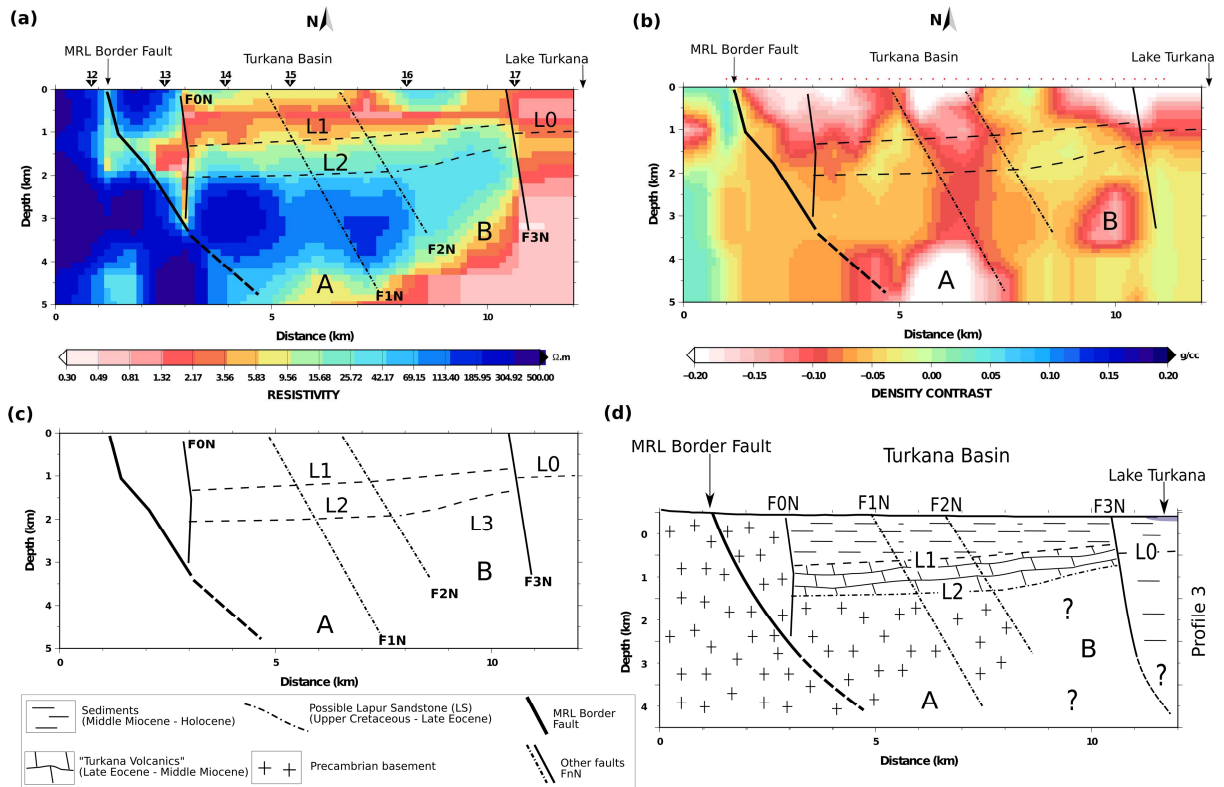
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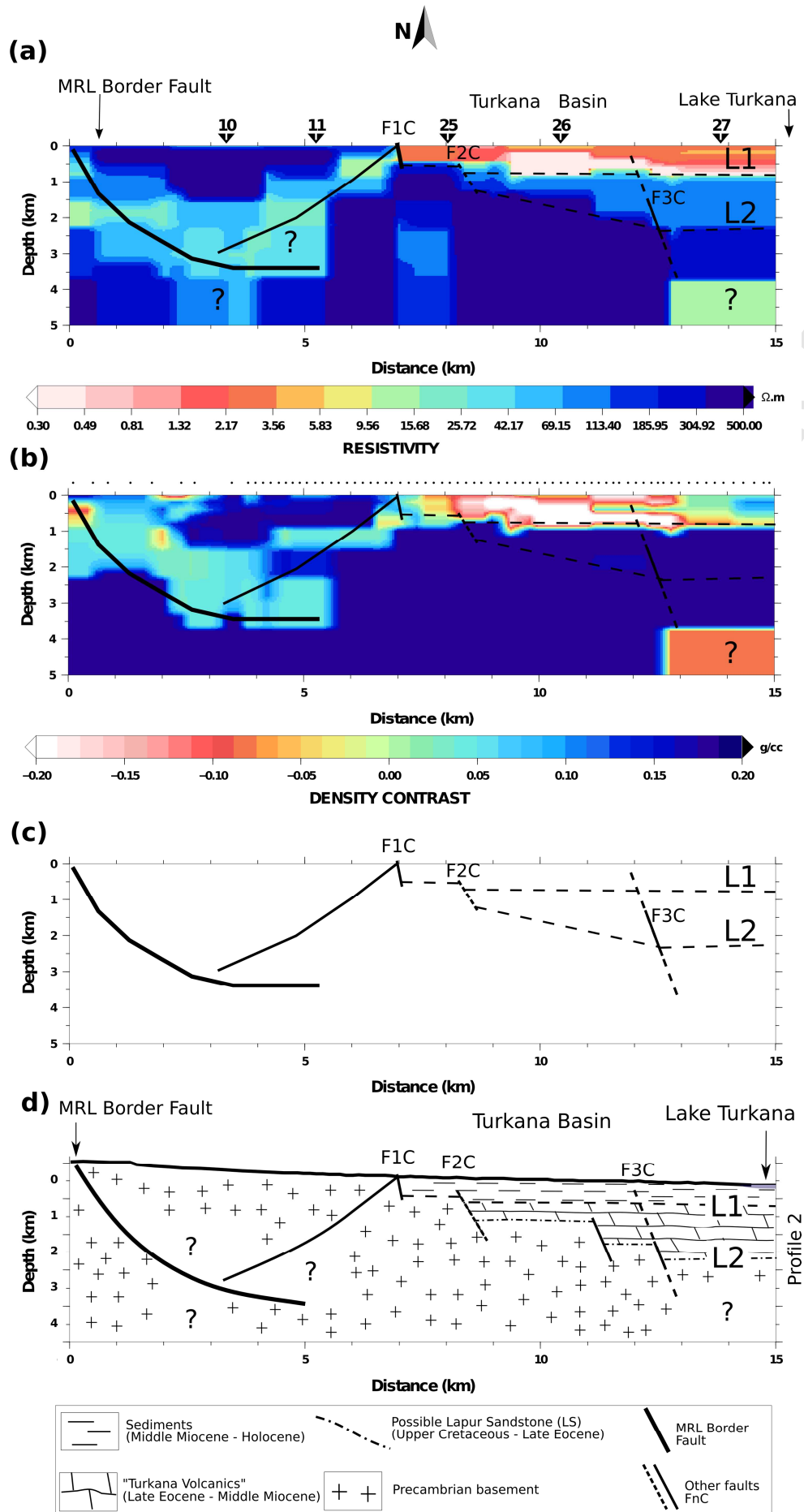
East

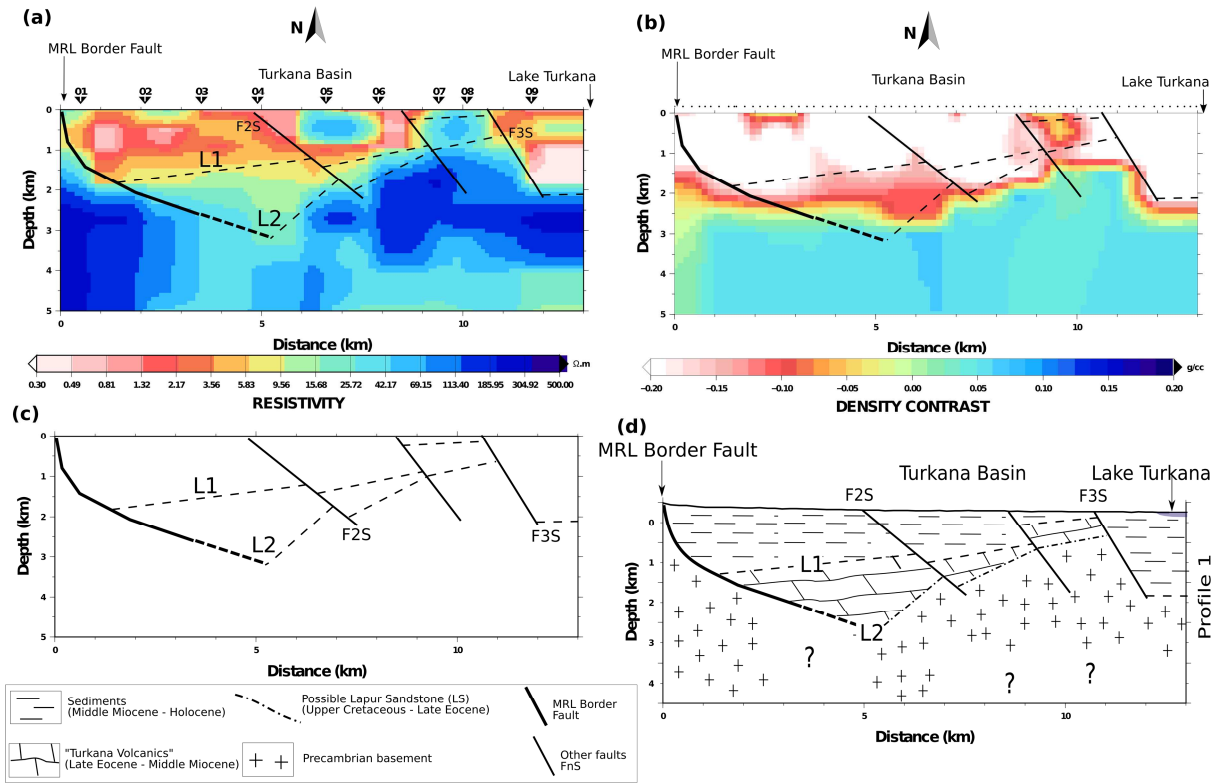




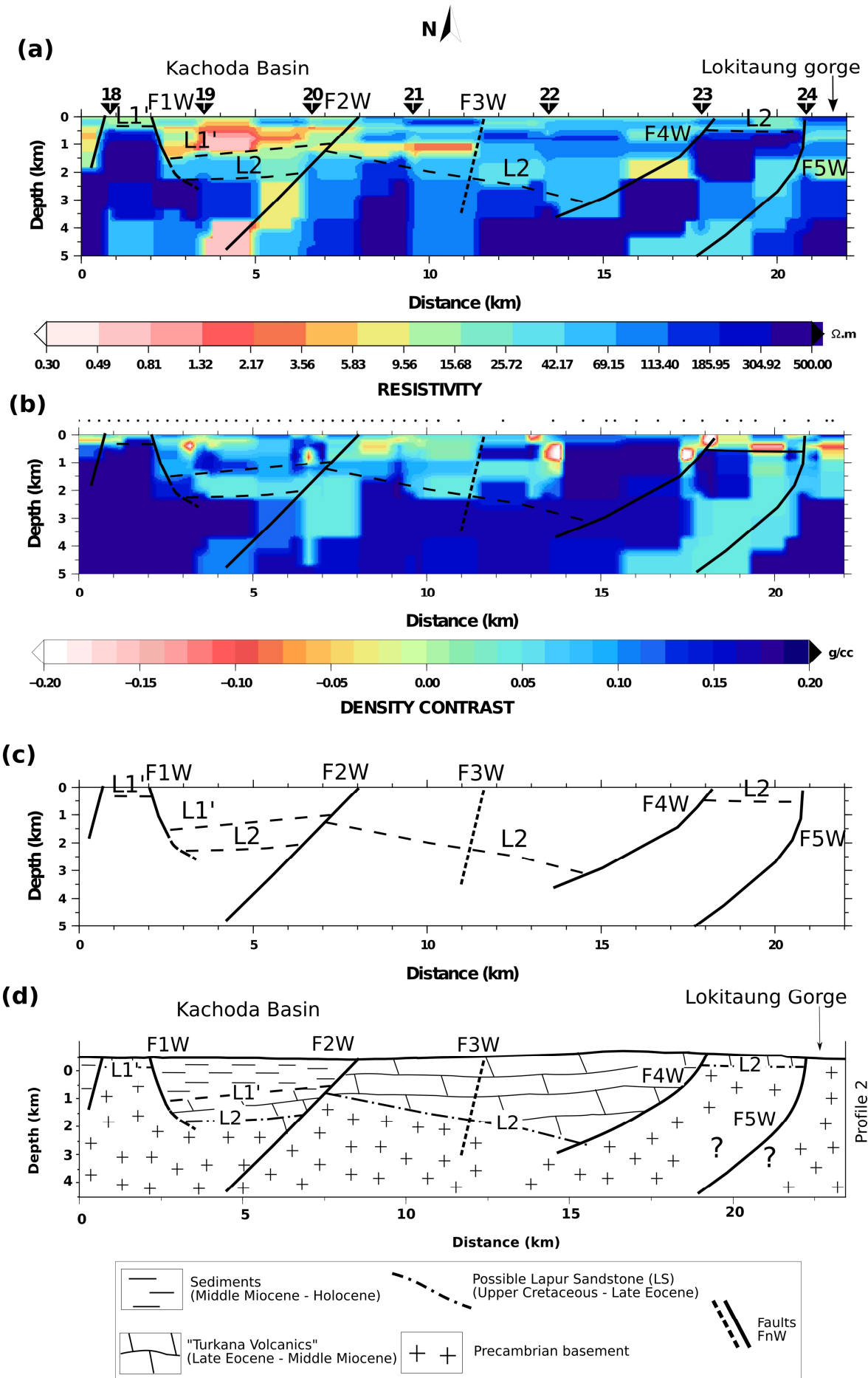


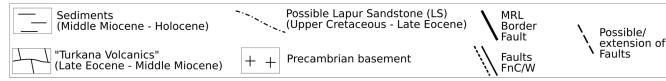
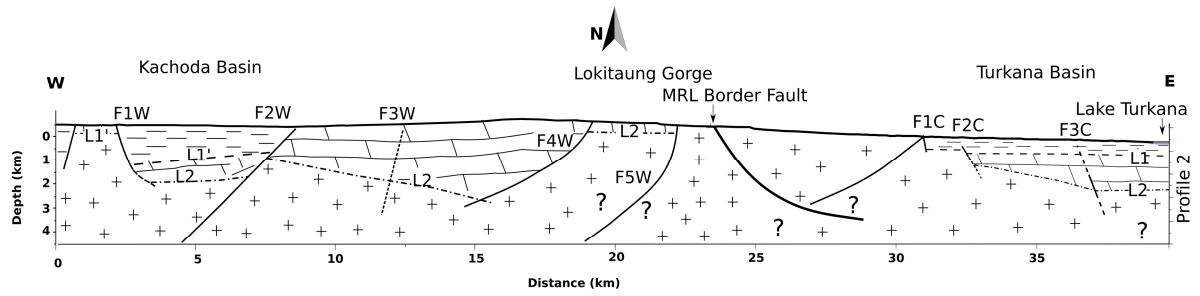






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**Highlights**

- 1) Confirm the Turkana half-graben basins geometry and organization at depth.
- 2) Delineate the “Turkana Volcanics” unit as well as horizontal/vertical variations
- 3) Characterize the depth and topography of the basement in the Northwest Turkana and Kachoda basins.
- 4) Characterization of the new Kachoda half-graben basin, thickness of its sedimentary infill; presence and thickness of the Turkana Volcanics at depth units; uncertainty in terms of presence of the Lapur Sandstone at depth; variations of basement topography.
- 5) MT and gravity data used in Turkana to surpass the poor quality of seismic.