

1 **Neogene-Recent Reactivation of Jurassic-age Faults in Southern Vietnam, with Implications for the**
2 **Extrusion of Indochina**

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8 **ABSTRACT**

9 Onshore Vietnam contains a complex series of faults coupled with a diffuse igneous province that has
10 been active since the mid-Miocene. However, there are several conflicting fault maps in the literature and
11 no consensus concerning the relative age of mapped faults and Neogene basalt flows, which becomes
12 problematic when trying to use structural data to distinguish between competing tectonic models for the
13 SE Asia region. This paper aims to define the Neogene-Recent tectonic setting and kinematics of the Da
14 Lat block of the onshore Vietnam region, by analyzing the orientation, kinematics and ages of faults across
15 a sub-region of the block. Fault ages can be constrained by the cross-cutting relationships with dated
16 basalt flows. Results from remote sensing show a strong NE-SW fault trend for southern Vietnam, with
17 additional, minor N-S, E-W and NW-SE trends. Fault orientations observed in the field fall into this NE-SW
18 trending class, and are sub-vertical. In the basalt flows (with eruption ages < 5 Ma) these faults have
19 oblique lineations with a strong strike-slip component. In Jurassic sediments, these faults show two sets
20 of lineations: an older, dip-slip set, and a younger, oblique-slip set. We postulate that Jurassic-age dip-slip
21 faults have been reactivated as strike-slip faults post 5 Ma. Strike-slip motion on NE-SW oriented faults is
22 consistent with rotation and extrusion of the Kontum and Da Lat blocks. Rotation of the blocks is

23 consistent with continuum rubble behavior of small crustal blocks under the influence of extrusion-driven
24 asthenospheric flow.

25

26 Keywords: Vietnam, Indochina, tectonic extrusion, block rotation, strike-slip faults, fault reactivation

27

28 **1. Introduction**

29 Onshore Vietnam is a complex region of faulting coupled with a diffuse igneous province that has
30 been active since the mid-Miocene (Figure 1a, b). However, there is no agreement over the relative ages
31 of mapped faults and known volcanic centers, as there are several conflicting fault maps and
32 interpretations of present-day fault activity (e.g. Huchon et al., 1994a; Rangin et al., 1995; Figure 2) for
33 the southern Vietnamese region. This lack of consensus over relative age becomes problematic when
34 trying to use structural data to distinguish between the two competing tectonic models for the evolution
35 of southern Vietnam, that of extrusion tectonics related to the collision of India with Eurasia, which is
36 thought to have ceased at ~5 Ma (Leloup et al., 2001; Zhu et al., 2009), or that of far-field extension related
37 to past spreading in the South China Sea region which ceased at ~16 Ma (e.g. Li et al., 2015). Onshore
38 Vietnam is also characterized by complex stress fields and absolute motions (Michel et al., 2001; Simons
39 et al., 2007; Tingay et al., 2010; Tran et al., 2013) which cannot easily be explained if the region is a
40 coherent part of the stable Sundaland block (Tingay et al., 2010).

41 The first model considered here is that of “extrusion” or “escape” tectonics, the process by which
42 the collision of two tectonic blocks leads to lateral escape of material formerly located between those
43 blocks. Extrusion has also been invoked to explain the evolution of areas including Alaska and the
44 Anatolian block in Turkey (Finzel et al., 2011; Gursoy et al., 1997, 2003; Mantovani et al., 2002; Redfield

45 et al., 2007; Ridgeway and Flesch, 2007; Tapponier et al., 1986). The mechanisms behind extrusion
46 tectonics remain poorly constrained, however. The proposed extrusion model for Indochina (see e.g.
47 Chamot-Rooke and Le Pichon, 1999; Chi and Dorobek, 2004; Chi and Geissman, 2013; Flower et al., 1998;
48 Hoang and Flower, 1998; Michel et al., 2001; Morley, 2007; Tingay et al., 2010; Yan et al., 2006) posits
49 that 1) strong coupling between the asthenosphere and lithosphere and a significant mantle drag torque
50 has translated the Southern Indochina microplate in response to extrusion of asthenosphere by the
51 closure of the Tethys Sea and Himalayan collision; and 2) the extruded lithospheric block is characterized
52 by giant strike-slip faults, smaller scale strike-slip faults and pull-apart basins, and minor normal faulting.

53 Seismic interpretation from two basins offshore from southern Vietnam, however, indicates a
54 phase of rifting coeval with the propagation of the South China Sea rift zone, and ascribes the presence
55 of the more recent faulting and onshore diffuse volcanic activity purely to the westward propagation of
56 this rift and associated thermal subsidence (Fyhn et al., 2009a, b). These data suggest that normal faulting
57 off-shore predates the voluminous volcanism onshore, and suggests that the volcanic flows erupt into
58 existing rift or pull-apart basins (Huchon et al., 1994b). However, South China Sea spreading ceased about
59 16 Ma (Li et al., 2015), and it is unclear whether far-field thermal subsidence can induce fault activity. The
60 extension-dominated model is expected to produce faults that 1) either pre-date or are synchronous with
61 volcanic activity, but do not post-date volcanic activity; and 2) have a dominant sense of motion that is
62 normal.

63 As noted above, existing fault maps are inconclusive (e.g. Huchon et al., 1994a; Rangin et al., 1995;
64 Figure 2) as to the age relationships between faulting and the basalts of the diffuse igneous province.
65 These maps are also inconsistent with respect to the sense of motion on the mapped faults (e.g. Searle et
66 al., 2010; Zhu et al., 2009), making it difficult to reconcile the tectonics of the region with either of the
67 two models proposed above. The scenario is further complicated by the recognition by local workers (e.g.
68 Kasatkin et al., 2017) of major strike-slip faults within the Indochina block that dissect southern Vietnam,

69 forming the Da Lat and associated blocks (Figure 1b), and suspected to be lithospheric in scale. This paper
70 aims to define the Neogene-Recent tectonic setting and kinematics of the Da Lat block of the onshore
71 Vietnam region, by analyzing the orientation, kinematics and ages of faults across a sub-region of the
72 block. Fault ages can be constrained by the cross-cutting relationships with dated basalt flows. These
73 results are used to demonstrate that there has been Cenozoic fault activity in the Da Lat block of southern
74 Vietnam that (a) post-dates the activity in the diffuse igneous province, (b) potentially reactivates older
75 faults, (c) is more consistent with an extrusion-based tectonic history than an extension-based tectonic
76 history for the region, and (d) has implications for how extrusion may be accommodated once a free
77 surface is no longer present.

78

79 **2. GEOLOGIC SETTING**

80 A series of structural, tectonic, and geophysical lines of evidence have been put forward to support
81 tectonic extrusion as the key driver of tectonic and volcanic activity in Indochina. That evidence includes
82 the presence of large-scale transform faults such as the Red River Fault Zone (linked to the East Vietnam
83 Transfer Zone) and the Mae Ping Fault Zone. The pattern of these major strike-slip faults in Southeast Asia
84 is markedly similar to the pattern of large-scale, left-lateral strike slip faults generated in analog
85 experiments by Tapponier et al. (1982, 1986). These experiments assume that the western Pacific is acting
86 as a free surface, that Greater India acts as a rigid indenter, and that Eurasia is segmented and extruded
87 toward the free surface in order to accommodate the collision. For example, the Red River fault zone
88 separates the South China block from the Indochina block, and showed left-lateral movement for much
89 of its history (Rangin et al., 1995). The extrusion model for Indochina further assumes a component of
90 mantle flow roughly parallel to the strike of the major faults (e.g., Flower et al., 1998; Hoang and Flower,
91 1998; Yan et al., 2006), which is corroborated by anisotropy recorded in shear-wave splitting data for the

92 upper mantle beneath the northern part of the Indochina-Shan Tai complex (Bai et al., 2009).
93 Paleomagnetic and GPS data suggest that the lithosphere is broken into a series of rigid blocks, where the
94 Kontum and associated blocks may be moving eastwards and rotating, and the Shan Tai block may be
95 rotating and moving to the south (Chamot-Rooke and Le Pichon, 1999; Chi and Dorobek, 2004; Chi and
96 Geissman, 2013; Michel et al., 2001; Morley, 2007; Tingay et al., 2010). One major challenge to the
97 extrusion model is that left-lateral motion along the Red River fault zone, a key signature of extrusion of
98 Indochina, ceased around 17 Ma, and became right-lateral motion by 5.5 Ma (e.g., Leloup et al., 2001; Zhu
99 et al., 2009). This cessation of left-lateral movement is frequently considered to mark the end of extrusion
100 of the Indochina block, but may instead mark a change in regional or local kinematics. Coeval with the
101 change in motion is inversion of some of the northern-most basins along the Red River Fault Zone, such
102 as the Song Hong Basin (Fyhn et al., 2018). Inversion can also be noted in Cuu Long and Nam Con Son
103 basins of south Vietnam (Pubellier & Morley, 2014). The cause of this change in plate kinematics is
104 variously ascribed to the ridge jump in the SCS, a change in Indian indentor motion (e.g. coupling the
105 Indian and Burmese blocks; Fyhn et al., 2009a, b), or an additional plate tectonic reconfiguration in the
106 region such as the collision of Australian fragments to the SE of Sundaland (Pubellier & Morley, 2014).

107 Extensional tectonics in Indochina have been well documented, starting with Jurassic-Cretaceous age
108 back-arc rifting, due to the subduction of the proto-Pacific crust under Vietnam, Borneo and South China
109 (Nam, 1995; Morley, 2012). Jurassic-Cretaceous rift locations were partially influenced by weak zones
110 resulting from the Indosinian Orogeny, the collision of the Sibumasu, South China and Indochina blocks
111 during the Triassic (Lepvrier et al., 2004; Pubellier & Morley, 2014). The Jurassic-Cretaceous event was
112 initially followed by Late Cretaceous rifting along the proto-South China basin (Barckhausen et al., 2014;
113 Chung et al., 1997; Zhou et al., 1995) and subsequently by the opening of the SCS, which experienced
114 ocean spreading from 32 Ma. Spreading either ceased at 20.5 Ma (Barckhausen et al., 2014) or at 16 Ma
115 for the southwest sub-basin of the SCS, closest to our study area (Li et al., 2015). After SCS spreading

116 ceased, rifting may have propagated onshore, while lingering upper mantle upwelling generated ongoing
117 diffuse seamount activity within the SCS (Barckhausen et al., 2014; Cullen et al., 2010; Matthews et al.,
118 1997; Swiecicki & Maynard, 2009; Yan et al., 2006). The date of 16 Ma also corresponds with the change
119 in motion along the Red River fault zone described above, marking a change in regional plate kinematics.
120 Regional compression and uplift led to widespread erosion across southern Indochina during the
121 Paleocene, with the development of significant unconformities across southern Indochina (Fyhn et al.,
122 2009a; Tri et al., 2011).

123 After the cessation of SCS rifting, regional uplift rates also became more rapid, contemporaneous
124 with the initiation of onshore volcanism in the Miocene (Carter et al., 2000; Fyhn et al., 2009a; Wang et
125 al., 2006). Onshore, eruptions of basalt have occurred in four significant phases since the Miocene: 17-12
126 Ma, 9-7.4 Ma, 5.4-1.75 Ma and 0.7-0.57 Ma (Tri et al., 2011). Fyhn et al. (2009a, b), Cullen et al. (2010)
127 and Savva et al. (2013) asserted that the observed patterns of uplift and on- and offshore volcanism are
128 purely the product of regionally propagating extension following the cessation of oceanic rifting, though
129 they do not otherwise explicitly account for the large volume of onshore volcanics. All sets of work
130 produced seismic lines across the offshore Phu Khanh, Cuu Long, and Nam Con Song basins and interpret
131 two to three stages of rifting, separated by a period of tectonic quiescence. Crucially, the last rifting phase
132 is after the cessation of active SCS spreading (Matthews et al., 1997; Swiecicki & Maynard, 2009; Savva et
133 al., 2013). In the Phu Khanh basin, rifting is interpreted to be transtensional and related to the offshore
134 trace of the Red River Fault Zone (Fyhn et al., 2009a, b; Cullen et al., 2010; Savva et al., 2013). Rifting in
135 the Cuu Long and Nam Con Song basins is interpreted by these authors to be related to continued regional
136 extension associated with SCS extension, even though active spreading to the east has ceased (Matthews
137 et al, 1997; Fyhn et al., 2009a, b; Dung et al., 2018). Volcanic eruptions there appear to have been
138 emplaced along fault planes, suggesting rifting predates volcanic activity (Fyhn et al., 2009 a, b), but it is

139 not clear if this pattern continues onshore, where the major tectonic regime during the Pliocene-Holocene
140 is thought to be thermal subsidence (Tri et al., 2011).

141 There are thus a number of observations that are not well explained by an extensional tectonic model
142 for southern Vietnam, such as the ongoing and voluminous volcanism, the origins of offshore rifting after
143 SCS spreading ended, and the change in fault motion of the Red River fault. Using fault geometries and
144 timing, palinspastic reconstructions, and geophysical data, some workers have thus instead attempted to
145 reconcile the extrusion model of Indochina with the opening of the SCS. The end-member models state
146 that SCS rifting is completely independent of the extrusion of Indochina (e.g., Chung et al., 1997; Clift et
147 al., 2008; Yan et al., 2006), or that the opening of the SCS basin is a direct consequence of the stress regime
148 imposed by the extrusion of Indochina (e.g., Briais et al., 1993). Zhou et al. (1995) and Fyhn et al. (2009a)
149 propose that extrusion tectonics had some effect on ridge axial relocations in the SCS as noted by Briais
150 et al. (1993), but that initial opening of the basin was independent of the India-Himalaya collision. Cullen
151 et al. (2010) propose that neither slab rollback in the western Pacific, nor extrusion of Indochina can fully
152 explain the tectonic setting of southern Vietnam, and invoke additional asthenospheric upwelling to
153 provide sufficient crustal extension, heat flow, and volcanism. Seismic data support the presence of a
154 shallow mantle thermal anomaly underlying Indochina, which may reflect diffuse mantle upwelling in
155 support of dispersed volcanic activity (Liu et al., 2004), and the region has documented high heat flow
156 (Duchkov et al., 1992; Uyeda, 1994).

157 Further, GPS data, albeit a sparse dataset, indicates that the Sunda block moves as a rigid and
158 coherent unit, with an absolute motion to the ESE (Michel et al., 2001; Simons et al., 2007; Tran et al.,
159 2013). However, the stress field across the Sunda block is heterogeneous, rather than subparallel to the
160 absolute motion vector (Tingay et al., 2010; Van Nquyen & Hoai, 2019) suggesting that the question of
161 whether this region can best be described in terms of block tectonics or continuous deformation (Calais
162 et al., 2006) is unresolved. In the case of Indochina, the block tectonics hypothesis of Calais et al. (2006)

163 is potentially compatible with an extrusion-driven origin for Neogene-Recent deformation in the region,
164 whereas the continuous deformation field hypothesis is more compatible with regional stretching and
165 thermal subsidence related to South China Sea rifting.

166 Existing data shows other discrepancies in the Da Lat and surrounding blocks (Figure 1b, 2), where
167 previously generated remote sensing and field focused maps (e.g. Huchon et al., 1994a; Rangin et al.,
168 1995) do not agree on fault locations or trajectories, nor on whether faults cut the voluminous basalt
169 flows or whether the flows overrun the major faults. Van Nguyen & Hoai (2019) provide several data
170 points where faults are observed to cut the Neogene or Quaternary basalts, although the bulk of their
171 data points are in the Cretaceous age granites. Studies of basalt flow ages (e.g. An et al. 2017; Lee et al.
172 1998) show that many of the flows in the Da Lat block are significantly younger than 5 Ma, indicating that
173 volcanism and potentially faulting are ongoing in the study area.

174

175 **3. METHODS**

176 This study was a joint remote-sensing and field study. We interpreted lineaments across the field
177 area, using both Landsat ETM+ data and SPOT data. Figure 3 shows Landsat ETM+ and SPOT coverages,
178 together with field locations. Landsat ETM+ datasets were sourced from the Global Land Cover Facility
179 (GLCF) and the SPOT data were sourced from Apollo Mapping. Landsat ETM+ data were downloaded as
180 separate bands and combined into a false color composite. Bands 531 were combined as RGB in ArcGIS.
181 This raster was stretched using the histogram equalize operation. Landsat ETM+ data were also combined
182 as a true color composite using bands 321 as RGB in ArcGIS. This imagery was blended using a standard
183 deviation stretch. SPOT data was provided as a true color composite by the vendor. The data were already
184 georeferenced to the Landsat ETM+ reference frame. Digital Elevation Model (DEM) data were also
185 sourced from the GLCF and displayed as classified datasets in ArcGIS. As for the Landsat ETM+ datasets,

186 the interactive map tool was used to define the study area and locate the datasets. The remote datasets
187 were compiled into an ArcGIS project and the field locations and other information were added by
188 database upload or by georeferencing jpg files. Other information comprises: 1) maps from Huchon et al.
189 (1994a), Rangin et al. (1995), and the Department of Geology and Minerals, Vietnam; and 2) locations
190 with dated basalt samples from Lee et al. (1998) and An et al. (2017).

191 Lineaments were picked from the satellite maps on the basis of textural changes in the images, or by
192 considering the changes in stream patterns. For example, abrupt changes in direction of stream channels,
193 or abnormally straight segments of streams, indicate the presence of joints or faults in the subsurface
194 governing that stream pattern (Drury, 2004). In addition, linear changes in texture of the land surface
195 often indicate a fault-controlled change, although care must be taken to avoid regions where the land
196 surface has been altered by humans. Such regions can be identified by the typical regular checkerboard
197 pattern of cultivated fields and field boundaries and the proximity to dwellings. It should be noted that
198 there are two resolutions of data in the imagery and thus there will be areas where lineaments may be
199 more densely picked than others; in addition, there are regions of the study area that are densely
200 populated and cultivated, such that there is not an even coverage of lineaments across the study area.
201 Once picked, the lineament map was classified using the ArcGIS Grouping Analysis algorithm, nearest
202 neighbor option, within ArcGIS. The lineaments were classified into 50, 75 and 100 bins, and the 75-bin
203 option was used to compare the lineaments to the field dataset and known earthquake locations in order
204 to produce a predicted deep-seated fault map of the area. The predicted deep-seated faults were picked
205 based on dominant orientation within the lineament clusters. The 75-bin option was used because, on
206 inspection, this option did not split trends that were apparent from the satellite data, which the 100-bin
207 option was prone to doing. The 50-bin option gave clusters that were too coarse when compared to the
208 field dataset.

209 We also undertook a reconnaissance field trip in 2016 to the southern part of the Central
210 Highlands, near Ho Chi Minh City, Buon Ma Thuot, and Vung Tau. We observed lithology at every stop,
211 and where relevant, we took measurements of bedding attitude, fault attitude and fault lineation pitch
212 within the fault plane. At each site, we noted the relationship of faults and the host lithology, considering
213 whether the fault terminated against lithological elements, or cut all observable lithologies. On our return
214 to the lab, these data were synthesized using GIS and Stereonet 10™ to determine similarity in fault
215 orientations, possible fault kinematics and the relationship to the lineament map.

216 To clarify the age of structural elements, the age of one alkali basalt flow (field sample number
217 2016-CH-10, retrieved from location 10.5076°N, 107.2729°E, and 229 ft. elevation), was determined using
218 $^{40}\text{Ar}/^{39}\text{Ar}$ methods at the Oregon State University Argon Geochronology Lab in Corvallis, Oregon. The
219 sample was crushed, sieved to $\sim 300\ \mu\text{m}$ grain size, rinsed in distilled water and dried at low temperature
220 in an oven ($\sim 80^\circ\text{C}$), then mildly leached to remove impurities. The procedure for leaching was a 20 min.
221 soak in 5% HNO_3 in an ultrasonic bath, followed by 3 rinses in distilled water, then a 20 min. soak in distilled
222 water in the ultrasonic bath and 3 more distilled water rinses; the sample was then again dried at 80°C or
223 lower in the oven. Following this preparation procedure, the sample was irradiated in the TRIGA
224 experimental reactor at the OSU Radiation Center at 1 MW power. The neutron flux during irradiation
225 was monitored using the FCT-NM standard, with an adopted age of 28.20 ± 0.02 Ma (after Kuiper et al.,
226 2008), and a $^{40}\text{Ar}/^{39}\text{Ar} = 9.733 \pm 0.008$ and J-value of 0.001615 ± 0.000001 . For mass spectrometry, the
227 sample was analyzed by incremental heating using a bulk CO_2 laser heating method on the ARGUS-VI-D
228 instrument at OSU. Ages were determined using a decay constant of $5.53 \pm 0.05 \times 10^{-10}\ \text{a}^{-1}$ (Steiger and
229 Jäger, 1977) using age correction methods after Min et al. (2000). Heating plateau ages were determined
230 using an error weighted mean of plateau steps. Additional standard and procedural blank results are
231 available in the Supplementary Information.

232

233 **4. RESULTS**

234 **4.1 Remote sensing**

235 Figure S1 shows lineament orientations mapped via remote sensing across the study area. In total,
236 2323 lineaments were picked across the study area using the methods described above. Figure S2 shows
237 a rose diagram of those lineament orientations, and shows a strong N-S to NE-SW fault trend, with very
238 minor components in other cardinal directions. 11.7% of the data is distributed between a bearing of 031
239 and 040. Figure 4 shows the classified lineaments, which were classified using the ArcGIS algorithm as
240 described above, and each cluster is shown in a different color. Note that there is a strong preferred
241 orientation within many of these clusters. For example, in the NW of the study area and to the W of the
242 lake, there is a teal-colored cluster which trends NNE-SSW. These lineaments all cut basalt flows which
243 have been previously dated as 4.3 \pm 0.2 Ma (An et al. 2017) or ranging between 2.42 \pm 0.08 Ma (south
244 of Xuan Loc center) to 0.24 \pm 0.06 Ma (north of Xuan Loc center; Lee et al., 1998; Figure 5) and thus fall
245 within the second youngest and youngest phases of basalt extrusion. Figure 5 further shows that the
246 lineaments do not preferentially cut basalts or clastic units, but are distributed between the Jurassic to
247 Quaternary formations without an apparent skew to one type of formation.

248 These data imply that there is a strong lineament orientation trending NE-SW across the study
249 area and that is in many cases younger than 4.3 \pm 0.2 Ma (An et al. 2017). Below we compare the
250 lineament data with the field data to further assess the nature of these lineaments.

251

252 **4.2 Field data**

253 Here we describe field observations for a series of sites across the study area (Table 1, Figure 3),
254 in order of observation. All strike and dip data is expressed using the Right Hand Rule convention, so no
255 dip quadrant is listed.

256 At location 1 (Figure 3), a series of faults cutting Jurassic sediments were observed (Figure 6). One
257 key fault (Figure 6a, b) had an attitude of 024/88 with two sets of lineations, one pitching 16°SW and the
258 other pitching 80°SW (Figure 6c). Figure 8b shows that the sub-horizontal lineation cross-cuts the dip-slip
259 lineation on this fault surface. On the other side of the same quarry, faults were observed with attitudes
260 of 027/58 (dip-slip lineations) and 015/48 (no visible lineations) (Figure 6c). We could not identify whether
261 the oblique slip lineaments were left-lateral or right-lateral as there were no identifiable “steps” in these
262 lineaments.

263 At location 2 (Figure 3), a series of faults cutting the Soc Lu Formation were observed (e.g. Figure
264 7a). The Soc Lu Formation at this locality has been dated to 4.3 +/- 0.2 Ma (An et al., 2017). Field
265 observations of plagioclase and biotite phenocrysts in Soc Lu volcanics suggest that the Soc Lu Formation
266 eruptives include basaltic andesite, and the observed flow coverage (not shown in Figure 5 due to its
267 limited extent) suggests a relatively small flow unit within the Xuan Loc volcanic center. The faults at this
268 location strike NE-SW and are sub-vertical. One fault has an attitude of 036/76 and two other fault
269 surfaces are oriented 023/85 and 028/80. On each fault surface, sub-horizontal lineations were observed,
270 with pitches of 12°NE, 12°NE and 18°NE respectively (Figure 7b). Again, we were not able to discern
271 whether the lineations gave a sense of left- or right-lateral movement because convincing “steps” in the
272 lineations were not identifiable on these fault planes.

273 At location 3 (Figure 3), an old quarry in the alkali basalts of the Xuan Loc Formation where mantle
274 xenoliths were observed, additional faults were observed with orientations of 172/57 and 121/80. The
275 first of these faults was marked by heavily foliated basalt, and neither fault displayed lineations.

276 Locations 4-7 are clustered close together in faulted Cretaceous age granites near Vung Tau. These
277 granites are part of the Deo Ca complex which has been dated at either 88-92 Ma or c. 118 Ma by U-Pb
278 zircon geochronology (Ngyuen et al. 2004; Shellnutt et al., 2013; Hennig et al., 2018). One major fault with

279 several strands and a damage zone of tens of cm wide has an attitude of 236/84 (Figure S3a). Other fault
280 surfaces have attitudes of 228/74 and 294/76, and these fault zones contain black material that may be
281 pseudo-tachylite or later intruded and sheared mafic material (Figure S3b). The major fault zone oriented
282 at 236/84 corresponds to the known Ca Na-Vung Tau fault zone (Figure 1b) which bounds the Da Lat block
283 to the south.

284 At location 8, an alkali basalt quarry north of Vung Tau, a series of joints were measured, as there
285 was no visible evidence of faulting on the safely accessible exposed faces of this active quarry. The pole
286 figure for this dataset is found in Figure S4. A strong cluster of poles is found marking a joint set oriented
287 ENE-WSW, amongst a near uniform distribution of other joints. We infer that this outcrop was cut by a
288 combination of columnar, i.e. basaltic cooling joints, and a systematic set of joints oriented ENE-WSW.

289 Sample 2016-CH-10 from location 8 was determined using $^{40}\text{Ar}/^{39}\text{Ar}$ age dating methods to have
290 an initial eruption age of 0.600 ± 0.004 Ma (2σ). This weighted mean plateau age is consistent with ages
291 calculated using the alternative total fusion (0.599 ± 4 Ma), normal isochron (0.599 ± 0.006 Ma), and
292 inverse isochron methods (0.599 ± 0.006 Ma) (see Supplementary Information for additional raw data and
293 plateau age results for this analysis). The mean squared weighted deviation for the plateau age is 0.002
294 Ma, and calculated K/Ca ratio is 0.21 ± 0.09 (2σ).

295 These data indicate that there are small-scale faults and fractures that both pre and post-date the
296 basalt flows across the studied area of the Da Lat block. The following section will compare this dataset
297 to the lineament dataset and derive a model for the generation of the small-scale faults and fractures.

298 **4.3 Combining the datasets**

299 The small-scale faults and fractures of the field dataset are overall interpreted to be the classified
300 lineaments of the remote sensing dataset. However, some of the faults in the field dataset predate the
301 basalts while others post-date the basalts. In addition, at Location 1, the fault in the Jurassic-Cretaceous

302 sediments has been reactivated, indicating the occurrence of multiple events. We infer that the faults
303 documented at Locations 1 and 4-7 with age constraints of either post-Jurassic or post-Cretaceous (that
304 is, post c. 118 Ma or post 88-92 Ma) are deeper seated or pre-existing faults. These pre-existing faults
305 predate Late Cretaceous and younger sedimentation and basalt effusion in the region. Such faults can be
306 estimated from the average orientations of classified lineament clusters as shown in Figure 8. In some
307 cases, additional data such as earthquake event locations were used to identify these deeper seated or
308 pre-existing faults. We infer that many of these deeper and/or pre-existing faults initiated as rifts in the
309 Jurassic or Cretaceous and have since been reactivated as strike-slip faults during later deformation. In
310 some cases (e.g., Figure 9a, b) classic lineament patterns are observed that suggest reactivation of the
311 deeper-seated fault as a transpressional flower structure.

312 **4.4 Model for faulting across the Da Lat Block**

313 Considering the faults at locations 1 and 2, we infer that the NE-SW trending faults cutting the
314 basalt flows are genetically related to the NE-SW trending faults in the Jurassic sediments. We postulate
315 that (a) the Jurassic-Cretaceous, steeply dipping dip-slip faults or joints have been reactivated as strike-
316 slip faults during the Neogene (location 1), and (b) this reactivation of deeper-seated faults led to the
317 generation of damage in the overlying Neogene basalts. This damage is manifested as the smaller-scale
318 strike slip faults observed at location 2 and potentially as the fractures noted and measured at location 8,
319 although we acknowledge that these fractures may be due to a different phase of relatively recent
320 deformation within the Da Lat block. The development of strike-slip motion on faults oriented dominantly
321 NE-SW within the Da Lat block is consistent with the continued extrusion of this block within the large-
322 scale shear zone created by the Three Pagodas Fault and Ailo Shan-Red River-East Vietnam shear zones
323 (Figure 1a). We therefore propose that extrusion did not cease at 5 Ma as has been previously suggested,
324 but is ongoing, and is now accommodated by the rotation of blocks such as Da Lat and by internal
325 deformation within this part of Sundaland. We speculate that the kinematics of the extrusion regime

326 changed with the change in regional plate dynamics, as discussed in Section 2, and with the effective
327 removal of the Western Pacific free surface by the collision of Luconia, Dangerous Grounds and Reed Bank
328 with NW Borneo and Palawan (Hall, 2002; Hall et al., 2008; Clift et al., 2008). In our conceptual model, the
329 individual blocks shown in Figure 1b are moving semi-independently, similar to the continuum
330 deformation style proposed by Calais et al. (2006). Under the existing extrusion model, Vietnam and the
331 Da Lat block move to the SE (e.g. Tingay et al., 2010). Under our new model, the Da Lat block moves semi-
332 independently to the SW to accommodate extrusion.

333

334 **5. DISCUSSION**

335 Contrary to existing literature (e.g. Rangin et al., 1995; Searle et al., 2010; Zhu et al., 2009) which
336 states that faulting of both extrusion and extension regimes has ceased in the Indochina Peninsula, our
337 results demonstrate that faulting has been more recent than 4.3 ± 0.2 Ma (An et al. 2017), 0.600 ± 0.004
338 (this study), or 0.24 ± 0.1 Ma (Lee et al., 1998). This is more recent than the postulated end of extrusion
339 based on the change in motion of the Red River Fault Zone (5.5 Ma; Leloup et al., 2001; Zhu et al., 2009)
340 and, significantly, the cessation of rifting in the South China Sea (16 Ma: Li et al, 2015). Thus, a tectonic
341 regime more complex than thermal subsidence must be operating across onshore Vietnam, and we
342 propose that this regime is extrusion-related. We do not favor the extension argument because the key
343 faults observed at locations 1 and 2 were oriented NE-SW and showed oblique to strike-slip movement,
344 whereas under an extensional regime, faults in this orientation would show oblique to dip-slip movement.
345 Our proposed model of continuum block deformation of the onshore Vietnam region and southwestwards
346 movement of the Da Lat block further predicts dominantly left-lateral movement on the NE-SW oriented
347 strike-slip faults that were observed in the field and on the East Vietnam Transfer Zone (Trinh et al., 2015).
348 While the lineations observed to-date do not show stepwise patterns that allow us to identify the sense

349 of motion to test this prediction, because we do not observe dip-slip motion on these faults we can still
350 effectively rule out an extension-dominated regime related to the SCS. The presence of strike-slip faulting
351 is compatible with the results from extensive field mapping in the Cretaceous granites reported by Van
352 Nguyen and Hoai (2019). Van Nguyen and Hoai (2019) further reported four stress regimes operating
353 since the end of the Oligocene and interpreted a rotation in the stress field associated with extrusion. We
354 note that there is some spatial variation in each stress field across the Song Ba fault, which separates the
355 Kontum and Da Lat blocks. Thus, we surmise that the Van Nguyen and Hoai (2019) dataset is compatible
356 with our model.

357 We have generated a proposed pre-Neogene fault map (Figure 8) for a sub-region of the Da Lat
358 block, based upon lineament mapping and cluster analysis, which is distinctly different from the fault
359 maps generated by previous authors and shown in Figure 2. Our fault map has a denser distribution of
360 structural features than the maps shown in Figure S5 and consists of shorter discrete fault segments, due
361 to improved imagery resolution. Our fault map is also unique in that it constrains the ages of the remotely
362 sensed faults (post-Jurassic and pre-Neogene, i.e. pre-basalt effusion) and distinguishes these older,
363 deeper-seated faults from the more recent, smaller-scale faults and fractures visible on the lineament
364 map that cut Neogene-Recent basalt flows. We further suggest that the older structures (Figure 8) date
365 from late Jurassic subduction under the leading edge of the Kontum block and contemporaneous,
366 associated intraplate extension, as documented by Tri and Bao (2011). An episode of basin inversion may
367 have reactivated these faults in the late Miocene-early Pliocene (Tri and Bao, 2011) due to a change in
368 direction of Indian plate subduction, coincident with the change in sense of motion of the Red River Fault
369 Zone (e.g., Leloup et al., 2001; Zhu et al., 2009).

370 The Red River Fault Zone ceased left lateral motion around 17 Ma and initiated right-lateral
371 motion approximately 5.5 Ma (e.g., Leloup et al., 2001; Zhu et al., 2009; Zuchiewicz et al., 2013). As noted
372 above, this change was previously inferred to mark the end of extrusion of Indochina, but instead we

373 suggest that this marks a change in the kinematics of the extrusion process. During right-lateral motion,
374 the major block being extruded is the South China block (Guo et al., 2001; Meng et al., 2005). However,
375 this does not account for asthenospheric flow associated with the extrusion of Indochina, or for
376 documented ongoing volcanism (e.g., the 1923 eruption of Ile des Cendres), which suggests continued
377 mantle flow and upwelling (e.g. Hoang and Flower, 1998). To accommodate the motion of the mantle
378 conveyor belt beneath, the Shan Tai, Kontum, Da Lat and other blocks would need to rotate within the
379 confines of the larger scale shear zone defined by the Red-River – East Vietnam Transform and the Mae
380 Ping Fault Zones. This is required because there is no free surface into which these blocks can be extruded,
381 given their position in the core region of Sundaland. This suggestion posits a strong coupling between the
382 asthenosphere and the lithospheric blocks in this area, in contrast to the relatively weak mantle drag
383 torque inferred for areas with high subduction zone torques (e.g., the Nazca and Pacific plates; Chapple
384 & Tullis, 1977). We therefore suggest that extrusion tectonics require a strong lithosphere-asthenosphere
385 coupling, and that once the free surface is removed by other tectonic processes, block rotation is the
386 inevitable consequence of ongoing mantle flow.

387 Paleomagnetic and GPS data from the core of Sundaland show that the Kontum block region is
388 likely moving to the east and rotating clockwise within Sundaland (Chamot-Rooke and Le Pichon, 1999;
389 Chi and Dorobek, 2004; Chi and Geissman, 2013; Cung and Geissman, 2013; Michel et al., 2001; Morley,
390 2007; Tingay et al., 2010; Tran et al., 2013). This rotation is consistent with a regional model whereby
391 Sundaland is composed of not a rigid core, but instead a continuum rubble of fragments that interact and
392 “jostle” or rotate with respect to one another under regional stresses. The eastward motion of the
393 Kontum block is consistent with a continued overall extrusion of material from the Himalayan collision to
394 the east and southeast. The Da Lat block lacks GPS and paleomagnetic data at a fine enough scale to
395 resolve the proposed southwest-wards motion and merits further investigation (Van Nguyen and Hoai,
396 2019 and references therein).

397

398 **6. CONCLUSIONS**

399 Results from remote sensing show a strong NE-SW fault trend for southern Vietnam, with additional,
400 minor N-S, E-W and NW-SE trends. The dominant trend characterized as NE-SW is composed of a dataset
401 dispersed between N and NE orientations, with a peak at the NNE orientation. Many of these lineaments
402 cut basalt flows previously dated at 4.3 ± 0.2 Ma (An et al. 2017) or 0.24 ± 0.1 Ma (Lee et al., 1998), as
403 well as one measured here to be 0.600 ± 0.004 Ma. Fault orientations observed in the field fall into this
404 NE-SW trending class, and are sub-vertical. In the basalt flows (with eruption ages < 5 Ma) these faults
405 have oblique lineations with a strong strike-slip component. In the Jurassic sediments, these faults show
406 two sets of lineations; an older, dip-slip set, and a younger, oblique-slip set.

407 These results indicate that the NE-SW dominant set of faults cuts basalt flows significantly younger than
408 5 Ma, and movement on these faults is therefore younger than both the cessation of rifting in the SCS and
409 the cessation of sinistral movement on the Red River Fault. We infer that the NE-SW trending faults cutting
410 the basalt flows are related to the NE-SW trending faults in the Jurassic sediments, and postulate that
411 Jurassic-age dip-slip faults have been reactivated as strike-slip faults post 5 Ma. Strike-slip motion on NE-
412 SW oriented faults is consistent with rotation and extrusion of the Kontum and Da Lat blocks, rather than
413 extension and subsidence, in which case dip-slip (normal) motion would be expected. Furthermore,
414 rotation of the blocks is consistent with continuum rubble behavior of small crustal blocks under the
415 influence of extrusion-driven asthenospheric flow.

416

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422

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616

617 **Table 1**

Location #	Latitude (°N)	Longitude (°E)	Elevation (ft)	Brief field description
1	11.4091	107.6399333	788	Quarry in Dambri town, in Jurassic sediments; faulted
2	10.9964	107.1432833	864	Quarry in Soc Lu Formation – basaltic andesite; faulted
3	10.87686667	107.2284	841	Old quarry in alkali basalt; faulted
4	10.38025	107.2564	6	Cretaceous granite outcrop on the coast near Vung Tau; Ca Na-Vung Tau fault zone prominent
5-7	10.38073333	107.2524667	3	Cretaceous granite outcrops on the coast near Vung Tau; subsidiary fault systems to Ca Na-Vung Tau fault zone

8	10.50761667	107.2729167	229	Alkali basalt quarry with xenoliths; jointed but not faulted.
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619 Table 1: Co-ordinates and brief field descriptions for the locations referenced in this study. Co-ordinates
620 are given in decimal degrees and in WGS 84 convention. Elevations are given in feet above sea level.

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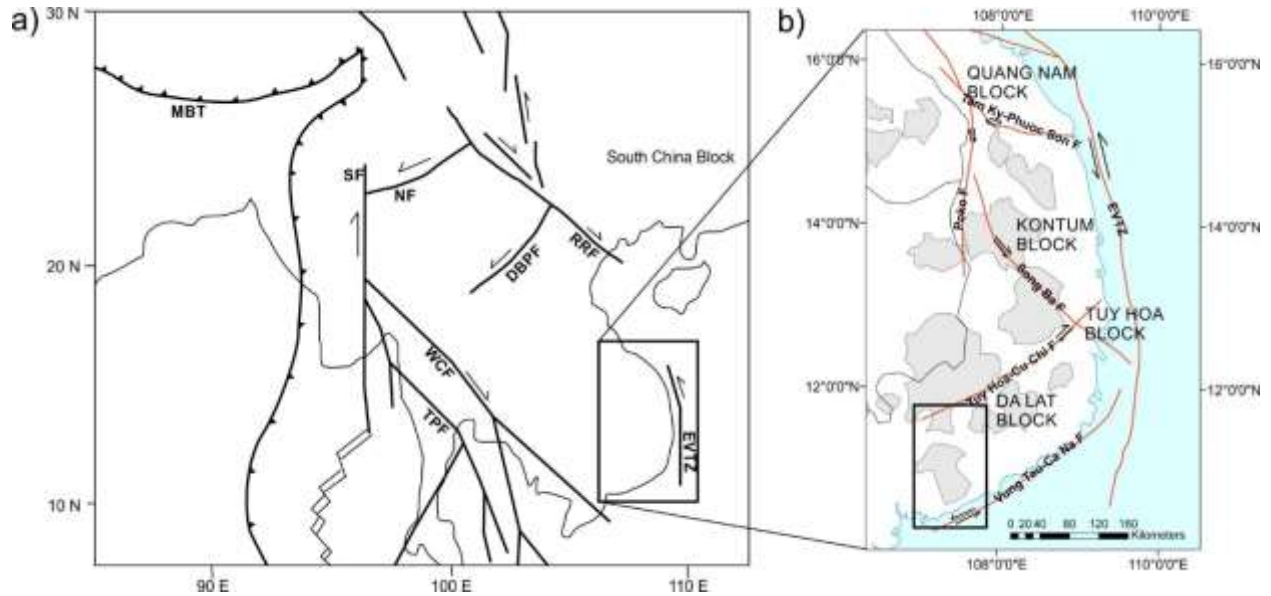
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635 Figure 1



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637 Tectonic maps of the region. a) shows regional faults of the Himalayan orogen as well as the major
 638 strike-slip faults of the Indochina Peninsula, modified after Leloup et al. (1995) and Nam (1995). MBT,
 639 Main Boundary Thrust; SF, Sagaing Fault; NF, Nanting Fault; TPF, Three Pagodas Fault; WCF, Wang Chao
 640 Fault; EVTZ, East Vietnam Transfer Zone; RRF, Red River Fault; DBPF, Dien Bien Phu Fault. b) Block map
 641 of the wider study area after Kasatkin et al. (2017). Red lines mark faults, grey areas are volcanic
 642 centers. Black box marks the present detailed study area.

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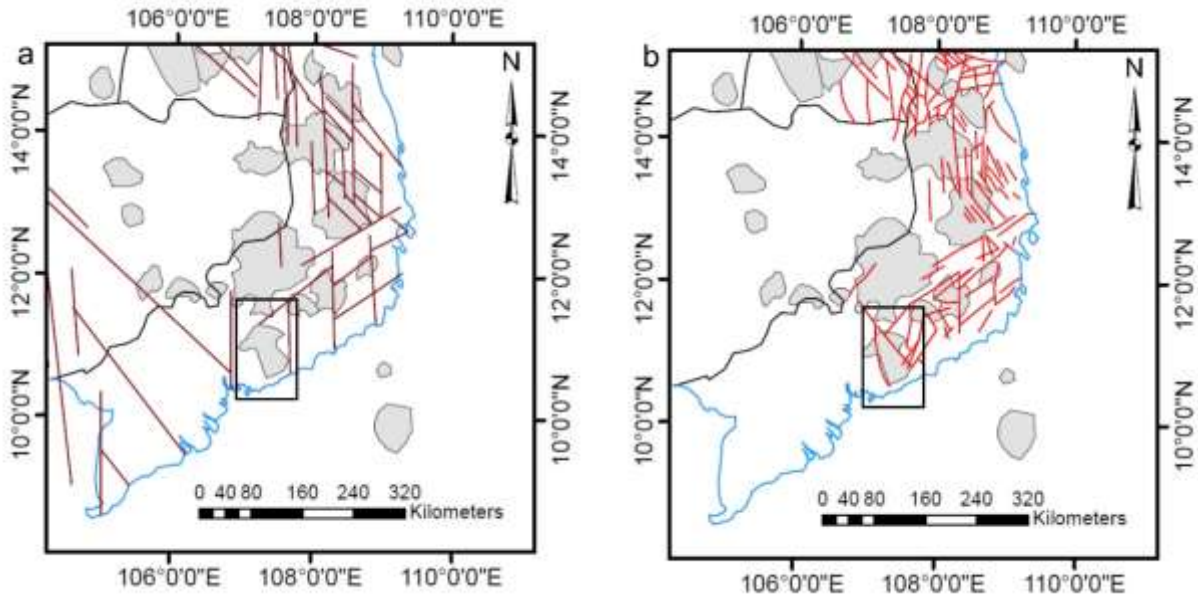
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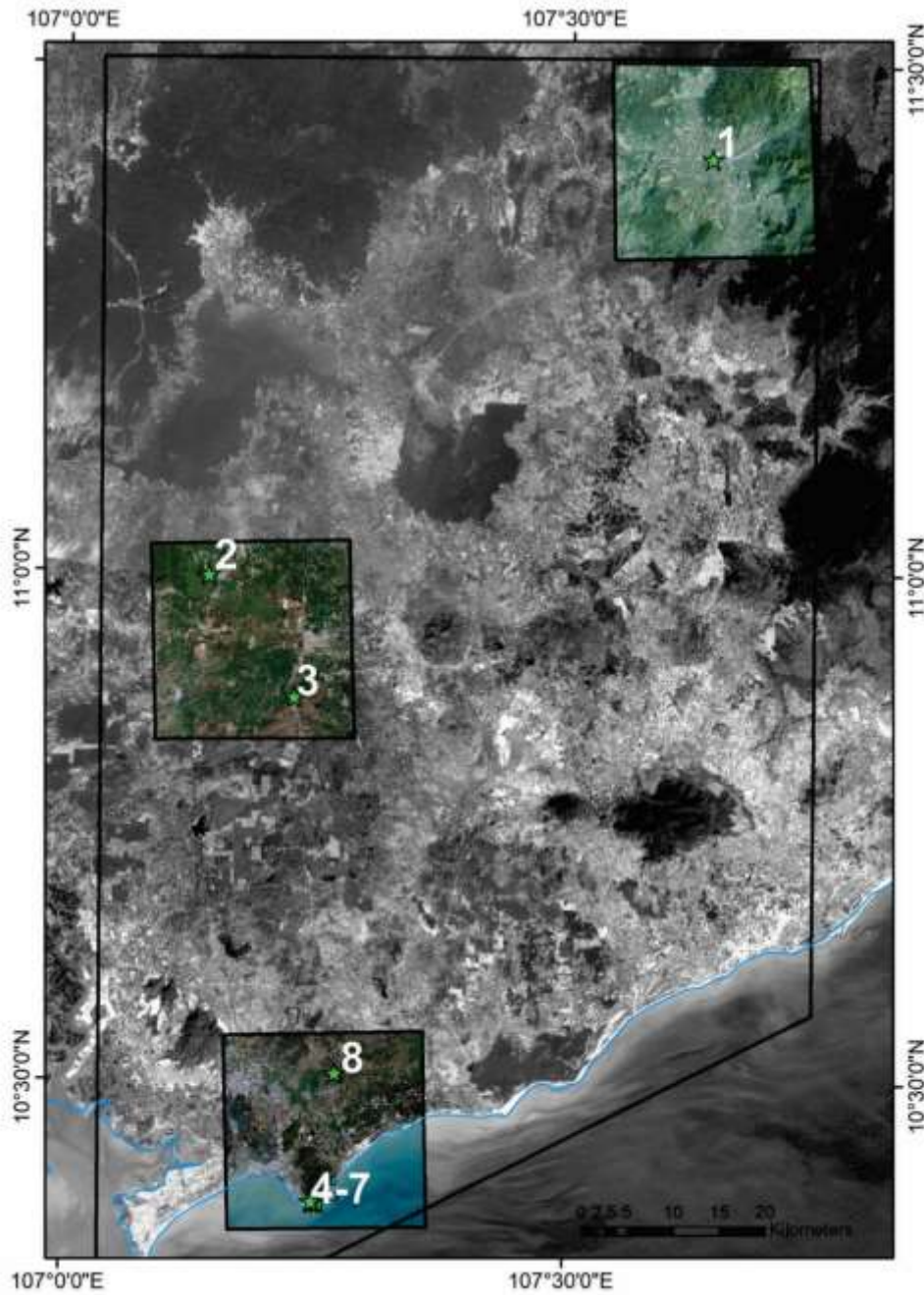
656 Figure 2:



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658 Contrasting fault maps for the Da Lat block and southern part of the Kontum block. a) is from Huchon et
659 al. (1994a), and shows their interpretation of the Paleogene fault framework in the region. b) is from
660 Rangin et al. (1995) and shows their contrasting interpretation of the dominant fault patterns in the
661 area. Grey areas are volcanic centers and the black box marks the location of the present study area.

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675 Figure 3:



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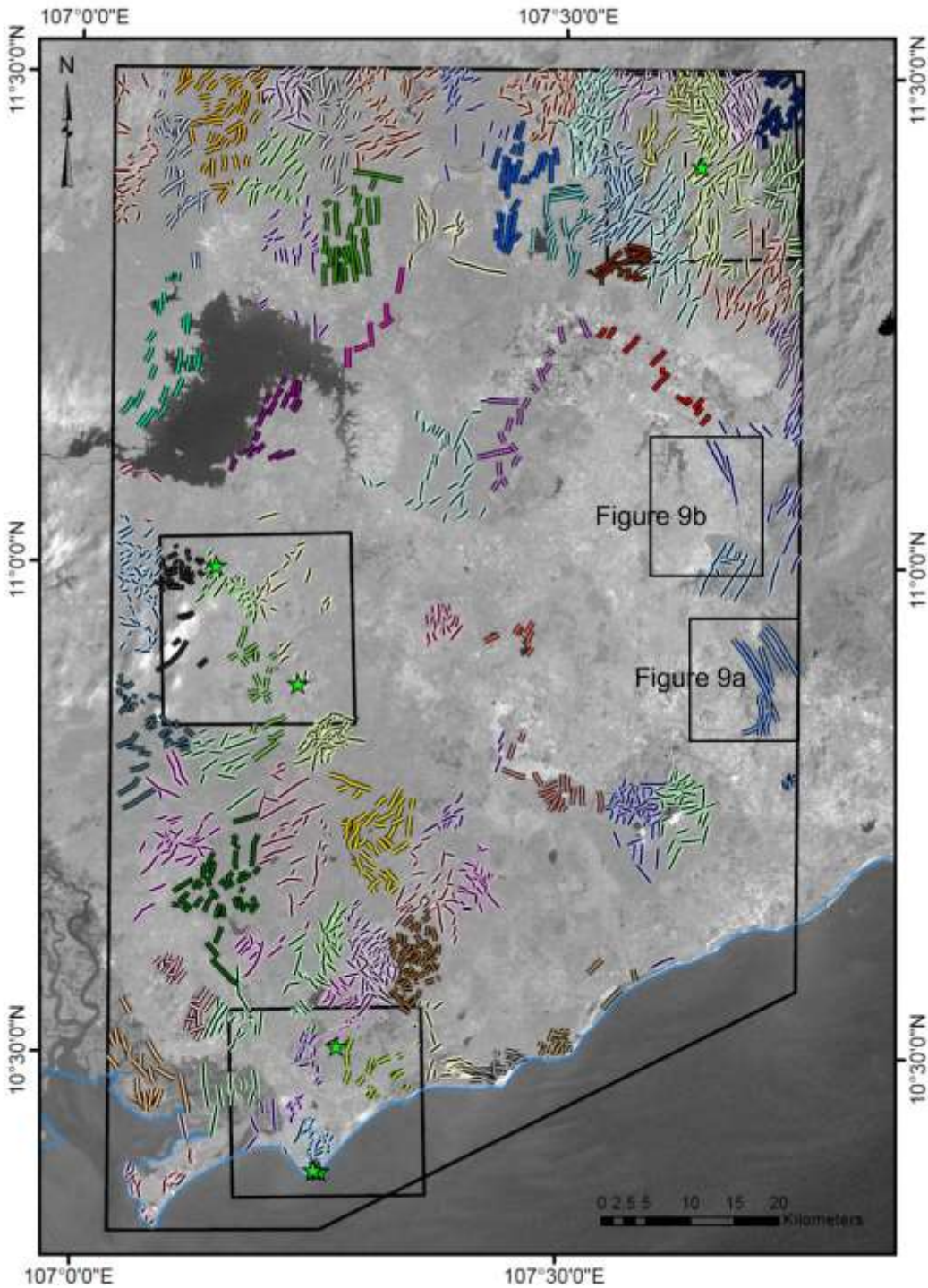
677 Landsat ETM+ coverage of the study area, in greyscale, showing field locations (green stars with white
678 numbers) and locations of the SPOT patches used for detailed analysis of key areas (colored squares of
679 higher resolution imagery).

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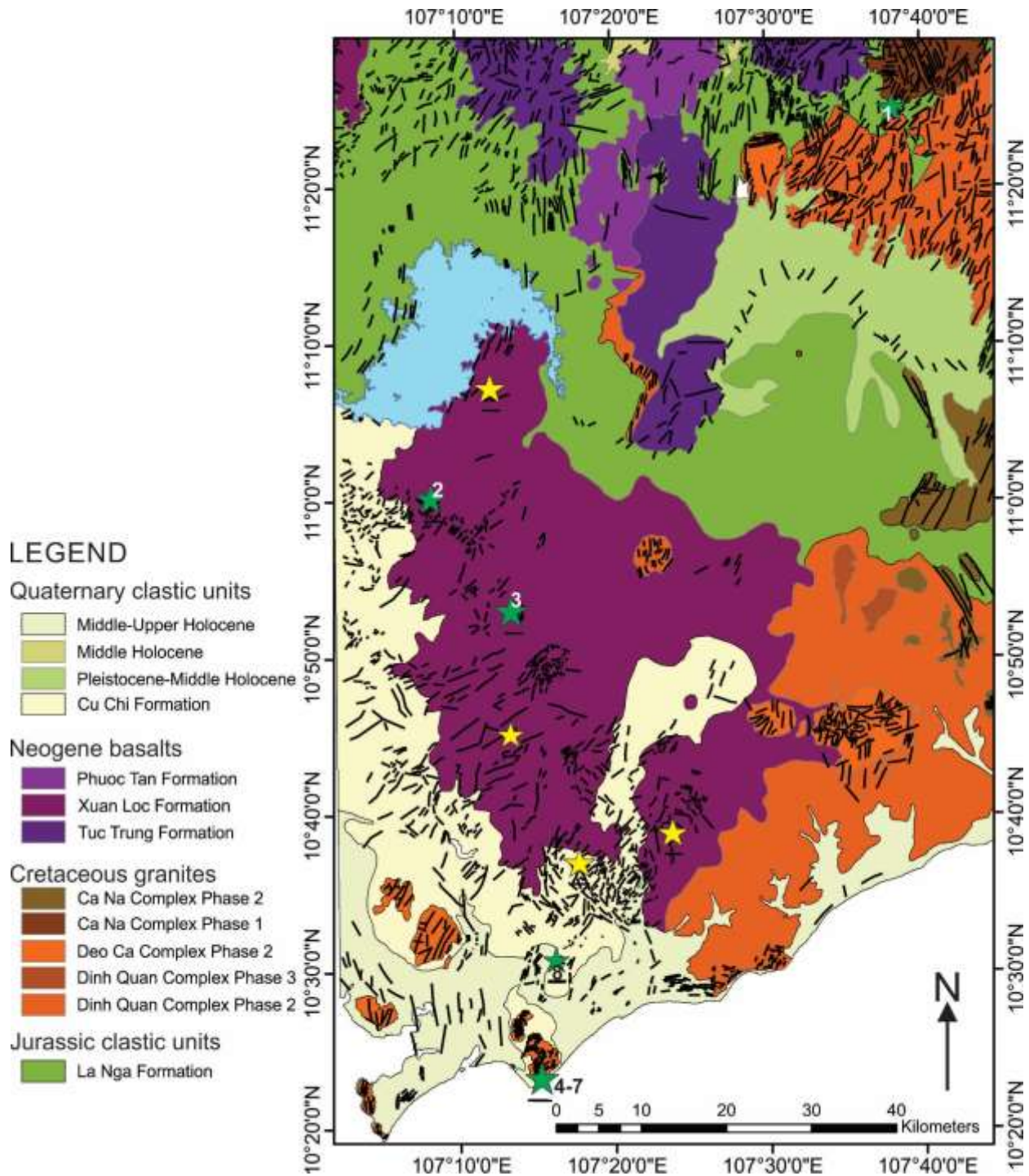
683 Figure 4:



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685 Classified lineaments across the study area, superimposed on a Landsat ETM+ image. Lineaments have
686 been classified into 75 bins based on a nearest neighbor algorithm in the ArcGIS Grouping Analysis. Black
687 boxes show the location of SPOT datasets. Green stars represent the locations visited in the field, with
688 location numbers as in Figure 3. The location of Figure 13a and Figure 13b are also shown.

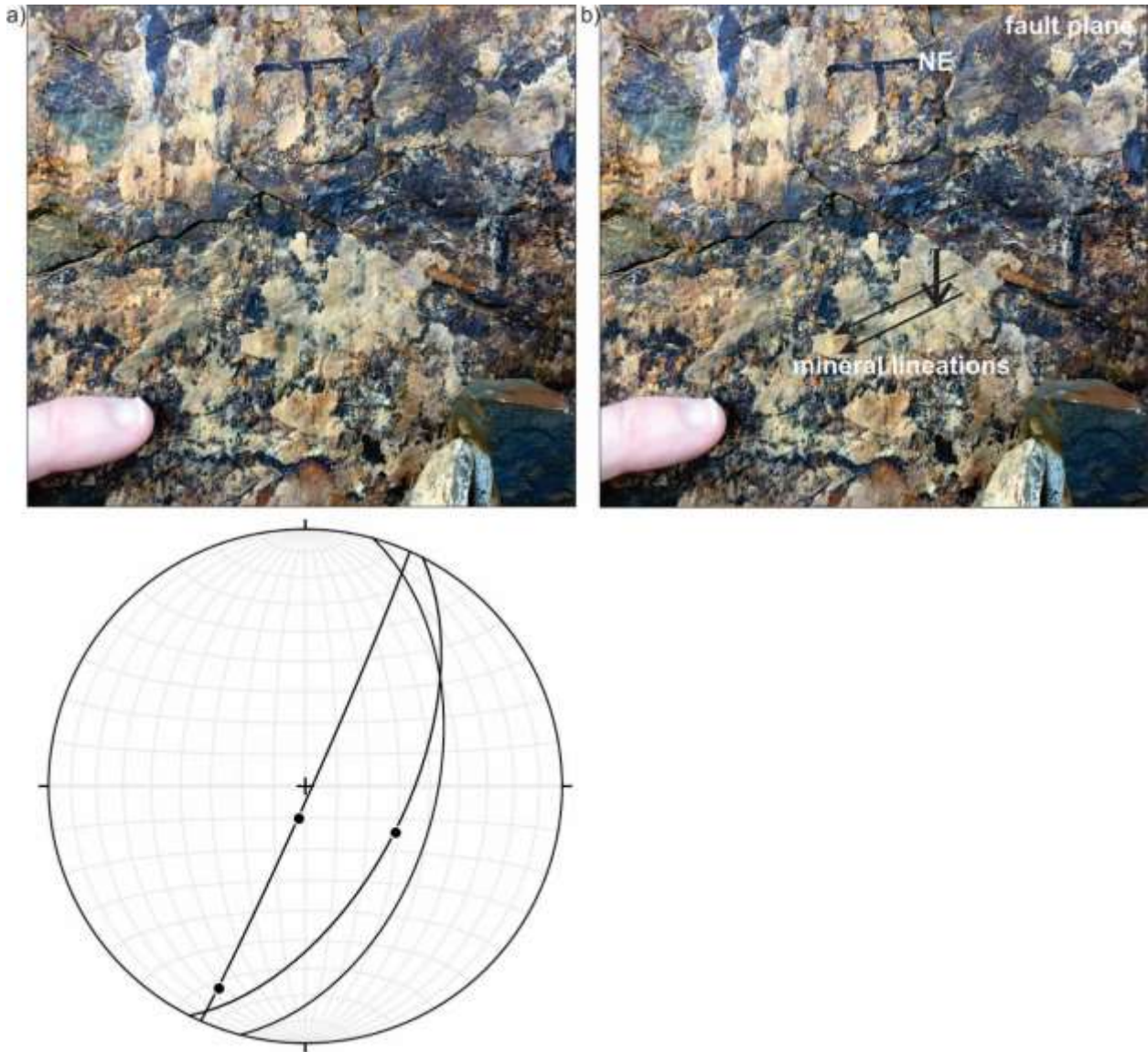
689 Figure 5



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691 Geologic map of the study area showing that lineaments cut both young (Neogene) and older
 692 (Cretaceous-Jurassic) formations. Numbered green stars mark field locations from this study. Yellow
 693 stars mark locations with previously dated basalts (either from outcrop or from core) from Lee et al.
 694 (1998) ranging in age from 2.42 ± 0.08 Ma in the south, to 0.24 ± 0.06 Ma in the north of the Xuan Loc
 695 Formation. Basalts at location 2 have been previously dated by An et al. (2017) to be 4.3 ± 0.2 Ma.

696 Figure 6



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699 a) Field photograph showing fault plane with mineral lineations in the Jurassic sediments at location 1.
700 b) Annotated version of image in part (a); black arrows show orientations of mineral lineations, where
701 the longer arrows cross-cut the shorter, dip-slip arrow. c) stereonet with great circles indicating fault
702 planes, and dots indicating lineations on fault planes where observed. The stereonet shows all faults
703 present at this location. The near-vertical fault plane with two lineations is the fault plane shown in
704 parts a and b.

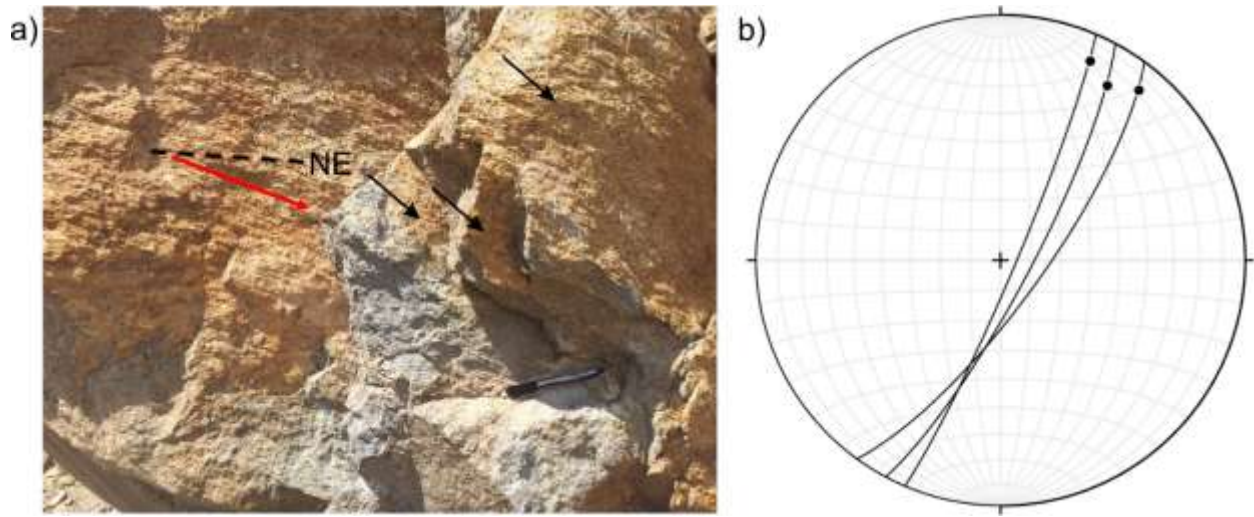
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709 Figure 7



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711 a) Faults in the Pliocene Soc Lu Formation, at location 2. The black dashed line shows the strike of the
712 fault, and the red arrow shows the trend and plunge of the lineations on one fault plane. Other fault
713 planes are arrowed. b) Stereonet as for Figure 6, showing fault planes and lineations recorded at this
714 location. Note the lack of dip-slip lineations and the prevalence of strike-slip lineations.

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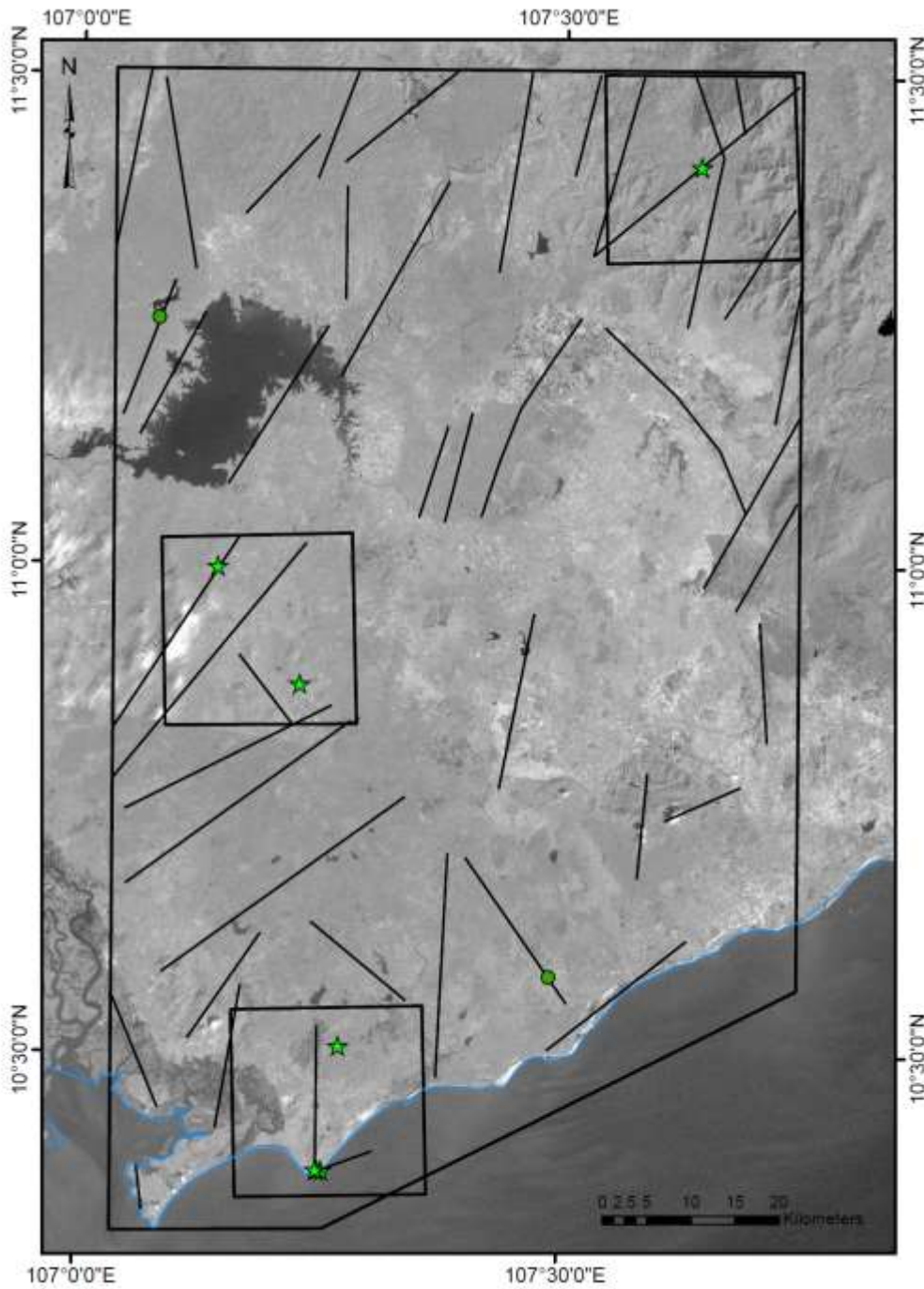
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730 Figure 8



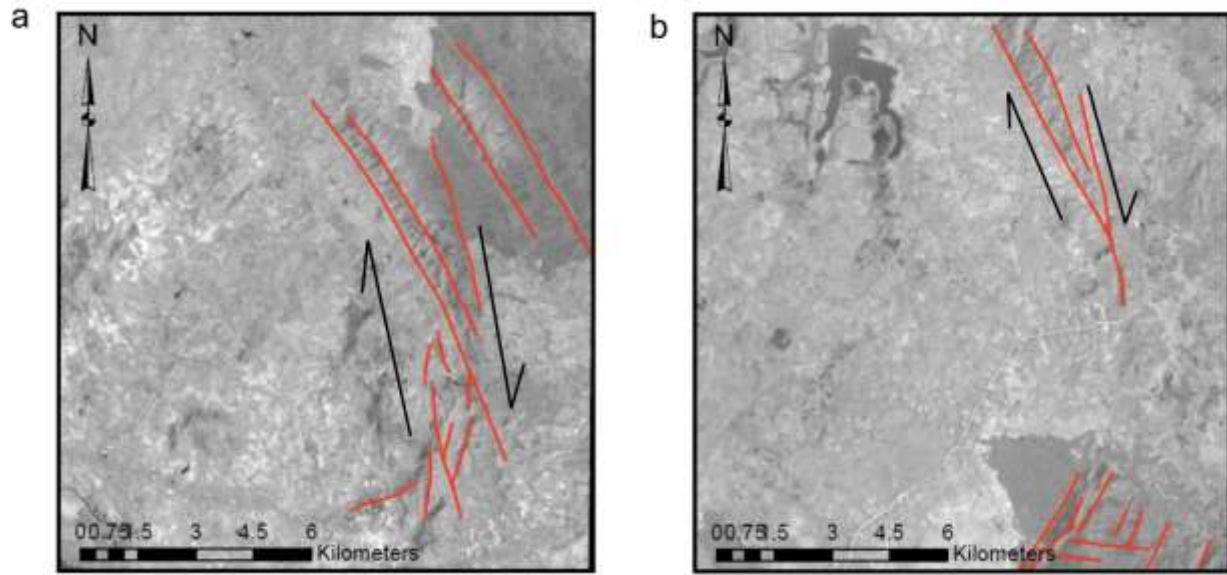
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732 Post-Jurassic, pre-Neogene fault map of the study area, derived from the classified lineaments. Black
733 boxes show the location of SPOT datasets. Green stars represent the locations visited in the field, with
734 location numbers as in Figure 3. Green dots represent the locations of known earthquakes.

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737 Figure 9



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739 Examples of lineament patterns developing above a reactivated strike slip fault. For the location of each
740 of these examples, see Figure 4.

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