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1 Triassic-Jurassic evolution of the eastern North China Craton: insights
2 from the Lushun-Dalian area, South Liaodong Peninsula, NE China

3

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14 **Abstract**

15 The Lushun-Dalian area of the South Liaodong Peninsula located in the SE margin
16 of the North China Craton (NCC) exposes a suite of Middle-Late Proterozoic low-grade
17 metamorphic sedimentary rocks which can be divided into a lower competent layer, a
18 middle incompetent layer, and an upper competent layer on the basis of lithology and
19 deformation style. Two stages of deformation recorded both in the metasedimentary
20 rocks and a magmatic complex intruded in them indicate that the Lushun-Dalian area
21 is a key region to decipher the Triassic-Jurassic tectonic evolution of the eastern NCC.
22 The earliest D₁ deformation mylonitized the magmatic complex and thrust it NE-

23 ward over the low-grade metasedimentary rocks, in which a series of NE-verging folds
24 and NE-directed brittle thrust faults developed. The D₂ deformation erased the D₁
25 fabrics in the incompetent layer by a top-to-the-NW ductile shearing and refolded the
26 D₁ fabrics in the lower and upper competent units, producing a series of km-scale SW-
27 plunging folds. New SIMS zircon U-Pb ages from the magmatic complex combined
28 with the unconformity between the low-grade metasedimentary rocks and the Early
29 Cretaceous volcanic rocks indicate that D₁ and D₂ occurred after 211 Ma and before the
30 Early Cretaceous. The decrease of the deformation intensity of D₁ and D₂ from the
31 Lushun-Dalian area toward the interior of the NCC in the NE and NW directions
32 suggests that D₁ was the structural response in the overriding plate to the NCC-South
33 China Block (SCB) convergence during the Late Triassic to Early Jurassic, and D₂ was
34 the structural response to the NW-ward subduction of the Paleo-Pacific plate beneath
35 the NCC in the Middle-Late Jurassic. The superimposition of D₂ on D₁ recorded a
36 significant tectonic transformation from the nearly E-W trending Tethysian domain to
37 the NE-SW trending Pacific domain.

38

39 **Keywords:** Superimposed compressional deformation; Mesozoic tectonics of East Asia;
40 Paleo-Pacific Subduction; South Liaodong Peninsula; North China Craton-South China
41 Block convergence

42

43 **1. Introduction**

44 During the long orogenesis of continent-continent collision, the bulk of

45 compressional strain is mostly accumulated in the subducting plate (Schäfer et al.,
46 2000), and lead to the formation of broad external fold-and-thrust belts and the large-
47 scale internal HP-UHP metamorphic terranes, such as those in the Western Alps
48 (Chopin, 1984; Escher et al., 1993; Ceriani and Schmid, 2004; Ganne et al., 2005).
49 Contrastingly, the overriding plate absorbed the deformation in smaller, steeper fold-
50 and-thrust belts with opposite polarity to the main tectonic transport direction (Schäfer
51 et al., 2000). Such an asymmetry has been corroborated as a fundamental characteristic
52 of the collisional orogens by numerical and analogue models (Willett et al., 1993;
53 Beaumont et al., 1996). The relatively weak deformation and metamorphism may be
54 the reason why less attention had been paid on the compressional deformation in the
55 overriding plate compared to the lower one. However, such structural studies were
56 demonstrated to be helpful in deciphering the convergence history between two
57 continental plates, such as those in the Eastern and Southern Alps (Ratschbacher, 1986;
58 Ratschbacher and Oertel, 1987; Doglioni, 1987; Linzer et al., 1995; Castellarin and
59 Cantelli, 2000).

60 Comparing to the above Cenozoic collisional orogens, evidence for the
61 compressional deformation in the overriding plate of a pre-Cenozoic collisional orogen,
62 however, is still rare (Schäfer et al., 2000; Higgins and Leslie, 2000). The Dabie-Sulu
63 orogenic belt of the central-eastern China is widely considered to be resulted from the
64 Triassic continental convergence between the NCC and the SCB (Fig. 1; Mattauer et
65 al., 1985; Li et al., 1993; Okay et al., 1993). Extensive fold-and-thrust belts and the
66 world's largest UHP terranes are well exposed in the northern margin of the SCB (Fig.

67 1; Faure et al., 1998, 1999, 2001, 2003a, 2003b; Lin et al., 2000, 2001, 2005a, 2005b,
68 2005c, 2009). During the last 30 years, limited structural analysis has been focused on
69 the deep subduction of continental crust of SCB and the subsequent exhumation of HP-
70 UHP terranes (Xue et al., 1996; Wang et al., 1998; Faure et al., 1999, 2003a, 2003b;
71 Wang et al., 2003; Xu et al., 2006; Wang et al., 2010; Liu et al., 2011a; Li et al., 2009a,
72 2010, 2011). However, the compressional structural response to these processes in the
73 overriding plate (i. e. the southern margin of NCC) that may provide us important
74 insights into the Triassic orogenesis had been rarely studied. This is partly due to the
75 poor exposure of pre-Mesozoic rocks that were covered by the Late Mesozoic Hefei
76 Basin north of the Dabie orogenic belt (Fig. 1; Zhu et al., 2017), or the intense
77 modification by the lithosphere-scale Early Cretaceous extension in the Jiaobei terrane
78 north of the Sulu belt (Charles et al., 2011; 2013; Lin et al., 2015; Xia et al., 2016). By
79 contrast, the Mesozoic compressional structures derived from the NW-SE and the
80 NE-SW shortening were reported in the weakly metamorphosed sedimentary rocks of
81 the Lushun-Dalian area, South Liaodong Peninsula about 100 km north of the Sulu
82 orogenic belt (Fig. 2a). However, controversies still exist in their timing,
83 superimposition relationship and geodynamic setting (Xu et al., 1991; Yin and Nie,
84 1993; Wang et al., 2000a, 2000b; Yang et al., 2002, 2011; Lin et al., 2007, 2008). Xu et
85 al. (1991) argued that the NW-directed folds and thrusts are the dominant structures in
86 the sedimentary cover of the Lushun-Dalian area. The timing of the NW-SE
87 compression is loosely constrained from Triassic to Early Jurassic. In their indentation
88 model, Yin and Nie (1993) believed that the sedimentary cover of the Lushun-Dalian

89 area is characterized by the nearly E-W trending fold-and-thrust belts, and interpreted
90 them as the result of the NCC-SCB collision during the Late Permian to Early Jurassic.
91 This is further evidenced by the top-to-the-N or NE ductile shearing in the margin of
92 the magmatic complex intruding into the southernmost of the Liaodong Peninsula and
93 the N-directed folds and thrusts near Jinzhou, but the age of this N-S shortening event
94 was constrained to be Early-Middle or Late Triassic (Lin et al., 2007, 2008). Based on
95 the detailed mapping, Wang et al. (2000a, 2000b) considered that the main structural
96 framework of the Lushun-Dalian area resulted from the superimposition of the N-S
97 compression and the E-W compression. The former is characterized by a series of E-W
98 trending large overturned and recumbent folds and was interpreted as the result of the
99 NCC-SCB collision in Triassic (i.e. Indonisian). The later is dominated by an intense
100 top-to-the-NW layer-parallel ductile shearing in the weak layers, such as the Nanfen
101 Formation and the lower part of the Qiaotou Formation. The E-W compression also
102 mylonitized the margin of the Yinjiacun magmatic complex and was interpreted as the
103 structural response to the NW-ward subduction of Paleo-Pacific plate below eastern
104 China in the Early Jurassic. However, Wang et al. (2001) proposed a contrary viewpoint
105 that the E-W compression was older than the N-S compression, but the geodynamic
106 setting of it was not discussed. By analyzing the meso- to macroscopic fold interference
107 patterns of the sedimentary layers, Yang et al. (2011) suggested that the South Liaodong
108 Peninsula experienced simultaneous orogen-normal (NW-SE) and orogen-parallel (NE-
109 SW) shortening in one single phase of compression during the Triassic NCC-SCB
110 collision. In summary, three problems can be concluded from the overview of the

111 previous work: (1) The N-S or NE-SW compression of the Lushun-Dalian area was
112 commonly considered as the result of the NCC-SCB collision, but its timing varies from
113 Late Permian to Early Jurassic and needs to be more precisely constrained; (2) The
114 timing, superimposition relationship with the NE-SW compression and the geodynamic
115 setting of the E-W or NW-SE compression are still highly controversial; (3) The
116 deformation of the magmatic complex intruding into the southernmost of the Liaodong
117 Peninsula is still unclear.

118 To resolve the above problems and better constrain the tectonic evolution of the
119 Dabie-Sulu orogenic belt, we carried out a detailed structural field survey in the
120 Lushun-Dalian area and mapped the magmatic complex at 1:2000 scale. By combining
121 the structural data with available geochronological data, we aim to: (1) clarify the
122 deformation history of the Lushun-Dalian area during Mesozoic, (2) provide structural
123 constraints on the tectonic framework in the southern margin of the NCC, (3) compare
124 the structures of the Lushun-Dalian area with its surrounding areas to unravel the
125 Mesozoic tectonic evolution of the eastern NCC.

126 **2. Regional Geology**

127 The Liaodong Peninsula is bounded by the Paleozoic Central Asian Orogenic Belt to
128 the north and faces the Yanshan fold-and-thrust belt and the Sulu UHP orogenic belt
129 across the Bohai Sea to the northwest and the southeast, respectively (Fig. 1). It is an
130 important part of the eastern NCC and consists of an old basement mainly formed by
131 Neoproterozoic TTG gneisses and Paleoproterozoic highly metamorphosed rocks (Luo et
132 al., 2004; Faure et al., 2004; Wan et al., 2012; Li et al., 2017). The basement is

133 unconformably overlain by a thick, weakly metamorphosed to unmetamorphosed
134 sedimentary cover that consists, from bottom to top, of: (1) Late Mesoproterozoic to
135 Early Neoproterozoic shallow marine clastic rocks and platform-shelf carbonate rocks
136 (Fig. 2b; Yang et al., 2011); (2) Cambrian to Early Ordovician platform-shelf carbonate
137 rocks (Fig. 2b; Yang et al., 2011; Qiu et al., 2018); (3) Late Carboniferous to Permian
138 shallow marine clastic rocks alternating with terrigenous coal-bearing rocks (Fig. 2b;
139 Yang et al., 2011; Qiu et al., 2018). All these sedimentary series were deformed during
140 the Mesozoic and unconformably overlain by Middle-Late Jurassic to Early Cretaceous
141 terrigenous rocks alternating with volcanic rocks (Fig. 2b; Wang et al., 2000a; Qiu et
142 al., 2018).

143 Like the other part of the eastern NCC, the Liaodong Peninsula also experienced the
144 continent-scale NW-SE extension during the Early Cretaceous that is widely considered
145 to be the climax of destruction of the NCC (Zhu et al., 2012; Lin and Wei, 2018). The
146 extension is expressed by: (1) the emplacement of voluminous granitic rocks of the
147 Early Cretaceous (Wu et al., 2005a), (2) the development of small half graben basins
148 filled with the Early Cretaceous terrigenous rocks and volcanic rocks (Shen et al., 2011;
149 Liu et al., 2013), and (3) the formation of a metamorphic core complex in the South
150 Liaodong Peninsula, also known as the Liaonan MCC (Fig. 2a; Liu et al., 2005, 2011b,
151 2013; Lin et al., 2007, 2008). Top-to-the NW or SE extensional shearing is documented
152 by various kinematic indicators in the detachment fault zones of the Liaonan MCC (Liu
153 et al., 2005, 2011b, 2013; Lin et al., 2007, 2008). The duration of extension is
154 constrained by abundant geochronological data from the volcanic rocks of the

155 supradetachment half graben basins, the mylonites of the detachment fault zones, the
156 syntectonic granite plutons, and various veins to be 135-107 Ma, with a peak at 126 Ma
157 (Yin and Nie, 1996; Wu et al., 2005a; Yang et al., 2007a; Ji et al., 2009; Lin et al., 2011;
158 Wang et al., 2011a, 2012; Liu et al., 2011b, 2013; Shen et al., 2011; Lin and Wei, 2018).
159 In addition, numerous Middle-Late Jurassic granitic plutons of various sizes and minor
160 Late Triassic plutons are also distributed in the Liaodong Peninsula (Wu et al., 2005b,
161 2005c; Yang et al., 2007b, 2007c).

162 In the South Liaodong Peninsula, despite the important modification by the Early
163 Cretaceous extension, pre-Cretaceous multiphase compressional deformation is well
164 preserved in the thick sedimentary strata surrounding the Liaonan MCC (Fig. 2a; Xu et
165 al., 1991; Yin and Nie, 1993, 1996; Wang et al., 2000a, 2000b, 2001; Yang et al., 2002;
166 Lin et al., 2007, 2008). In particular, the structures of the Lushun-Dalian area south of
167 the Jinzhou city formed a complex fold interference pattern (Fig. 3a; Yang et al., 2011).
168 The sedimentary strata of the Lushun-Dalian area were deposited during 1056-924 Ma
169 (Yang et al., 2012; Zhang et al., 2016), and contains two main sequences separated by
170 a depositional hiatus (Fig. 2b; Yang et al., 2011). The upper and lower sequences are
171 mainly composed of carbonate rocks and shallow marine clastic rocks (for the detailed
172 lithological contents of Formations see Fig. 2b), and occupy the northern and southern
173 parts of the Lushun-Dalian area, respectively (Fig. 3a). The clastic rocks and the
174 argillaceous limestone were metamorphosed under greenschist facies conditions into
175 schists, phyllite, slate and quartzite (Xu et al., 1991; Wang et al., 2000b). In the
176 southernmost tip of the Liaodong Peninsula, the sedimentary strata were intruded by a

177 crescent-shaped magmatic complex, here named the Yinjiacun complex, and overlain
178 by Early Cretaceous volcanic rocks (Fig. 3a; Wang et al, 2000a, Yang et al., 2011). The
179 Yinjiacun complex occupies about 10 km² and consists of syenite and gabbro (Fig. 3a),
180 the age of which were dated to be Late Triassic (Wang et al., 2002; Wu et al., 2005c).

181 **3. Structural analysis**

182 The structure in the sedimentary cover of the Lushun-Dalian area is characterized by
183 folds and ductile shear zones (Xu et al., 1991; Wang et al., 2000a, 2000b, 2001; Yang
184 et al., 2002, 2011; Lin et al., 2007, 2008). Our detailed regional structural fieldwork
185 allowed us to recognize two deformation events on the basis of structural styles from
186 the outcrops, and fold interference patterns from the map view. For the convenience of
187 description, we divided the sedimentary cover of the Lushun-Dalian area into three
188 structural layers based on lithology and structural pattern: (1) The lower competent
189 layer, including the Yongning Formation and the lower part of the Diaoyutai Formation
190 which consists of several kilometers thick sandstone and conglomerate (Fig. 2b;
191 LBGMR, 1989), is characterized by large open folds without axial planar cleavage
192 (Wang et al., 2000a, 2000b, 2001), and only exposed in several localities as anticlines
193 (Fig. 3a); (2) the middle incompetent layer, composed of schist, phyllite, slate, and thin
194 quartzite metamorphosed in greenschist facies conditions from mudstone, pelitic
195 siltstone, siltstone and thin sandstone belonging to the upper part of the Diaoyutai
196 Formation, Nanfen Formation, and the lower part of the Qiaotou Formation, occupies
197 almost 40% of the whole Lushun-Dalian area, with a thickness larger than 2 km (Fig.
198 2b, 3a; LBGMR, 1989); (3) the upper competent layer, more than 3 km thick, composed

199 of thick sandstone belonging to the upper part of the Qiaotou Formation and carbonates
200 belonging to the Formations of Changlingzi, Ganjingzi, Nanguanling and Yingchengzi,
201 occupies more than 40% of the Lushun Dalian area (Fig. 2b, 3a; LBGMR, 1989). The
202 structure of the upper competent layer is characterized by NW- and NE-verging km-
203 scale recumbent or overturned folds (Fig. 3b, 3c, 3d). These two nearly perpendicular
204 structural trends define a complex fold interference pattern (Fig. 3a; Yang et al., 2002,
205 2011).

206 ***3.1. D₁ Deformation***

207 Except for the Early Cretaceous volcanic rocks, all the lithotectonic units of the
208 Lushun-Dalian area were involved in the D₁ deformation event. In the southwestern
209 end of the Liaodong Peninsula, the Late Triassic Yinjiacun complex and its country
210 rocks were concurrently foliated, even mylonitized (Fig. 4a, 4b). Although the dip of
211 the S₁ foliation changed from SW to NW during the later structural event, the L₁
212 lineation consistently trends NE-SW (Fig. 4c, 4d). Along L₁, various kinematic
213 indicators showing a top-to-the-NE shear sense can be clearly observed in the
214 mylonitized gabbro and syenite, such as the sigma- or delta-type K-feldspar
215 porphyroclasts (Fig. 4e). A NE-directed ductile thrust fault zone located at the boundary
216 between the complex and its country rocks can be inferred from the SW-dipping S₁
217 foliations and the top-to-the-NE kinematic indicators along the L₁ lineations. The
218 complex was thrust northeastward from the middle-lower crust level over the low-
219 grade metasedimentary rocks (Lin et al., 2007).

220 In the sedimentary rocks, D₁ is mainly expressed by F₁ folds, the hinges of which are

221 subhorizontal and trend consistently NW-SE (Fig. 3e). The style of F_1 and the
222 development of an axial planar cleavage S_1 change regularly from south to north.
223 Specifically, in the country rocks of the Yinjiacun complex, the original bedding S_0 was
224 almost completely transposed into S_1 which dips to the SW with high angle, only a few
225 small SW-plunging isoclinal folds can be observed in the schist (Fig. 4f). As the hinges
226 of these folds are parallel to the L_1 lineation, we prefer to interpret them as a-type folds
227 formed during the top-to-the-NE shearing. In the incompetent layer, F_1 are mainly NE-
228 verging or nearly upright folds with penetrative SW-dipping or subvertical axial planar
229 cleavage S_1 (Fig. 3e, 4g). Notably, F_1 and S_1 in this unit are only preserved in the
230 mudstone and siltstone near the lower sandstone anticlines (Fig. 3a). In the upper
231 competent layer, F_1 forms a series of km-scale NE-verging overturned or recumbent
232 folds (Fig. 3a, 3b). The axial planar cleavage S_1 is rarely developed in this unit. Upward
233 and northward continuously, km-scale NE-verging inclined folds and kink folds are the
234 main fold types in the Cambrian-Ordovician carbonate rocks (Fig. 2a, 4h). No axial
235 planar cleavage S_1 is observed in this unit, conversely, the NE-directed brittle thrust
236 faults become common (Fig. 4h).

237 ***3.2. D₂ Deformation***

238 The D_2 deformation overprinted the D_1 fabrics and formed various types of folds and
239 fold interference patterns in different lithotectonic units. In the lowest Yinjiacun
240 complex and its country rocks, the SW-dipping foliation S_1 and the NE-directed ductile
241 thrust fault were folded and formed a kilometer-scale SW-plunging vertical fold F_2 (see
242 details in section 3.3).

243 In the middle incompetent layer, the D_2 fabrics are characterized by intrafolial and
244 intraformational recumbent folds F_2 , S_2 foliation and L_2 lineation. The hinges of F_2 are
245 commonly subhorizontal and consistently trend NE-SW (Fig. 3f). The S_2 foliation is
246 actually the penetrative axial planar cleavage of F_2 . This can be inferred from the S_{0-1}
247 $/S_2$ cross-cutting relationships which are rarely preserved in the intrafolial folds of
248 slates and the intraformational recumbent folds of thin sandstones (Fig. 5a). The S_{0-1}
249 surface was pervasively transposed into S_2 which is subparallel and oblique to the S_{0-1}
250 in the limbs and hinge zones of F_2 folds, respectively (Fig. 5a). Maybe due to a late
251 reworking by later deformation events, S_2 dips to various directions with low angles
252 (Fig. 3f), but the mineral and stretching lineation L_2 marked by the preferred orientation
253 of quartz aggregates, sericite and chlorite clots consistently trend NW-SE (Fig. 3f, 5b).
254 Along L_2 , top-to-the-NW shearing can be inferred from the sigmoidal quartz boudins
255 in outcrops (Fig. 5c). In thin sections, cut perpendicular to the S_2 foliation and parallel
256 to the L_2 lineation, the same shear sense is indicated by sigma-type quartz
257 porphyroclasts (Fig. 5d). All these features suggest that the incompetent layer is a huge
258 folded layer formed under a subhorizontal intense ductile shearing. It is noteworthy that
259 no L_1 lineation developed in this unit and the subvertical S_1 foliation is only found in
260 the siltstone near the lower sandstone anticlines (Fig. 3a).

261 In the upper sandstone layer, a series of km-scale overturned F_2 folds with NW
262 vergence are outlined by the alternation occurrence of normal and reversed strata (Fig.
263 3a, 3c). These folds refolded the F_1 ones, and formed a basin structure around the
264 Lushun gulf (Fig. 3a, 3c). Upward and northward, in the Neoproterozoic carbonate

265 rocks, the overturned and recumbent folds F_1 were also refolded by the F_2 and formed
266 the map-scale SW-plunging folds which are well exposed in the Huanglongwei and
267 Heishishan areas (Fig. 3a, 3d). Another striking compressional structures are a set of
268 small-scale NE-SW trending thrust faults developed in the area between Yinggeshi and
269 Huangnichuan (Fig. 3a, 3d; Yang et al., 2011). These thrust faults dip to NW with low
270 angles and can cut through the lower thick sandstone, although most of them die out
271 into the incompetent layer. They juxtapose the older strata over the younger one, i.e.
272 the upper sandstone over the argillaceous limestone of the Changlingzi Formation near
273 Yinggeshi, the incompetent layer over the upper sandstone between Yinggeshi and
274 Huangnichuan, the lower sandstone over the incompetent layer near Huangnichuan, and
275 indicate a sense of SE-directed thrusting (Fig. 3a, 3d).

276 ***3.3. Polyphase deformation in the Yinjiacun complex***

277 The crescent-shaped Yinjiacun complex exposed at the southernmost Liaodong
278 Peninsula had been considered as a massive body with a mylonitized margin for a long
279 time (Wang et al., 2000a; Lin et al., 2007). Wang et al. (2000a) interpreted the
280 mylonitized margin as the result of a regional NW-SE compression. While Lin et al.
281 (2007) recognized pervasive SW-dipping foliation containing SW-plunging lineation in
282 the margins of gabbro and the country rocks. Along the lineation, top-to-the-NE ductile
283 shearing was indicated by the asymmetric porphyroclasts of feldspar and amphibole.
284 Accordingly, Lin et al. (2007) thought that the margins of gabbro and the country rocks
285 were mylonitized in a NE-directed compression and inferred that there existed a ductile
286 thrust fault between the gabbro and the country rocks. The ductile thrust fault dips to

287 SW and juxtaposes the gabbro over the country rocks and they were then intruded by
288 the undeformed syenite. Apparently, the Yinjiacun complex plays an important role in
289 understanding the tectonic evolution of the South Liaodong Peninsula, but the
290 deformation of it has not been clearly investigated.

291 In order to clarify the deformation of the Yinjiacun complex, we carried out a detailed
292 field structural mapping of the magmatic complex at scale of 1: 2000 and obtained
293 several new findings as follows: (1) The syenite is predominant and distributed
294 throughout almost the whole complex (Fig. 6a). The gabbro is only continuously
295 distributed in the SE part of the complex and encompassed by the syenite as decameter
296 to hectometer-scale blocks in other parts of the complex (Fig. 6a); (2) Both the syenite
297 and gabbro intruded into the country rocks and were together intensely foliated, even
298 mylonitized (Fig. 4a, 4b). The ductile thrust fault can be extended into the boundary
299 between the syenite and the country rocks (Fig. 6a). The intrusive relationships between
300 the complex and the country rocks are not only expressed in the outcrops, but also in
301 the map view in which the limestone of the Nanguanling Formation was separated into
302 two parts by the syenite (Fig. 6a). Marble can be observed in the outcrops at the
303 boundary between the syenite and the limestone; (3) In the country rocks, from the NE
304 toward the SE, the dip of the foliation together with the boundary ductile thrust fault
305 changes regularly from SW to NW with high angle (Fig. 6a, 6b). The foliation trajectory
306 and the bended thrust fault outline a km-scale SW-plunging subvertical fold; (4) The
307 complex was heterogeneously deformed and several ductile shear zones have been
308 mapped. The syenite and gabbro in the ductile shear zones were also intensely foliated

309 and even mylonitized, while those between the ductile shear zones are almost massive
310 (Fig. 6a). The dip of foliation in the ductile shear zones exhibits a similar change to
311 those of the country rocks. The foliation trajectories of the complex outlines numerous
312 SW-plunging subvertical folds with smaller wavelengths (Fig. 6a); (5) Although the
313 foliation attitude in both the complex and its country rocks changes regularly, the
314 lineation contained on the foliation consistently plunges down to the SW with moderate
315 to gentle angles (Fig. 4c, 4d, 6a, 6b). Along the lineation, top-to-the-NE shearing is
316 indicated by the sigma- or delta-type K-feldspar porphyroclasts in the mylonitized
317 syenite (Fig. 4e).

318 The above observations suggest that the Yinjiacun complex and its country rocks
319 record two stages of deformation. The first one deformed the complex into several SW-
320 dipping ductile shear zones, formed the SW-plunging lineation and the NE-directed
321 thrust fault (Fig. 6c). The geometric and kinematic features are similar to those of the
322 sedimentary cover in other parts of the Lushun-Dalian area. Therefore the first stage of
323 deformation recorded in the complex corresponds to the D₁ deformation observed in
324 the sedimentary cover. The second one folded the foliation of ductile shear zones and
325 the thrust fault, the dips of which turn from SW to NW, and formed the large steeply
326 plunging subvertical folds in map view, together with the numerous small parasitic
327 plunging subvertical folds in the complex. A large NW-verging fold is also indicated by
328 the contrasting occurrence of the sandstone beds in NW and SE flanks of the Laotieshan
329 (Fig. 6d). This indicates that the second stage of deformation recorded in the complex
330 corresponds to the D₂ deformation in the sedimentary cover.

331 **4. Geochronological constraints**

332 The field observations and structural analysis presented above suggest that the
333 Yinjiacun complex recorded the D₁ and D₂ deformation of the Lushun-Dalian area.
334 Therefore the precise ages of the syenite and gabbro of the complex can well constrain
335 the lower limit of D₁ and D₂. However, the emplacement age of the complex is poorly
336 constrained. The available ages of the gabbro and syenite were commonly provided
337 without detailed sample descriptions and experiment procedures, and vary widely by
338 different dating methods. For example, the LA-ICP-MS zircon U-Pb age of the syenite
339 provided by Wu et al. (2005c) is 219 ± 1 Ma, older than the TIMS single zircon U-Pb
340 age 214.3 ± 1.5 Ma of the gabbro (Yang et al., 2011). However, the TIMS single zircon
341 U-Pb age of the syenite provided by Yang et al. (2011) is 208.8 ± 1.3 Ma, younger than
342 that of the gabbro. The difference between the two ages of the syenite is about 10 Ma,
343 therefore the ages of the syenite and gabbro remain to be improved. One gabbro sample
344 (DL101) and one syenite sample (LS04A) were collected from the complex for zircon
345 SIMS U-Pb dating. Sample locations are marked in Fig. 6a.

346 ***4.1. Analytical techniques***

347 The samples were processed by crushing, heavy liquid and subsequent magnetic
348 separations. Zircons were hand-picked and mounted in epoxy mounts together with
349 zircon standards, and then polished to section the crystals in half for analysis. All
350 zircons were photographed in transmitted and reflected light, and the
351 cathodoluminescence (CL) image in order to reveal their internal structures (Fig. 7a).
352 The mount was vacuum-coated with high-purity gold for SIMS analysis. Measurements

353 of U, Th and Pb isotopes were conducted using a Cameca IMS-1280 at the Institute of
354 Geology and Geophysics, Chinese Academy of Sciences (IGGCAS), Beijing. The
355 instrument description and analytical procedure can be found in Li et al. (2009b). The
356 beam spot was about $20 \times 30 \mu\text{m}$ in size, and positive secondary ions were extracted
357 with a 10 kV potential. Standard zircons Plešovice (Sláma et al., 2008) and Qinghu (Li
358 et al., 2013) were alternately analyzed with unknown zircons from the samples.
359 Measured compositions were corrected for common Pb using the non-radiogenic ^{204}Pb .
360 Uncertainties of individual analyses are reported at 1σ in Table 1. The concordia
361 diagrams of U–Pb data are shown in Fig. 7b and 7c, where weighted mean $^{206}\text{Pb}/^{238}\text{U}$
362 ages or concordia ages are quoted at either 95% confidence interval. Data reduction
363 was carried out using the Isoplot program (Ludwig, 2003).

364 *4.2. Analytical results*

365 *4.2.1. Sample DL101*

366 Sample DL101 is a dark gray weakly foliated gabbro that is mainly composed of
367 medium- to coarse-grained plagioclase, pyroxene, hornblende, biotite and minor quartz.
368 Zircons from sample DL101 are commonly euhedral, colorless and transparent, ranging
369 from 120 to 400 μm in length with aspect ratios of 1:1-3:1. They show conspicuous
370 oscillatory zoning and no inherited cores under CL (Fig. 7a). Eighteen zircons were
371 analyzed, their U and Th contents range from 120 to 722 ppm, and 130 to 1216 ppm,
372 respectively. The Th/U ratios of 0.44 to 1.75 (Table 1) suggest a magmatic origin. The
373 concordant age of $211.0 \pm 1.5 \text{ Ma}$ (MSWD=0.064) represents the crystallization time
374 of the gabbro (Fig. 7b).

375 **4.2.2. Sample LS04A**

376 Sample LS04A is a light red massive syenite that is mainly composed of medium- to
377 fine-grained K-feldspar, plagioclase, quartz and minor biotite. Zircons from sample
378 LS04A are mostly euhedral, colorless and transparent, ranging from 100 to 400 μm in
379 length with aspect ratios of 1:1-3:1. Most grains are characterized by magmatic growth
380 zonation in CL images (Fig. 7a). Eighteen zircons were analyzed, their U and Th
381 contents range from 127 to 597 ppm and 70 to 383 ppm, respectively, with Th/U ratios
382 of 0.40 to 0.86 (Table 1), indicating a magmatic origin. The analyses yield a concordia
383 age of 214.7 ± 1.5 Ma (MSWD=0.036), interpreted as the crystallization age of the
384 syenite (Fig. 7c).

385 **5. Discussion**

386 **5.1 Polyphase deformation and its geochronological constraint**

387 As presented above, the Lushun-Dalian area experienced two stages of
388 deformation which are recorded in every unit except for the Early Cretaceous volcanic
389 rocks (Fig. 8). D_1 is not only well recorded in the pre-Mesozoic lithotectonic units of
390 the South Liaodong Peninsula (Wang et al., 2000a, 2000b; Yang et al., 2002, 2011; Lin
391 et al., 2007, 2008), but also in those of the Changshan islands east of the Liaodong
392 Peninsula (Fig. 2a; Ren and Lin, 2019). The NE-verging F_1 folds and NE-directed thrust
393 faults in the metasedimentary rocks suggest that D_1 is a top-to-the-NE compressional
394 event. From the SW to the NE, the development of the axial planar cleavage S_1 of the
395 fold F_1 varies from penetrative slaty cleavage to less spaced one and disappears
396 northeastward. The thrust fault changes from ductile fault zones to brittle ones. The

397 SW-plunging L_1 lineation is only exhibited on the S_1 foliation of the Yinjiacun complex
398 and its country rocks, but disappears in the sedimentary series far away from the
399 Yinjiacun complex. All these structural features suggest that the D_1 intensity decreases
400 from the southwest to the northeast (Yang et al., 2002, 2011).

401 The D_2 deformation is characterized by a subhorizontal foliation S_2 , a NW-SE
402 trending mineral and stretching lineation L_2 , NW-verging folds F_2 and SE-directed
403 brittle thrust faults. A subhorizontal ductile shearing can be inferred from the well-
404 developed S_2 , L_2 and the top-to-the-NW kinematic indicators in the incompetent layer.
405 The abundant intrafolial and intraformational recumbent folds F_2 with subhorizontal
406 NE-SW trending hinges were formed during the D_2 ductile shearing. Their axial planar
407 cleavage S_2 almost completely transposed the S_{0-1} surfaces which are rarely preserved,
408 except in the residual hinge zones of the folds (Fig. 5a). Therefore the incompetent layer
409 is actually a decollement zone above which a series of NW-verging km-scale recumbent
410 folds developed in the upper competent layer (Fig. 3c), and below which large open
411 folds and slightly inclined folds with NW vergence developed in the lower competent
412 layer (Fig. 3c, 3d, 6d). All these structural elements suggest that D_2 is a top-to-the-NW
413 compressional event. Another significant compressional structures are the arrays of NE-
414 SW trending thrust faults in the areas from Yinggeshi to Huangnichuan, however, their
415 kinematics are top-to-the-SE (Fig. 3d; Wang et al., 2002; Yang et al., 2011). These SE-
416 directed thrust faults were considered as the secondary structures during the formation
417 of the NE-SW trending folds under the NW-SE or E-W compression (Wang et al., 2002).
418 Therefore, we prefer to interpret them as results of the back-thrusting during the lasting

419 NW-directed compression. It is worth noting that the occurrence of axial planes of the
420 original NW-verging recumbent folds in the Heishishan and Huanglongwei were also
421 changed from subhorizontal to slightly dipping to NW during the stage of back-
422 thrusting (Fig. 3d).

423 The superposition of D_2 on D_1 is clearly expressed by the F_2 folds refolding the F_1
424 ones in the lower and upper competent units and produced numerous km-scale SW-
425 plunging folds. However, in the incompetent layer, only the subhorizontal S_2 foliation
426 and NW-SE trending L_2 lineation are observed. The SW-dipping axial planar cleavage
427 S_1 is commonly preserved in the siltstone near the northeast limb of the lower sandstone
428 anticlines (Fig. 3a, 8). One reasonable interpretation for this phenomenon is that the
429 intense top-to-the-NW subhorizontal D_2 ductile shearing erased the D_1 structures.
430 Toward the sandstone anticlines, the subhorizontal ductile shearing weakened and the
431 SW-dipping S_1 cleavages were well preserved and exposed to the surface during the
432 uplift of these anticlines (Fig. 8). In the incompetent layer just to north of the Yinjiacun
433 complex, S_1 was not erased by the ductile shearing of D_2 deformation, and only bended
434 under the D_2 compressional stress (Fig. 6a, 8). This mainly depends on the rock
435 associations and the striking difference of the mechanical properties among them. As a
436 product of the D_1 deformation, the incompetent layer next to the Yinjiacun complex
437 was distributed in a narrow strip and sandwiched between the wider and more rigid
438 Yinjiacun complex and the thick sandstone of Laotieshan (Fig. 6a, 8). While the thick
439 incompetent layer far away from the Yinjiacun complex was distributed in a vast plane
440 and sandwiched between thick sandstone and carbonate rocks (Fig. 8). From a

441 mechanical point of view, the rigidity of the former rock associations is much higher
442 than that of the latter. Thus, the former rock associations are more difficult to be
443 deformed under the same compressional stress than the latter. Consequently, S₁ in the
444 incompetent layer next to the Yinjiacun complex was well preserved in the D₂
445 deformation, but was almost erased in the incompetent layer far away from the
446 Yinjiacun complex (Fig. 8).

447 Our SIMS U-Pb dating results reveal that the emplacement ages of the syenite and
448 gabbro are 214.7 ± 1.5 Ma and 211.0 ± 1.5 Ma, respectively. Considering that the
449 syenite and gabbro were all deformed by both D₁ and D₂ (Fig. 8), the timing of which
450 can be inferred to be after 211Ma. According to Ren and Lin (2019), the NE-SW
451 compressional structures of the Changshan islands and the Lushun-Dalian area were
452 formed in one single deformation event, i.e. the D₁ deformation in this study. The D₁
453 event did not rework the granite pluton exposed on the Guanglu and Guapi islands, the
454 age of which was determined by the SIMS zircon U-Pb method to be 165 Ma (Ren and
455 Lin, 2019). Therefore, the D₁ deformation of the Lushun-Dalian area and the
456 Changshan islands occurred before 165 Ma. Wang et al. (2002) reported a muscovite
457 ⁴⁰Ar/³⁹Ar age of 192.7 ± 0.1 Ma from the micaschist north of the Yinjiacun complex
458 and interpreted it as the age of the N-S compression in the South Liaodong Peninsula.
459 In the well known indentation model of Yin and Nie (1993), the collision between NCC
460 and SCB lasted until 188 Ma and caused the greatest NE-SW shortening north of the
461 Sulu orogenic belt. All these previous works further constrain the upper limit of the D₁
462 deformation to be about 190 Ma. Therefore, the D₁ deformation in the South Liaodong

463 Peninsula occurred between 211 and 190 Ma, i.e. the Late Triassic to Early Jurassic.

464 The timing of the D₂ deformation can be further constrained to be after the Early
465 Jurassic, since then the tectonic evolution of the eastern China had been controlled by
466 the northwestward subduction of the Paleo-Pacific plate that gave rise to the NW-SE
467 shortening during the Middle-Late Jurassic (Liu et al., 2017; Li et al., 2019; Zhu et al.,
468 2019). The NW-SE compressional structures in the NCC derived from the shortening
469 are characterized by the NW-or SE-directed fold-and-thrust belts and are widely
470 distributed in the tectonic belts of Yinshan-Yanshan, Taihangshan, Luliangshan and
471 Helanshan (Wang et al., 2008, 2011, 2015; Faure et al., 2012; Huang et al., 2015; Wang
472 et al., 2017a; Clinkscales and Kapp, 2019). The lower limit of these compressional
473 structures has been constrained to be about 170 Ma (Wang et al., 2008, 2011; Dong et
474 al., 2015; Wang et al., 2017a). Similar geometric and kinematic features suggest that
475 the NW-SE compressional structures of the South Liaodong Peninsula were formed in
476 the same shortening event with those of the above tectonic belts of the NCC. Thus, the
477 lower limit of the D₂ deformation in the Lushun-Dalian area occurred after 170 Ma, but
478 earlier than the eruption of the massive volcanic rocks of the Guiyunhua Formation that
479 is distributed in the small Late Mesozoic extensional basins throughout the South
480 Liaodong Peninsula (Fig. 2a). The volcanic rocks of the Guiyunhua Formation, mainly
481 andesite and rhyolite, have been precisely dated by SHRIMP and LA-ICP-MS zircon
482 U-Pb methods and the results suggest that the maximum eruption age of these volcanic
483 rocks is 135 Ma (Liu et al., 2011b; Shen et al., 2011). Consequently, the D₂ deformation
484 occurred between 170 and 135 Ma, i.e., in the Middle-Late Jurassic to earliest

485 Cretaceous.

486 It is noteworthy that the decollement zone in the weakly metamorphosed sedimentary
487 rocks south of Dalian city is different from the detachment fault zones of the Liaonan
488 MCC north of Dalian city, although the NW-SE trending mineral and stretching
489 lineations and top-to-the-NW ductile shearing were developed in both of them. They
490 can be distinguished from the following three aspects: (1) Occurrence and scale. The
491 former occupies tens of km² in a vast plane and has a thickness larger than 1.5 km (Fig.
492 2). While the latter occurs as narrow strips around the MCC and usually have a
493 thickness of hundreds of meters (Fig. 2; Liu et al., 2005). So do the detachment fault
494 zones around the extensional domes of the Changshan islands (Ren and Lin, 2019); (2)
495 Structural levels. The former was developed in the upper crust level and only reworked
496 the sedimentary cover. The latter was developed in the middle-lower crust level and
497 intensely reworked not only the Archean basement, but also the Middle-Late Jurassic
498 to Early Cretaceous granitic plutons (Liu et al., 2005; Yang et al., 2007a; Lin et al.,
499 2008); (3) Timing. The former and the large NW-verging folds above it were
500 unconformably overlain by the Early Cretaceous volcanic rocks of the Guiyunhua
501 Formation (Fig. 3d). And the above analysis further constrains the timing of the
502 decollement zone of the Lushun-Dalian area to be the Middle-Late Jurassic. The latter
503 controlled the formation of the supradetachment basins which were filled with the
504 Guiyunhua Formation and other terrigenous deposits. The abundant ages suggest that
505 the detachment fault zones of the Liaonan MCC was active during 135-107 Ma, i.e. the
506 Early Cretaceous (Yang et al., 2007a; Lin et al., 2011; Liu et al., 2013). Therefore, the

507 D₂ deformation of the Lushun-Dalian area is not related to the Early Cretaceous
508 extension, but a Middle-Late Jurassic compressional event.

509 **5.2 The structural response in the overriding plate to the NCC-SCB convergence:**
510 **the NE-SW compression**

511 It is well known that the Dabie-Sulu orogenic belt resulted from the Triassic
512 convergence between NCC and SCB (Mattauer et al., 1985; Ames et al., 1993; Li et al.,
513 1993). The continental crust of the SCB was subducted into mantle and underwent an
514 ultra-high pressure (UHP) metamorphism, then it was exhumed to the surface (Ye et al.,
515 2000). Accompanying this process was the development of the broad fold-and-thrust
516 belt in the northern margin of the SCB which recorded not only the syn-convergence
517 compression but also the late convergence compression (Schmid et al., 1999; Liu et al.,
518 2001; Ratschbacher et al., 2003; Li et al., 2009c; Liu et al., 2011a, 2012). However,
519 such a compressional deformation had been rarely identified in the southern margin of
520 the NCC adjacent to the Dabie-Sulu orogenic belt.

521 North of the Dabie orogenic belt, the southern margin of the NCC is mostly covered
522 by the Mesozoic Hefei basin, north of which only a few NE-verging folds and NE-
523 directed thrust faults of the Middle-Late Triassic can be observed in the Bengbu uplift
524 (Fig. 1; Sun et al., 2004; Wang et al., 2016). In the Jiaobei massif north of the Sulu
525 orogenic belt, the NE-SW compressional deformation was only reported in the residual
526 weakly metamorphic sedimentary rocks (called the Penglai group; Zhu, 1993; Zhu et
527 al., 1994; Zhu and Xu, 1994). It is characterized by NW-SE trending folds coeval with
528 highly NE-dipping cleavages. These structures were interpreted as the result of a NE-

529 SW compression related to the NCC-SCB convergence, although its timing was
530 constrained to be the Late Carboniferous (Zhu, 1993; Zhu et al., 1994; Zhu and Xu,
531 1994).

532 Contrastingly, 100-200 km north of the Sulu orogenic belt, the NE-SW
533 compressional deformation is unambiguously recorded in the South Liaodong
534 Peninsula and the Changshan islands. It is commonly expressed by the NW-SE or
535 nearly E-W trending folds and thrusts in the sedimentary cover and the top-to-the-NE
536 ductile shearing in the basement, and considered as the structural response to the NCC-
537 SCB convergence in the overriding plate (Yin and Nie, 1993; Wang et al., 2000a, 2000b,
538 2001; Yang et al., 2002, 2011; Lin et al., 2007, 2008; Ren and Lin, 2019). Our field
539 structural mapping and new SIMS zircon U-Pb ages of the Yinjiacun complex allow us
540 to constrain the age of the NE-SW compression at 211-190 Ma, since then the Paleo-
541 Pacific plate had subducted NW-ward below the eastern China (Zhou et al., 2014; Liu
542 et al., 2017; Li et al., 2019). However, there is no genetic connection between them
543 because the compressional direction of D₁ deformation was nearly perpendicular to the
544 subduction of the Paleo-Pacific plate. The NE-ward decreasing of the D₁ deformation
545 intensity suggests that the compressional stress derived from the SW and can only be
546 provided by the NCC-SCB convergence. However, during 211-190 Ma, the NCC-SCB
547 convergence had entered into a late stage. Consequently, the NE-SW compression
548 recorded in the South Liaodong Peninsula and the Changshan islands actually belongs
549 to a late convergence compression, rather than a syn-convergence one.

550 This new insight helps us to reappraise the tectonic evolution of the southern margin

551 of NCC north of the Sulu orogenic belt during the Triassic convergence, and propose
552 the following scenario: (1) During the syn-convergence compression (254-220 Ma), the
553 continental crust of the SCB was subducted beneath the NCC, and experienced the
554 prograde to HP-UHP metamorphism (Liu et al., 2006; Hacker et al., 2009). Broad fold-
555 thrust belts were well developed in the northern SCB, while only narrow fold-thrust
556 belts were developed in the southern margin of the NCC (Fig. 9a). This is consistent
557 with the deformation asymmetry during the continent-continent collisional orogeny
558 (Willett et al., 1993; Beaumont et al., 1996); (2) The syn-convergence extensional
559 exhumation (220-211 Ma) brought the UHP metamorphic rocks to the middle crustal
560 level where they experienced an amphibolite facies metamorphic overprint (Liu et al.,
561 2006; Hacker et al., 2009). The top-to-the-NW extensional tectonics were well
562 developed in the upper part of the subducting plate (Faure et al., 2001, 2003a; Lin et al.,
563 2005c). Minor alkaline magmatic plutons intruded within and north of the Sulu
564 orogenic belt (Fig. 9b; Chen et al., 2003; Guo et al., 2005; Yang et al., 2005). At the
565 same time, the southern margin of the NCC might also be in an extensional regime and
566 the earlier thrust faults were inverted into normal faults (Fig. 9b). (3) The post-
567 convergence intracontinental NE-SW compression (211-190 Ma), probably caused by
568 the lasting convergence between the NCC and SCB, mylonitized and thrust the
569 Yinjiacun magmatic complex over the weakly metamorphic sedimentary rocks of the
570 South Liaodong area. A series of NE-verging folds and NE-directed thrust faults in the
571 sedimentary rocks of the southern margin of the NCC developed (Fig. 9c). The new
572 scenario suggests that the structural response of the overriding plate to the continent-

573 continent collisional orogeny might be more complex than the previously studied. It
574 might not always be compression throughout the convergence of two continents like that
575 of the indentation model proposed by Yin and Nie (1993), nor be compression only in
576 the syn-convergence stage, but be the alternation of compression and extension.

577 **5.3 The structural response of the NCC to the subduction of the Paleo-Pacific plate:** 578 **the NW-SE compression**

579 The NW-SE compressional deformation in the sedimentary cover of the Lushun-
580 Dalian area has been identified for a long time, however, controversies still exist in its
581 origin, timing and relationship with the NE-SW compression (Xu et al., 1991; Wang et
582 al., 2000a, 2000b; Yang et al., 2011). Our structural and geochronological data suggest
583 that the NW-SE compression in the Lushun-Dalian area occurred in the Middle-Late
584 Jurassic and superimposed on the Late Triassic-Early Jurassic NE-SW compression.
585 Actually, the NW-SE Middle-Late Jurassic compression was also developed in the
586 neighbouring areas of the Lushun-Dalian area. Near the Wafangdian city, the SE-
587 directed thrusting of the Cambrian limestone over the Middle Jurassic clastic rocks
588 exposed in the Zhayao tectonic window was considered as the result of the NW-ward
589 subduction of the Paleo-Pacific plate beneath the NCC during the Late Jurassic to the
590 earliest Cretaceous (Fig. 2a; Qiu et al., 2018). In the weakly metamorphic sedimentary
591 rocks of the Penglai Group in the Jiaobei massif, the NW-SE compressional
592 deformation mainly expressed by NE-SW trending folds that refolded the earlier NW-
593 SE trending folds and cleavages did not rework the Early Cretaceous volcanic rocks
594 and was loosely constrained to occur in the Jurassic (Zhu, 1993; Zhu and Xu, 1994).

595 In the NCC west of the Tan-Lu fault, the NW-SE compressional deformation of the
596 Middle-Late Jurassic was more developed (Fig. 1; Davis et al., 2001; Zhang et al., 2007;
597 Faure et al., 2012; Dong et al., 2015; Wang et al., 2017b, 2018), from the eastern
598 segment of the Yanshan tectonic belt in the western Liaoning province and eastern
599 Hebei province of the eastern NCC (Yang et al., 2001; Hu et al., 2010), through the
600 Western Hills of Beijing and the northern Taihangshan of the central NCC (Wang and
601 Li, 2008; Wang et al., 2011b; Clinkscales and Kapp, 2019), to the Helanshan tectonic
602 belt in the western margin of the Ordos basin (Darby and Ritts, 2007; Huang et al.,
603 2015). It superimposed on the earlier N-S compression in the Yanshan orogenic belt
604 and changed its tectonic trends from E-W to NE and NNE (Wang et al., 2015). The
605 driving mechanism of the compression was commonly attributed to the NW-ward
606 subduction of the Paleo-Pacific plate beneath the eastern China in the Middle-Late
607 Jurassic (Dong et al., 2015; Wang et al., 2017b, 2018). Corresponding to this process,
608 the compressional stress transmitted from the eastern margin of the NCC to its western
609 interior, and a series of fold-thrust belts with NW vergence were developed upon a basal
610 decollement zone located between the crystalline basement and the overlying
611 sedimentary rocks (Wang et al., 2015). The intensity and age of the NW-SE
612 compression became weaker and younger toward the interior of the NCC, respectively
613 (Wang et al., 2017b).

614 Compared to the NCC west of the Tan-Lu fault, the Lushun-Dalian area of South
615 Liaodong Peninsula exposes more ductile structures with a top-to-the-NW sense of
616 shear. The intensely deformed thick incompetent layer located at the base of the Middle-

617 Upper Proterozoic metasedimentary rocks are probably the SE extension of the
618 subhorizontal decollement zone developed in the SE part of the Yanshan orogenic belt
619 (Wang et al., 2015). Above this subhorizontal decollement zone, NW-vergent folds and
620 brittle thrusts were widely developed upward and westward, and intensely reworked
621 the earlier E-W trending structures (Fig. 8, 9d). The similarity in age and kinematics
622 combined with the eastward strengthening of deformation intensity lead us to consider
623 the NW-SE deformation of Lushun-Dalian area as the tectonic response to the NW-
624 ward subduction of the Paleo-Pacific plate beneath the NCC in the Middle-Late Jurassic,
625 during which a significant tectonic transformation from the E-W trending Tethysian
626 domain to the NE-SW trending Pacific domain occurred (Wang et al., 2015).

627 **6. Conclusion**

628 The Lushun-Dalian area of the South Liaodong Peninsula is a key area to decipher
629 the Mesozoic tectonic evolution of eastern NCC. Our new structural and
630 geochronological data show that this area experienced two stages of compressional
631 deformation. The D_1 deformation, characterized by the top-to-the-NE ductile shearing,
632 NE-verging folds with the SW-dipping axial planar cleavages S_1 and the NE-directed
633 thrust faults, was the tectonic response to the convergence between NCC and SCB
634 during the Late Triassic to Early Jurassic. The D_2 deformation, dominated by the top-
635 to-the-NW ductile shearing, NW-verging folds and SW-plunging folds, was the
636 structural response to the NW-ward subduction of the Paleo-Pacific plate beneath the
637 NCC during the Middle-Late Jurassic. Field observations and mapping suggest that the
638 top-to-the-NW shearing erased the D_1 structures in the thick incompetent layer. The D_2

639 NW-SE shortening reworked the earlier E-W trending structures in the lower and upper
640 competent units, and formed a series of km-scale SW-plunging folds. The
641 superimposition of D₂ on D₁ recorded a significant tectonic transformation from the E-
642 W trending Tethysian domain to the NE-SW trending Pacific domain.

643

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648

649 **References**

650 Ames, L., Tilton, G.R., and Zhou, G.Z., 1993, Timing of collision of the Sino-Korean and Yangtze
651 cratons: U-Pb zircon dating of coesite-bearing eclogites: *Geology*, v. 21, p. 339-342.

652

653 Beaumont, C., Ellis, S., Hamilton, J., and Fullsack, P., 1996, Mechanical model for subduction-
654 collision tectonics of Alpine-type compressional orogens: *Geology*, v. 24, no. 8, p. 675-678.

655

656 Castellarin, A., and Cantelli, L., 2000, Neo-Alpine evolution of the Southern Eastern Alps: *Journal*
657 *of Geodynamics*, v. 30, p. 251-274.

658

659 Ceriani, S., and Schmid, S.M., 2004, From N-S collision to WNW-directed post-collisional
660 thrusting and folding: Structural study of the Frontal Penninic Units in Savoie (Western Alps,
661 France): *Eclogae Geologicae Helvetiae*, v. 97, p. 347-369.

662

663 Charles, N., Gumiaux, C., Augier, R., Chen, Y., Zhu, R., and Lin, W., 2011, Metamorphic core
664 complex vs. synkinematic pluton in continental extension setting: insights from key structures
665 (Shandong Province, eastern China): *Journal of Asian Earth Sciences*, v. 40, p. 261-278.

666

667 Charles, N., Augier, R., Gumiaux, C., Monié, P., Chen, Y., Faure, M., and Zhu, R.X., 2013, Timing,
668 duration and role of magmatism in wide rift systems: Insights from the Jiaodong Peninsula (China,
669 East Asia): *Gondwana Research*, v. 24, p. 412-428.

670

671 Chen, J.F., Xie, Z., Li, H.M., Zhang, X.D., Zhou, T.X., Park, Y.S., Ahn, K.S., Chen, D.G., and

672 Zhang, X., 2003, U-Pb zircon ages for a collision-related K-rich complex at Shidao in the Sulu
673 ultrahigh pressure terrane, China: *Geochemical Journal*, v. 37, p. 35–46.
674

675 Cho, M., Kim, Y., and Ahn, J.H., 2007, Metamorphic Evolution of the Imjingang Belt, Korea:
676 Implications for Permo-Triassic Collisional Orogeny: *International Geology Review*, v. 49, p. 30-
677 51.
678

679 Chopin, C. 1984, Coesite and pure pyrope in high-grade blueschists of the Western Alps: a first
680 record and some consequences: *Contributions to Mineralogy and Petrology*, v. 86, p. 107-118.
681

682 Clinkscales, C., and Kapp, P., 2019, Structural style and kinematics of the Taihang-Luliangshan
683 fold belt, North China: Implications for the Yanshanian orogeny: *Lithosphere*, v. 11,
684 <https://doi.org/10.1130/L1096.1>.
685

686 Darby, B.J. and Ritts, B.D., 2007. Mesozoic structural architecture of the Lang Shan, North-central
687 China: intraplate contraction, extension, and synorogenic sedimentation. *Journal of Structural*
688 *Geology* 29, 2006-2007.
689

690 Davis, G.A., Zheng, Y.D., Wang, C., Darby, B.J., Zhang, C.H., and Gehrels, G., 2001, Mesozoic
691 tectonic evolution of the Yanshan fold and thrust belt, with emphasis on Hebei and Liaoning
692 provinces, northern China, *in* Hendrix, M.S., and Davis, G.A. eds., *Paleozoic and Mesozoic tectonic*
693 *evolution of Central and Asia: From Continental Assembly to Intracontinental Deformation:*
694 *Geological Society of American Memoir* 194, p. 171–194, [https://doi.org/10.1130/0-8137-1194-](https://doi.org/10.1130/0-8137-1194-0.171)
695 [0.171](https://doi.org/10.1130/0-8137-1194-0.171).
696

697 Doglioni, C., 1987, Tectonics of the Dolomites (Southern Alps, Northern Italy): *Journal of*
698 *Structural Geology*, v. 9, no. 2, p. 181-193.
699

700 Dong, S.W., et al., 2015, Late Jurassic-Early Cretaceous continental convergence and
701 intracontinental orogenesis in East Asia: A synthesis of the Yanshan Revolution: *Journal of Asian*
702 *Earth Sciences*, v. 114, p. 750-770.
703

704 Erscher, A., Masson, H., and Steck, A., 1993, Nappe geometry in the Western Swiss Alps: *Journal*
705 *of Structural Geology*, v. 15, no. 3-5, p. 501-509.
706

707 Faure, M., Lin, W., and Sun, Y., 1998, Doming in the southern foreland of the Dabieshan (Yangtse
708 block, China): *Terra Nova*, v. 10, no. 6, p. 307-311.
709

710 Faure, M., Lin, W., Shu, L.S., Sun, Y., and Schärer, U., 1999, Tectonics of the Dabieshan (eastern
711 China) and possible exhumation mechanism of ultra high-pressure rocks: *Terra Nova*, v. 11, no. 6,
712 p. 251-258.
713

714 Faure, M., Lin, W., and Le Breton, N., 2001, Where is the North China-South China block boundary
715 in eastern China: *Geology*, v. 29, no. 2, p. 119-122.

716

717 Faure, M., Lin, W., Monié, P., Le Breton, N., Poussineau, S., Panis, D., and Deloule, E., 2003a,
718 Exhumation tectonics of the ultrahigh-pressure metamorphic rocks in the Qinling orogen in east
719 China: New petrological-structural radiometric insights from the Shandong Peninsula: *Tectonics*, v.
720 22, no. 3, doi: 10.1029/2002TC001450.

721

722 Faure, M., Lin, W., Schärer, U., Shu, L.S., Sun, Y., and Arnaud, N., 2003b, Continental subduction
723 and exhumation of UHP rocks. Structural and geochronological insights from the Dabieshan (East
724 China): *Lithos*, v. 70, p. 213-241.

725

726 Faure, M., Lin, W., Monié, P., and Bruguier, O., 2004, Paleoproterozoic arc magmatism and
727 collision in Liaodong Peninsula (north-east China): *Terra Nova*, v. 16, no. 2, p. 75-80.

728

729 Faure, M., Lin, W., and Chen, Y., 2012, Is the Jurassic (Yanshanian) intraplate tectonics of North
730 China due to westward indentation of the North China block: *Terra Nova*, v. 24, no. 6, p. 456-466.

731

732 Ganne, J., Bertrand, J.M., and Fudral, S., 2005, Fold interference pattern at the top of basement
733 domes and apparent vertical extrusion of HP rocks (Ambin and South Vanoise massifs, Western
734 Alps): *Journal of Structural Geology*, v. 27, p. 553-570.

735

736 Guo, J.H., Chen, F.K., Zhang, X.M., Siebel, W., and Zhai, M.G., 2005, Evolution of syn- to post-
737 collisional magmatism from north Sulu UHP belt, eastern China: zircon U-Pb geochronology [in
738 Chinese with English abstract]: *Acta Petrologica Sinica*, v. 21, no. 4, p. 1281-1301.

739

740 Hacker, B.R., Wallis, S.R., McWilliams, M.O., and Gans, P.B., 2009, $^{40}\text{Ar}/^{39}\text{Ar}$ Constraints on the
741 tectonic history and architecture of the ultrahigh-pressure Sulu orogen: *Journal of Metamorphic
742 Geology*, v. 27, p. 827-844.

743

744 Hu, J.M., Zhao, Y., Liu, X.W., and Xu, G., 2010, Early Mesozoic deformations of the eastern
745 Yanshan thrust belt, northern China: *International Journal of Earth Science*, v. 99, p. 785-800.

746

747 Huang, X.F., Shi, W., Chen, P., and Li, H.Q., 2015, Superposed deformation in the Helanshan
748 Structural Belt: Implications for Mesozoic intracontinental deformation of the North China Plate:
749 *Journal of Asian Earth Sciences*, v. 114, p. 140-154.

750

751 Higgins, A.K., and Leslie, A.G., 2000, Restoring thrusting in the East Greenland Caledonides:
752 *Geology*, v. 28, no. 11, p. 1019-1022.

753

754 Ji, M., Liu, J.L., Hu, L., Guan, H.M., Davis, G.A., and Zhang, W., 2009, Zircon SHRIMP U-Pb age
755 of Yinmawanshan and Zhaofang pluton in South Liaoning metamorphic core complex and its
756 geological implications [in Chinese with English abstract]: *Acta Petrologica Sinica*, v. 25, no. 1, p.
757 173-181.

758

759 Li, S.G., et al., 1993, Collision of the North China and Yangtse Blocks and formation of coesite-

760 bearing eclogites: Timing and processes: *Chemical Geology*, v. 109, p. 89-111.
761
762 Li, S.Z., Kusky, T.M., Liu, X.C., Zhang, G.W., Zhao, G.C., Wang, L., and Wang, Y.J., 2009a, Two-
763 stage collision-related extrusion of the western Dabie HP–UHP metamorphic terranes, central China:
764 Evidence from quartz c-axis fabrics and structures: *Gondwana Research*, v. 16, p. 294-309.
765
766 Li, S.Z., Liu, X., Suo, Y.H., Liu, L.P., Qian, C.C., Liu, X.C., Zhang, G.W., and Zhao, G.C., 2009c,
767 Triassic folding and thrusting in the Eastern block of the North China Craton and the Dabie-Sulu
768 orogen and its geodynamics [in Chinese with English abstract]: *Acta Petrologica Sinica*, v. 25, no.
769 9, p. 2031-2049.
770
771 Li, S.Z., Kusky, T.M., Zhao, G.C., Liu, X.C., Zhang, G.W., Kopp, H., and Wang, L., 2010, Two-
772 stage Triassic exhumation of HP–UHP terranes in the western Dabie orogen of China: Constraints
773 from structural geology: *Tectonophysics*, v. 490, p. 267-293.
774
775 Li, S.Z., et al., 2019, Mesozoic tectono-magmatic response in the East Asian ocean-continent
776 connection zone to subduction of the Paleo-Pacific Plate: *Earth-Science Reviews*, v. 192, p. 91-137.
777
778 Li, X.H., Liu, Y., Li, Q.L., Guo, C.H., and Chamberlain, K.R., 2009b, Precise determination of
779 Phanerozoic zircon Pb/Pb age by multicollector SIMS without external standardization:
780 *Geochemistry Geophysics Geosystem*, v. 10, Q04010, <http://dx.doi.org/10.1029/2009GC002400>.
781
782 Li, X.H., Tang, G.Q., Gong, B., Yang, Y.H., Hou, K.J., Hu, Z.C., Li, Q.L., Liu, Y., and Li, W.X.,
783 2013, Qinghu zircon: a working reference for microbeam analysis of U-Pb age and Hf-O isotopes:
784 *Chinese Science Bulletin*, v. 58, p. 4647-4654.
785
786 Li, Z., Chen, B., and Wei, C.J., 2017, Is the Paleoproterozoic Jiao-Liao-Ji Belt (North China Craton)
787 a rift?: *International Journal of Earth Science*, v. 106, p. 355-375.
788
789 LBGMR (Liaoning Bureau of Geology and Mineral Resources), 1989, Regional geology of
790 Liaoning Province [in Chinese with English summary]: Beijing, Geological Publishing House, p.
791 89-100.
792
793 Lin, W., Faure, M., Monié, P., Schärer, U., and Zhang, L., 2000, Tectonic of SE China, new insights
794 from the Lushan massif (Jiangxi province): *Tectonics*, v. 19, p. 852-871.
795
796 Lin, W., Faure, M., Sun, Y., Shu, L.S., and Wang, Q.C., 2001, Compression to extension switch
797 during the Middle Triassic orogeny of Eastern China: the case study of the Jiulingshan massif in the
798 southern foreland of the Dabieshan: *Journal of Asian Earth Sciences*, v. 20, p. 31-43.
799
800 Lin, W., Faure, M., Wang, Q.C., Monié, P., and Panis, D., 2005a, Triassic polyphase deformation
801 in the Feidong-Zhangbaling Massif (eastern China) and its place in the collision between the North
802 China and South China blocks: *Journal of Asian Earth Sciences*, v. 25, p. 121-136.
803

804 Lin, W., Faure, M., Wang, Q.C., and Arnaud, N., 2005b, Tectonic evolution of Dabie orogeny, in
805 the view from polyphase deformation of Beihuaiyang metamorphic zone: *Science in China (D)*, v.
806 35, no. 2, p. 127-139.
807

808 Lin, W., Wang, Q. C., and Shi, Y. H., 2005c, Architecture, kinematics and deformation analysis in
809 Dabie-Sulu collision zone [in Chinese with English abstract]: *Acta Petrologica Sinica*, v. 21, no. 4,
810 p. 1195-1214.
811

812 Lin, W., Faure, M., Monié, P. and Wang, Q.C., 2007, Polyphase Mesozoic tectonics in the eastern
813 part of the North China Block: Insights from the Eastern Liaoning Peninsula massif (NE China), in
814 Zhai, M.G., Windley, B.F., Kusky, T.M., and Meng, Q.R., eds., *Mesozoic Subcontinental
815 Lithospheric Thinning Under Eastern Asia: Geological Society of London, Special Publications 280*,
816 p. 153-169.
817

818 Lin, W., Faure, M., Monié, P., Schärer, U. and Panis, D., 2008, Mesozoic extensional tectonics in
819 Eastern Asia: The South Liaodong Peninsula Metamorphic Core Complex (NE China): *Journal of
820 Geology*, v. 116, p. 134-154.
821

822 Lin, W., Shi, Y. H., and Wang, Q. C., 2009, Exhumation tectonics of the HP-UHP orogenic belt in
823 Eastern China: New structural-petrological insights from the Tongcheng massif, Eastern Dabieshan:
824 *Lithos*, v. 109, p. 285-303.
825

826 Lin, W., Monié, P., Faure, M., Schärer, U., Shi, Y.H., Le Breton, N. and Wang, Q.C., 2011, Cooling
827 paths of the NE China crust during the Mesozoic extensional tectonics: Example from the South
828 Liaodong Peninsula metamorphic core complex: *Journal of Asian Earth Sciences*, v. 42, p. 1048-
829 1065.
830

831 Lin, W., Ji, W. B., Faure, M., Wu, L., Li, Q. L., Shi, Y. H., Schärer, U., Wang, F., and Wang, Q.C.,
832 2015, Early Cretaceous extensional reworking of the Triassic HP-UHP metamorphic orogen in
833 Eastern China: *Tectonophysics*, v. 662, p. 256-270.
834

835 Lin, W., and Wei, W., 2018, Late Mesozoic extensional tectonics in the North China Craton and its
836 adjacent regions: a review and synthesis: *International Geology Review*, doi:
837 10.1080/00206814.2018.1477073.
838

839 Linzer, H.G., Ratschbacher, L., and Frisch, W., 1995, Transpressional collision structures in the
840 upper crust: the fold-thrust belt of the Northern Calcareous Alps: *Tectonophysics*, v. 242, p. 41-61.
841

842 Liu, F.L., Gerdes, A., Liou, J.G., Xue, H.M., and Liang, F.H., 2006, SHRIMP U-Pb zircon dating
843 from Sulu-Dabie dolomitic marble, eastern China: constraints on prograde, ultrahigh-pressure and
844 retrograde metamorphic ages: *Journal of Metamorphic Geology*, v. 24, p. 569-589.
845

846 Liu, J.L., Davis, G.A., Lin, Z.Y., and Wu, F.Y., 2005, The Liaonan metamorphic core complex,
847 southeastern Liaoning Province, North China: A likely contributor to Cretaceous rotation of eastern

848 Liaoning, Korea and contiguous areas: *Tectonophysics*, v. 407, p. 65-80.
849

850 Liu, J.L., Ji, M., Shen, L., Guan, H.M., and Davis, G.A., 2011b, Early Cretaceous extension in the
851 Liaodong Peninsula: Structural associations, geochronological constraints and regional tectonic
852 implications: *Science China Earth Science*, v. 54, p. 823-842.
853

854 Liu, J.L., Shen, L., Ji, M., Guan, H.M., Zhang, Z.C., and Zhao, Z.D., 2013, The Liaonan/Wanfu
855 metamorphic core complexes in the Liaodong Peninsula: Two stages of exhumation and constraints
856 on the destruction of the North China Craton: *Tectonics*, v. 32, p. 1121-1141.
857

858 Liu, S.F., Gurnis, M., Ma, P.F., Zhang, B., 2017, Reconstruction of northeast Asian deformation
859 integrated with western Pacific plate subduction since 200 Ma: *Earth-Science Reviews*, v. 175, p.
860 114-142.
861

862 Liu, W.C., Li, B.W., Pan, B.Y., and Liu, Y.B., 2001, Characteristics of deformation during
863 Mesozoic era in the Chaohu-Chuzhou region, Anhui province [in Chinese with English abstract]:
864 *Geoscience*, v. 15, no. 13, p. 13-20.
865

866 Liu, X., Li, S.Z., Suo, Y.H., Liu, X.C., Dai, L.M., and Santosh, M., 2011a, Structural anatomy of
867 the exhumation of high-pressure rocks: constraints from the Tongbai Collisional Orogen and
868 surrounding units: *Geological Journal*, v. 46, p. 156-172.
869

870 Liu, X., Li, S.Z., Suo, Y.H., Liu, X.C., Dai, L.M., and Santosh, M., 2012, Structural analysis of the
871 northern Tongbai Metamorphic Terranes, Central China: Implications for Paleozoic accretionary
872 process on the southern margin of the North China Craton: *Journal of Asian Earth Sciences*, v. 47,
873 p. 143-154.
874

875 Ludwig, K.R., 2003, User's Manual for Isoplot 3.00: A Geochronological Toolkit for Microsoft
876 Excel. Berkeley Geochronology Center Special Publication No. 4.
877

878 Luo, Y., S.M., Zhao, G.C., Li, S.Z., Xu, P., Ye, K., and Xia, X.P., 2004, LA-ICP-MS U–Pb zircon
879 ages of the Liaohe Group in the Eastern Block of the North China Craton: constraints on the
880 evolution of the Jiao-Liao-Ji Belt: *Precambrian Research*, v. 134, p. 349-371.
881

882 Mattauer, M., Matte, P., Malavieille, J., Tapponnier, P., Maluski, H., Xu, Z.Q., Lu, Y.L., and Tang,
883 Y.Q., 1985, Tectonics of Qinling belt: build-up and evolution of eastern Asia: *Nature*, v. 317, p.
884 496-500.
885

886 Okay, A., Sengör, A., and Satir, M., 1993, Tectonics of an ultrahigh-pressure metamorphic terrane:
887 the Dabie Shan/Tongbaishan orogen, China: *Tectonics*, v. 12, no. 6, p. 1320-1334.
888

889 Qiu, L., et al., 2018, The Zhayao tectonic window of the Jurassic Yuantai thrust system in Liaodong
890 Peninsula, NE China: Geometry, kinematics and tectonic implications: *Journal of Asian Earth
891 Sciences*, v. 164, p. 58-71.

892
893 Ratschbacher, L., 1986, Kinematics of Austro-Alpine cover nappes: changing translation path due
894 to transpression: *Tectonophysics*, v. 125, p. 335-356.
895
896 Ratschbacher, L., and Oertel, G., 1987, Superposed deformations in the Eastern Alps: strain analysis
897 and microfabrics: *Journal of Structural Geology*, v. 9, p. 263-276.
898
899 Ratschbacher, L., Hacker, B.R., Calvert, A., Webb, L.E., Grimmer, J.C., McWilliams, M.O., Ireland,
900 T., Dong, S.W., and Hu, J.M., 2003, Tectonics of the Qinling (Central China): tectonostratigraphy,
901 geochronology, and deformation history: *Tectonophysics*, v. 366, p. 1-53.
902
903 Ren, Z.H., and Lin, W., 2019, Mesozoic tectonic evolution of eastern China: Insights from the
904 Changshan Islands, NE China: *Tectonophysics*, v. 763, p. 46-60.
905
906 Schäfer, F., Oncken, O., Kemnitz, H., and Romer, R.L., 2000, Upper-plate deformation during
907 collisional orogeny: a case study from the German Variscides (Saxo-Thuringian Zone), *in* Franke,
908 W., Haak, V., Oncken, O., and Tanner, D., eds., *Orogenic Processes: Quantification and Modelling*
909 *in the Variscan Belt: Geological Society, London, Special Publications*, v. 179, p. 281-302.
910
911 Schmid, J.C., Ratschbacher, L., Hacker, B.R., Gaitzsch, I., and Dong, S.W., 1999, How did the
912 foreland react? Yangtze foreland fold-and-thrust belt deformation related to exhumation of the
913 Dabie Shan ultrahigh-pressure crust (eastern China): *Terra Nova*, v. 11, no. 6, p. 266-272.
914
915 Shen, L., Liu, J.L., Hu, L., Ji, M., Guan, H.M., and Davis, G.A., 2011, The Dayingzi detachment
916 fault system in Liaodong Peninsula and its regional tectonic significance: *Science China Earth*
917 *Science*, v. 41, p. 437- 451.
918
919 Sláma, J., et al., 2008, Plešovice zircon-a new natural reference material for U/Pb and Hf isotopic
920 microanalysis: *Chemical Geology*, v. 249, p. 1-35.
921
922 Sun, X.M., Zhang, M.S., Long, S.X., Hao, F.J., Liu, P.J., and Liu, C.Y., 2004, Overthrust tectonic
923 in northern Qinling-Dabie orogenic belt and basin-controlling faults in Zhoukou depression and
924 Hefei basin [in Chinese with English abstract]: *Oil & Gas Geology*, v. 25, no. 2, p. 191-198.
925
926 Wan, Y.S., Dong, C.Y., Liu, D.Y., Kröner, A., Yang, C.H., Wang, W., Du, L.L., Xie, H.Q., and Ma,
927 M.Z., 2012, Zircon ages and geochemistry of late Neoproterozoic syenogranites in the North China
928 Craton: A review: *Precambrian Research*, v. 222-223, p. 265-289.
929
930 Wang, E.C., Meng, Q.R., Burchfiel, B.C., and Zhang, G.W., 2003, Mesozoic large-scale lateral
931 extrusion, rotation, and uplift of the Tongbai–Dabie Shan belt in east China: *Geology*, v. 31, no. 4,
932 p. 307-310.
933
934 Wang, L., Kusky, T.M., and Li, S.Z., 2010, Structural geometry of an exhumed UHP terrane in the
935 eastern Sulu Orogen, China: Implications for continental collisional processes: *Journal of Structural*

936 Geology, v. 32, p. 423-444.
937
938 Wang, P.P., Song, C.Z., Li, J.H., Ren, S.L., Zhang, Y., and Wang, W., 2016, Tectonic characteristics
939 and geochronology of Mashan nappe structure in Bengbu [in Chinese with English abstract]: Journal
940 of Hefei University of Technology, v. 39, no. 3, p. 385-394.
941
942 Wang, T., Zheng, Y.D., Zhang, J.J., Zeng, L.S., Donskaya, T., Guo, L., and Li, J.B., 2011a, Pattern
943 and kinematic polarity of late Mesozoic extension in continental NE Asia: Perspectives from
944 metamorphic core complexes: Tectonics, v. 30, TC6007, doi:10.1029/2011TC002896.
945
946 Wang, T., Guo, L., Zheng, Y.D., Donskaya, T., Gladkochub, D., Zeng, L.S., Li, J.B., Wang, Y.B.,
947 and Mazukabzov, A., 2012, Timing and processes of late Mesozoic mid-lower-crustal extension in
948 continental NE Asia and implications for the tectonic setting of the destruction of the North China
949 Craton: Mainly constrained by zircon U-Pb ages from metamorphic core complexes: Lithos, v. 154,
950 p. 315-345.
951
952 Wang, X.D., Neubauer, F., Genser, J., and Yang, W.R., 1998, The Dabie UHP unit, Central China:
953 a Cretaceous extensional allochthon superposed on a Triassic orogen: Terra Nova, v. 10, no. 5, p.
954 260-267.
955
956 Wang, Y., and Li, H.M., 2008, Initial Formation and Exhumation of an Intracontinental Tectonic
957 Belt—An Example from the Northern Part of the Taihang Mountain Belt, Eastern Asia: Journal of
958 Geology, v. 116, p. 155–172.
959
960 Wang, Y., Zhou, L.Y., and Li, J.Y., 2011b, Intracontinental superimposed tectonics — A case study
961 in the Western Hills of Beijing, eastern China: Geological Society of America Bulletin, v. 123, no.
962 5/6, p. 1033–1055.
963
964 Wang, Y., Zhou, L.Y., Zhao, L.J., Cope, T., and Liu, J., 2015, Tectonic transformations in the north
965 of eastern China during 170–150 Ma: Causal linkage to the rapid formation of the paleo-Pacific
966 plate, in Anderson, T.H., Didenko, A.N., Johnson, C.L., Khanchuk, A.L., and MacDonald, J.H., Jr.,
967 eds., Late Jurassic Margin of Laurasia-A Record of Faulting Accommodating Plate Rotation:
968 Geological Society of America Special Paper 513, p. 561–587.
969
970 Wang, Y., Zhou, L.Y., and Luo, Z.H., 2017b, Kinematics and timing of continental block
971 deformation from margins to interiors: Terra Nova, v. 29, p. 253–263.
972
973 Wang, Y., Sun, L.X., Zhou, L.Y., and Xie, Y.T., 2018, Discussion on the relationship between the
974 Yanshanian Movement and cratonic destruction in North China: Science China Earth Sciences, v.
975 61, p. 499–514.
976
977 Wang, Y.C., Dong, S.W., Shi, W., Chen, X.H. and Jia, L.M., 2017a, The Jurassic structural
978 evolution of the western Daqingshan area, eastern Yinshan belt, North China: International Geology
979 Review, v. 59, no. 15, p. 1885-1907.

980
981 Wang, Z.X., Tang, Z.M., Yang, Z.Z., and Yang, X.B., 2000a, Ductile tectonic deformation of
982 Mesozoic time in the Dalian area [in Chinese with English abstract]: *Seismology and Geology*, v.
983 22, no. 4, p. 379-386.
984
985 Wang, Z.X., Tang, Z.M., Yang, Z.Z., and Yang, X.B., 2000b, Redetermination of the Meso-
986 Cenozoic structural framework of Dalian area [in Chinese with English abstract]: *Regional Geology*
987 of China, v. 19, no. 2, p. 120-126.
988
989 Wang, Z.X., Yang, T.N., and Tang, Z.M., 2001, The NS-trending shear traction deformation in
990 Dalian area, Northeast China [in Chinese with English abstract]: *Acta Petrologica et Mineralogica*,
991 v. 20, no. 2, p. 208-216.
992
993 Wang, Z.X., Yang, T.N., Peng, Y., Tang, Z.M., Yang, X.B., Yang, Z.Z., Gao, L.Z. and Li, D.Z.
994 2002, The People's Republic of China, Lushun-Dalian area, 1: 50,000 Geological Survey Report
995 [in Chinese], p. 100-104.
996
997 Willett, S., Beaumont, C., and Fullsack, P., 1993, Mechanical model for the tectonics of doubly
998 vergent compressional orogens: *Geology*, v. 21, p. 371-374.
999
1000 Wu, F.Y., Yang, J.H., and Liu, X.M., 2005a, Geochronological framework of the Mesozoic granitic
1001 magmatism in the Liaodong Peninsula, Northeast China [in Chinese with English abstract]:
1002 *Geological Journal of China Universities*, v. 11, no. 3, p. 305-317.
1003
1004 Wu, F.Y.; Yang, J.H.; Wilde, S. A.; and Zhang, X. 2005b, Geochronology, petrogenesis and tectonic
1005 implications of the Jurassic granites in the Liaodong Peninsula, NE China: *Chemical Geology*, v.
1006 221, p. 127-156.
1007
1008 Wu, F.Y., Lin, J.Q., Wilde, S. A., Zhang, X.O., and Yang, J.H., 2005c, Nature and significance of
1009 the Early Cretaceous giant igneous event in eastern China: *Earth and Planetary Science Letters*, v.
1010 233, p. 103-119.
1011
1012 Xia, Z.M., Liu, J. L., Ni, J.L., Zhang, T.T., Shi, X.M., and Wu, Y., 2016, Structure, evolution and
1013 regional tectonic implications of the Queshan metamorphic core complex in eastern Jiaodong
1014 Peninsula of China: *Science China Earth Science*, v. 46, p. 356-373.
1015
1016 Xu, Z.Q., Li, H.B., Wang, Z.X., and Li, D.Z., 1991, A contraction to extension in the crust of south
1017 Liaoning Peninsula [in Chinese with English abstract]: *Geological Review*, v. 37, no. 3, p. 193-202.
1018
1019 Xu, Z.Q., Zeng, L.S., Liu, F.L., Yang, J.S., Zhang, Z.M., McWilliams, M., and Liou, J.G., 2006,
1020 Polyphase subduction and exhumation of the Sulu high-pressure-ultrahigh-pressure metamorphic
1021 terrane, in Hacker, B.R., McClelland, W.C., and Liou, J.G., eds., *Ultrahigh-pressure metamorphism:*
1022 *Deep continental subduction*: Geological Society of America, Special Paper 403, p. 93-114.
1023

- 1024 Xue, F., Rowley, D.B., and Baker, J., 1996, Refolded syn-ultrahigh-pressure thrust sheets in the
1025 south Dabie complex, China: Field evidence and tectonic implications: *Geology*, v. 24, no. 5, p.
1026 455-458.
1027
- 1028 Yang, D.B., Xu, W.L., Xu, Y.G., Wang, Q.H., Pei, F.P., and Wang, F., 2012, U–Pb ages and Hf
1029 isotope data from detrital zircons in the Neoproterozoic sandstones of northern Jiangsu and southern
1030 Liaoning Provinces, China: Implications for the Late Precambrian evolution of the southeastern
1031 North China Craton: *Precambrian Research*, v. 216-219, p. 162-176.
1032
- 1033 Yang, G., Chai, Y.C., and Wu, Z.W., 2001, Thin-skinned thrust nappe structures in western
1034 Liaoning in the eastern sector of the Yanshan orogenic belt [in Chinese with English abstract]: *Acta*
1035 *Geologica Sinica*, v. 75, no. 3, p. 322–332.
1036
- 1037 Yang, J.H., Chung, S.L., Wilde, S.A., Wu, F.Y., Chu, M.F., Lo, C.H., and Fan, H.R., 2005,
1038 Petrogenesis of post-orogenic syenites in the Sulu Orogenic Belt, East China: geochronological,
1039 geochemical and Nd–Sr isotopic evidence: *Chemical Geology*, v. 214, p. 99-125.
1040
- 1041 Yang, J.H., Wu, F.Y., Chung, S.L., Lo, C.H., Wilde, S.A. and Davis, G.A., 2007a, Rapid
1042 exhumation and cooling of the Liaonan metamorphic core complex: Inferences from $^{40}\text{Ar}/^{39}\text{Ar}$
1043 thermochronology and implications for Late Mesozoic extension in the eastern North China Craton:
1044 *Geological Society of America Bulletin*, v. 119, no. 11/12, p. 1405-1414.
1045
- 1046 Yang, J.H., Wu, F.Y., Liu, X.M., Xie, L.W., and Yang, Y.H., 2007b, Petrogenesis and geological
1047 significance of the Jurassic Xiaoheishan pluton in the Liaodong Peninsula, East China: In-situ
1048 Zircon U-Pb dating and Hf isotopic analysis [in Chinese with English abstract]: *Bulletin of*
1049 *Mineralogy, Petrology and Geochemistry*, v. 26, no. 1, p. 29-43.
1050
- 1051 Yang, T.N., Peng, Y., Wang, Z.X., Li, D.Z., Yang, Z.Z., and Wang, G.Z., 2002, Nearly N-S
1052 compressional deformation of sedimentary cover in the Lushun-Dalian area: Intraplate deformation
1053 effect of overlying plate on continental deep-subduction of the Sulu area [in Chinese with English
1054 abstract]: *Geological Bulletin of China*, v. 21, no. 6, p. 308-314.
1055
- 1056 Yang, T.N., Peng, Y., Leech, M.L., and Lin, H.Y., 2011, Fold patterns indicating Triassic
1057 constrictional deformation on the Liaodong peninsula, eastern China, and tectonic implications:
1058 *Journal of Asian Earth Sciences*, v. 40, p. 72-83.
1059
- 1060 Ye, K., Cong, B.L., and Ye, D.N., 2000, The possible subduction of continental material to depths
1061 greater than 200 Km: *Nature*, v. 407, p. 734-736.
1062
- 1063 Yin, A., and Nie, S.Y., 1993, An indentation model for the North and South China collision and the
1064 development of the Tan-Lu and normal fault systems, eastern Asia: *Tectonics*, v. 12, no. 4, p. 801-
1065 813.
1066
- 1067 Yin, A., and Nie, S.Y., 1996, Phanerozoic palinspastic reconstruction of China and its neighboring

1068 regions, *in* Yin, A., and Harrison, T. A., eds., *The tectonic evolution of Asia*: New York, Cambridge
1069 University Press, p. 442-485.
1070

1071 Zhang, S.H., Zhao, Y., Ye, H., and Hu, G.H., 2016, Early Neoproterozoic emplacement of the
1072 diabase sill swarms in the Liaodong Peninsula and pre-magmatic uplift of the southeastern North
1073 China Craton: *Precambrian Research*, v. 272, p. 203-225.
1074

1075 Zhang, Y.Q., Dong, S.W., Zhao, Y., and Zhang, T., 2007, Jurassic Tectonics of North China: a
1076 synthetic view [in Chinese with English abstract]: *Acta Geologica Sinica*, v. 81, no. 11, p. 1462–
1077 1480.
1078

1079 Zhou, J.B., Cao, J.L., Wilde, S.A., Zhao, G.C., Zhang, J.J., and Wang, B., 2014, Paleo-Pacific
1080 subduction-accretion: Evidence from Geochemical and U-Pb zircon dating of the Nanhada
1081 accretionary complex, NE China: *Tectonics*, v. 33, p. 2444-2466.
1082

1083 Zhu, G., 1993, Geotectonic implications of the deformation and metamorphism of the Penglai Group
1084 of the Jiaobei region, China [in Chinese with English abstract]: *Geotectonica et Metallogenia*, v. 17,
1085 no. 3, p. 259-270.
1086

1087 Zhu, G., Evans, J.A., Fitches, W.R., Fletcher, C.J.N., Rundle, C.R., and Xu, J.W., 1994, Isotopic
1088 constraints on the Paleozoic evolution of the Shandong Peninsula, N.E. China: *Journal of Southeast
1089 Asian Earth Sciences*, v. 9, p. 241-248.
1090

1091 Zhu, G., and Xu, J.W., 1994, Deformation and metamorphic evolution in the Jiaobei region, eastern
1092 Shandong [in Chinese with English abstract]: *Journal of Hefei University of Technology*, v. 17, no.
1093 3, p. 148-162.
1094

1095 Zhu, G., Wang, Y.S., Wang, W., Zhang, S., Liu, C., Gu, C.C., and Li, Y.J., 2017, An accreted micro-
1096 continent in the north of the Dabie Orogen, East China: Evidence from detrital zircon dating:
1097 *Tectonophysics*, v. 698, p. 47-64.
1098

1099 Zhu, R.X., Yang, J.H., and Wu, F.Y., 2012, Timing of destruction of the North China Craton: *Lithos*,
1100 v. 149, p. 51–60.
1101

1102 Zhu, R.X. and Xu, Y.G., 2019, The subduction of the west Pacific plate and the destruction of the
1103 North China Craton. *Science China Earth Sciences*, v. 62, p. 1340-1350.

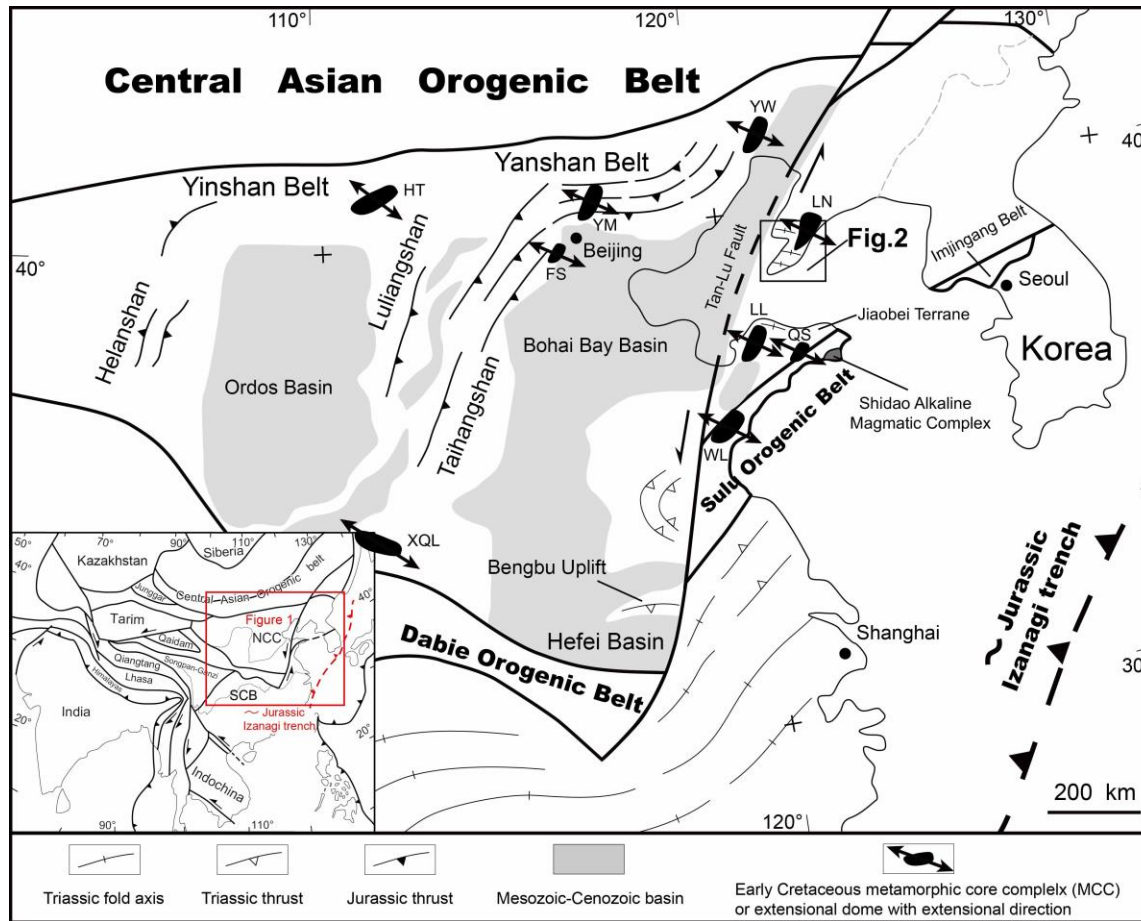


Fig. 1. Simplified tectonic framework of the NCC and the location of the South Liaodong Peninsula (modified from Cho et al., 2007; Wang et al., 2011b; Clinkscales and Kapp, 2019; Lin and Wei, 2018). NCC: North China Craton; SCB: South China Block; FS: Fangshan antiform; HT: Hohhot MCC; LL: Linglong dome; LN: Liaonan MCC; QS: Queshan MCC; WL: Wulian MCC; XQL: Xiaoqinling MCC; YM: Yunmengshan syntectonic pluton reworked by a ductile normal fault; YW:

Yiwulushan pluton reworked by a ductile normal fault

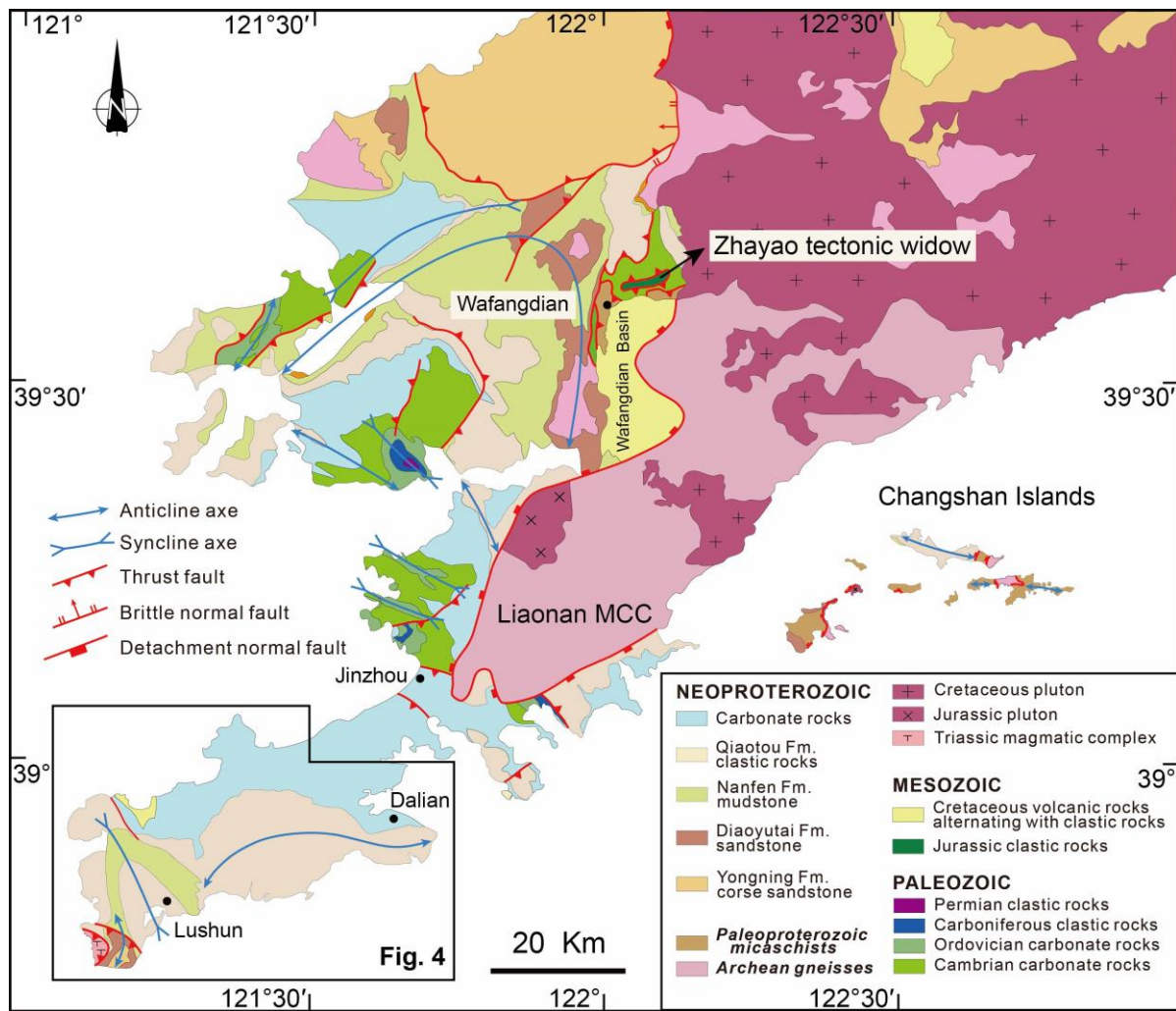


Fig. 2. Simplified geological map of the South Liaodong Peninsula.

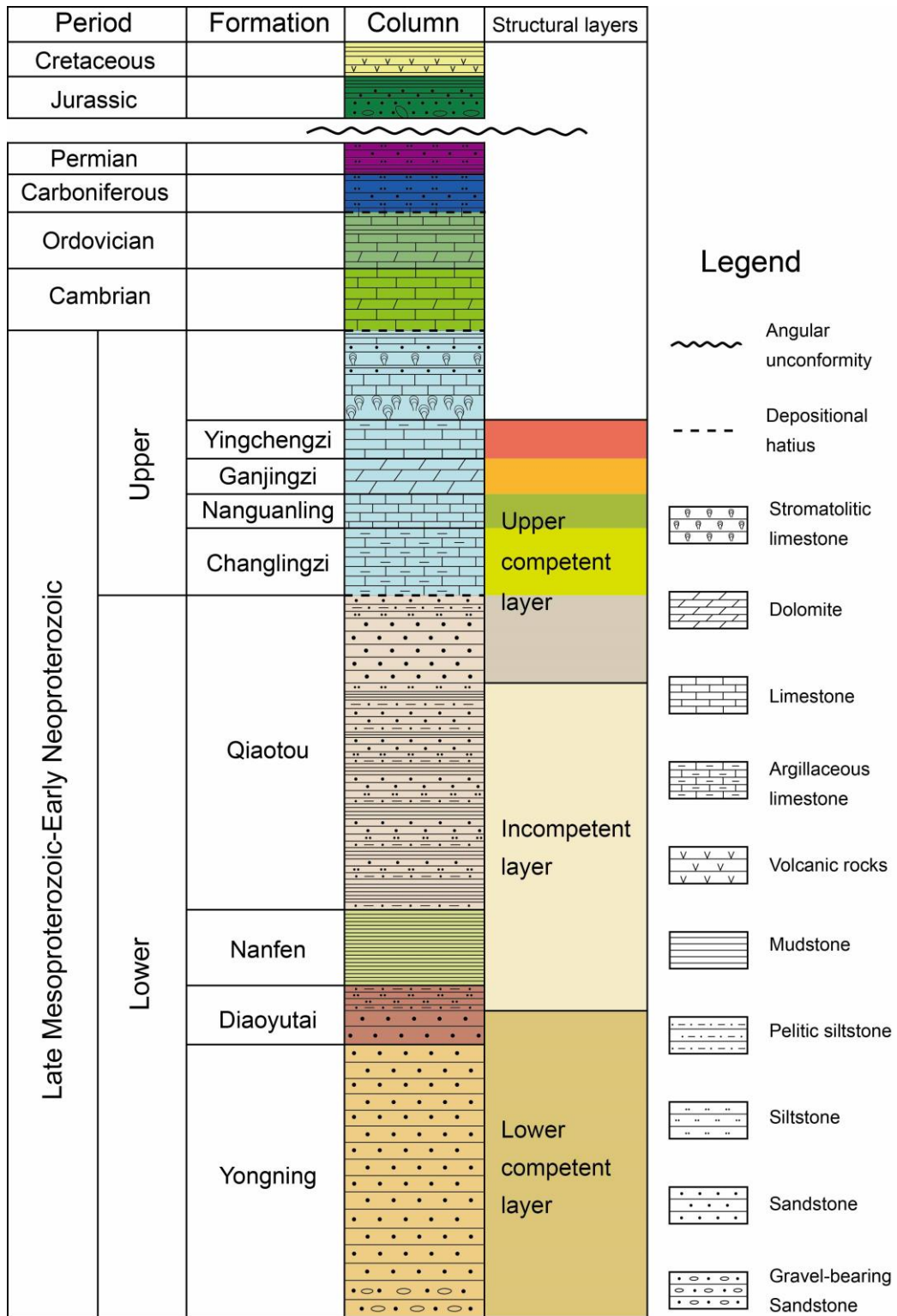


Fig. 3. The sedimentary sequence of the South Liaodong Peninsula (modified from Yang et al., 2011), and the structural layers of the Lushun-Dalian area.

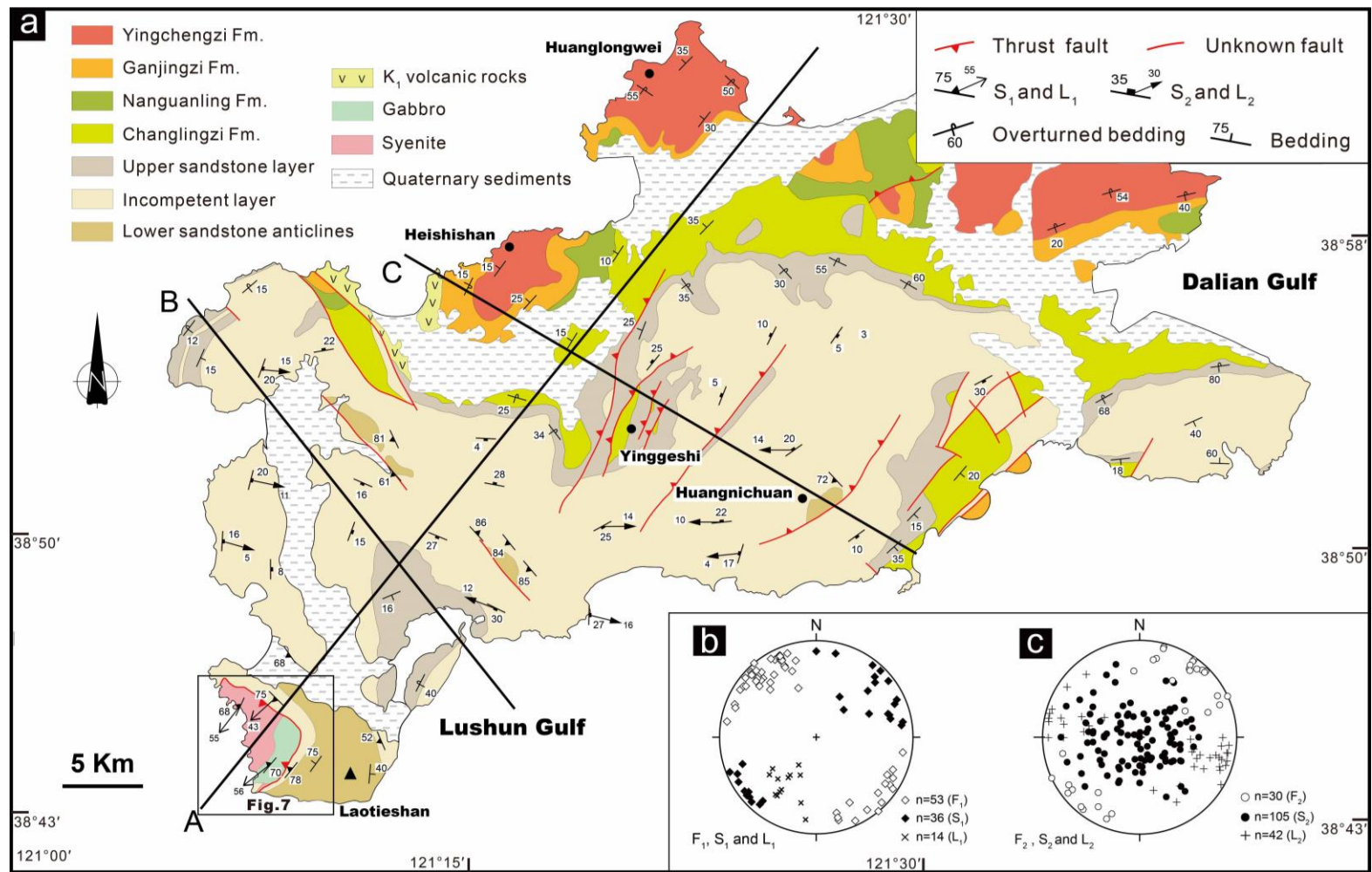


Fig. 4. a, Structural geological map of the Lushun-Dalian area. Equiareal stereograms (Schmidt net, lower hemisphere) of the structural elements. **b**, Fold axes F₁ and S₁ foliation. **c**, Fold axes F₂, S₂ foliation and L₂ lineation.

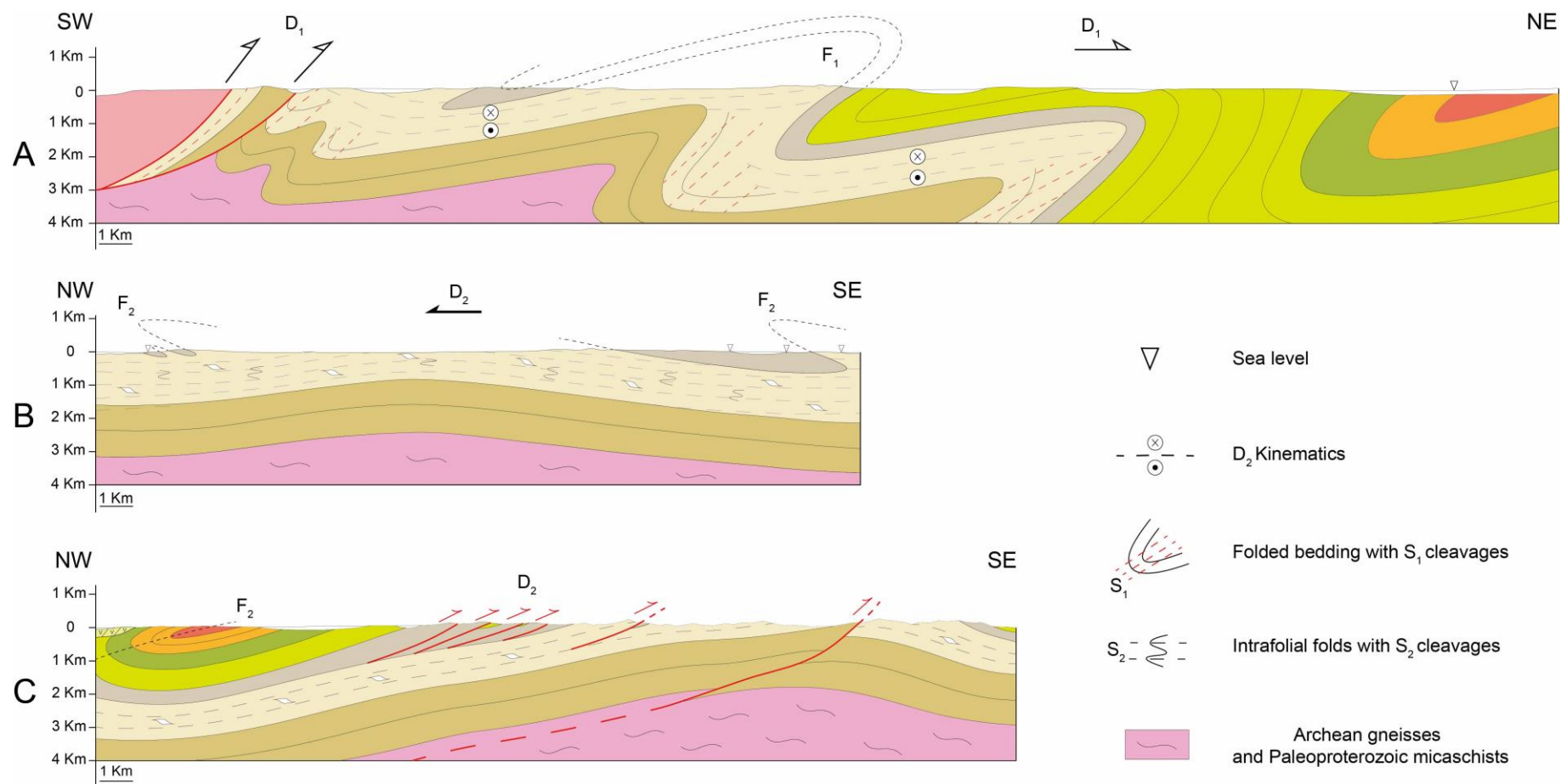


Fig. 5. Cross sections through the Lushun-Dalian area (locations in Fig. 3) drawn parallel to the direction of the main mineral and stretching lineation.

A, Section along D₁ lineation; **B** and **C**, Sections along D₂ lineation

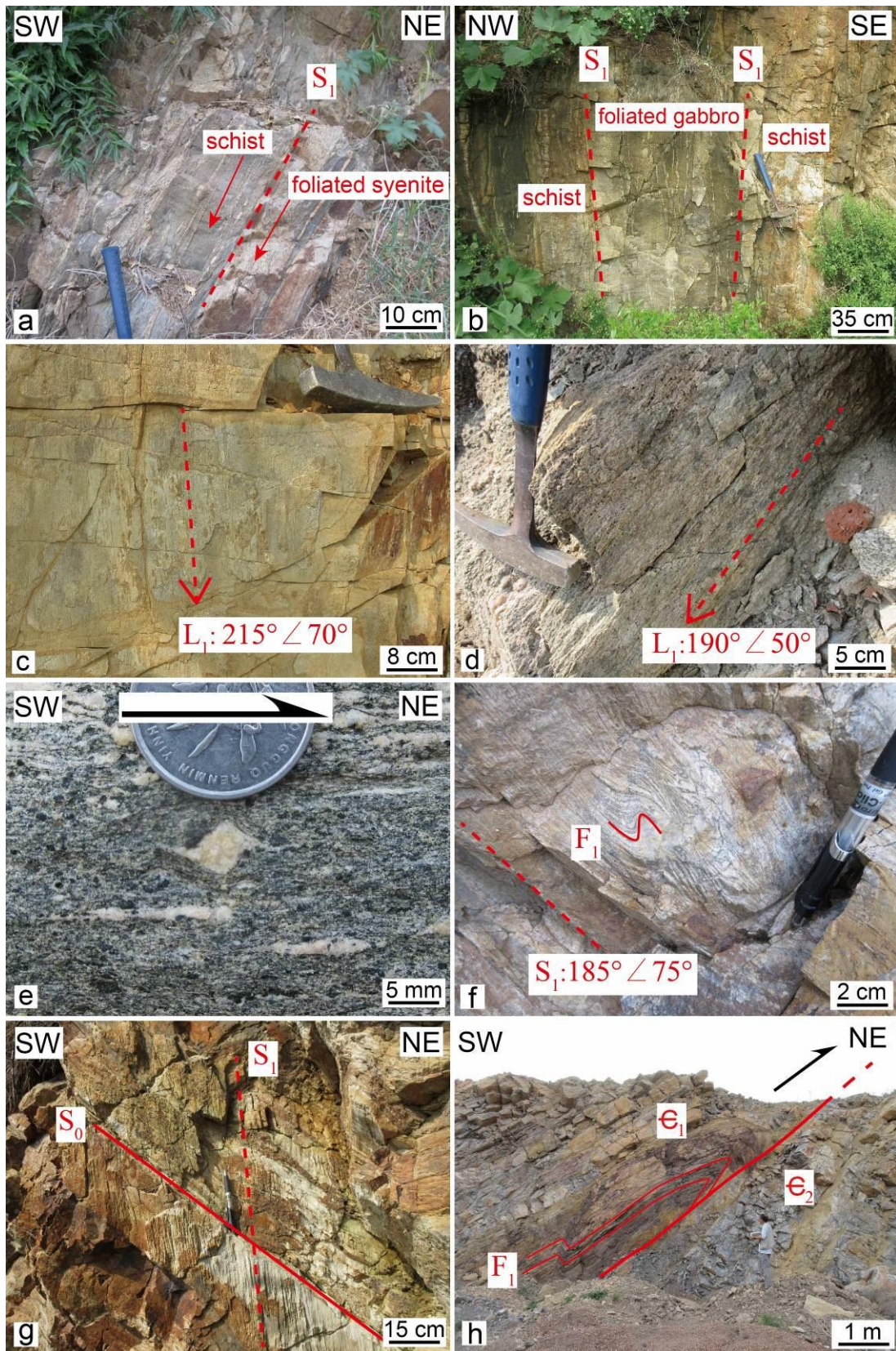


Fig. 6. Field photographs of structures associated with the D₁ deformation. **a**, Syenite intrusion and country rocks concurrently foliated (38°45'56.63", 121°8'43.91"). **b**, Gabbro intrusion and country rocks concurrently deformed (38°44'16.88", 121°9'7.52"). **c**, Stretching L₁ lineation exhibited on the S₁ foliation in slate (38°45'38.16", 121°9'15.48"). **d**, Stretching L₁ lineation

exhibited on the S_1 foliation of the mylonitized syenite ($38^{\circ}44'7.14''$, $121^{\circ}8'8.18''$). **e**, Delta-type K-feldspar porphyroclast in the mylonitized syenite indicating a top-to-the-NE shear sense ($38^{\circ}45'19.5''$, $121^{\circ}7'40.09''$). **f**, Penetrative SW-dipping S_1 and small intrafolial folds in the slate of the country rocks of the Yinjiacun complex ($38^{\circ}46'3''$, $121^{\circ}8'8.77''$). **g**, Subvertical S_1 in the siltstone of Diaoyutai Formation, east of Lushun city ($38^{\circ}49'51.06''$, $121^{\circ}16'47.94''$). **h**, Fold and thrust in the limestone, north of Jinzhou city ($39^{\circ}15'59.76''$, $121^{\circ}37'12.36''$).

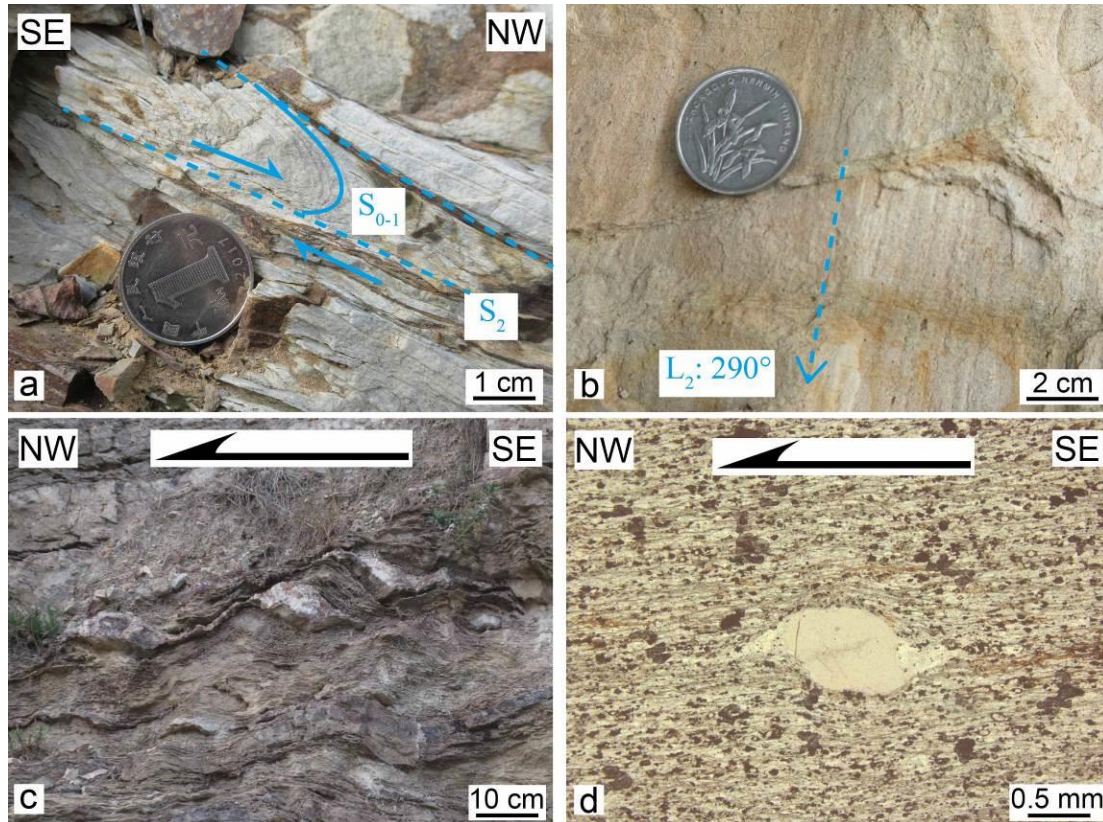


Fig. 7. Field photographs and microphotographs of structures associated with the D_2 deformation. **a**, Intrafolial F_2 fold preserved in slate of the Qiaotou formation ($38^{\circ}55'16.23''$, $121^{\circ}9'9.49''$). **b**, NW-SE trending mineral stretching L_2 lineation developed in the S_2 foliation of the Diaoyutai formation ($38^{\circ}48'24.97''$, $121^{\circ}17'27.72''$). **c**, Sigmoidal quartz boudins in the Qiaotou formation indicating a top-to-the-NW shearing ($38^{\circ}47'29.41''$, $121^{\circ}16'40.75''$). **d**, Sigma-type quartz porphyroclast in the slate of the Diaoyutai formation indicating a top-to-the-NW shearing ($38^{\circ}48'43.63''$, $121^{\circ}17'24.82''$).

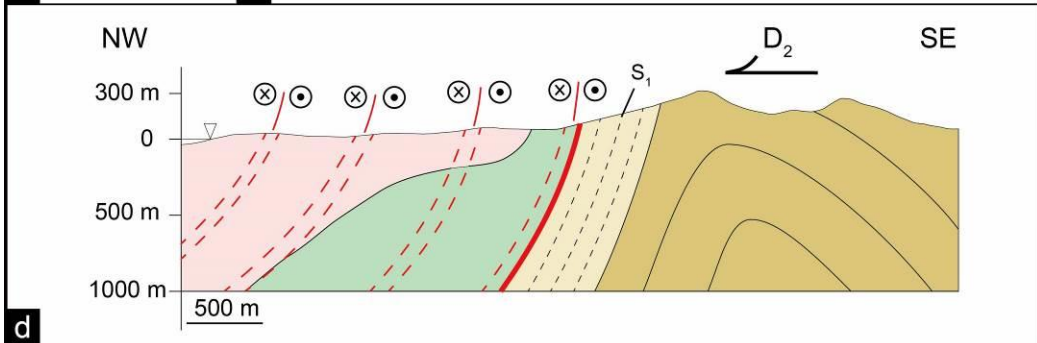
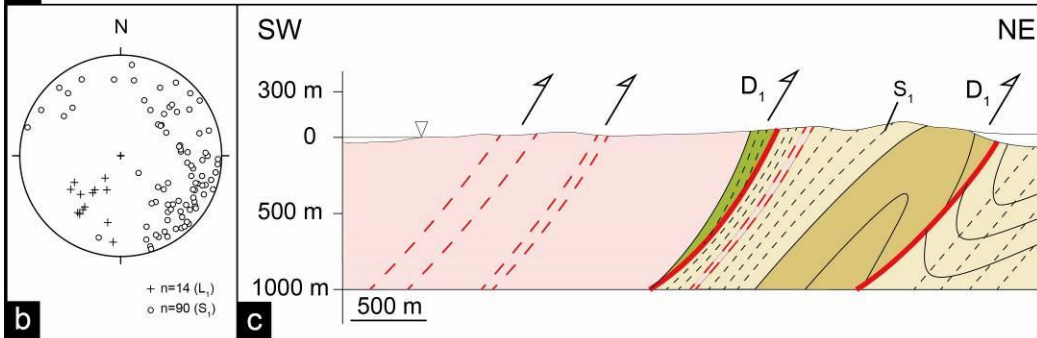
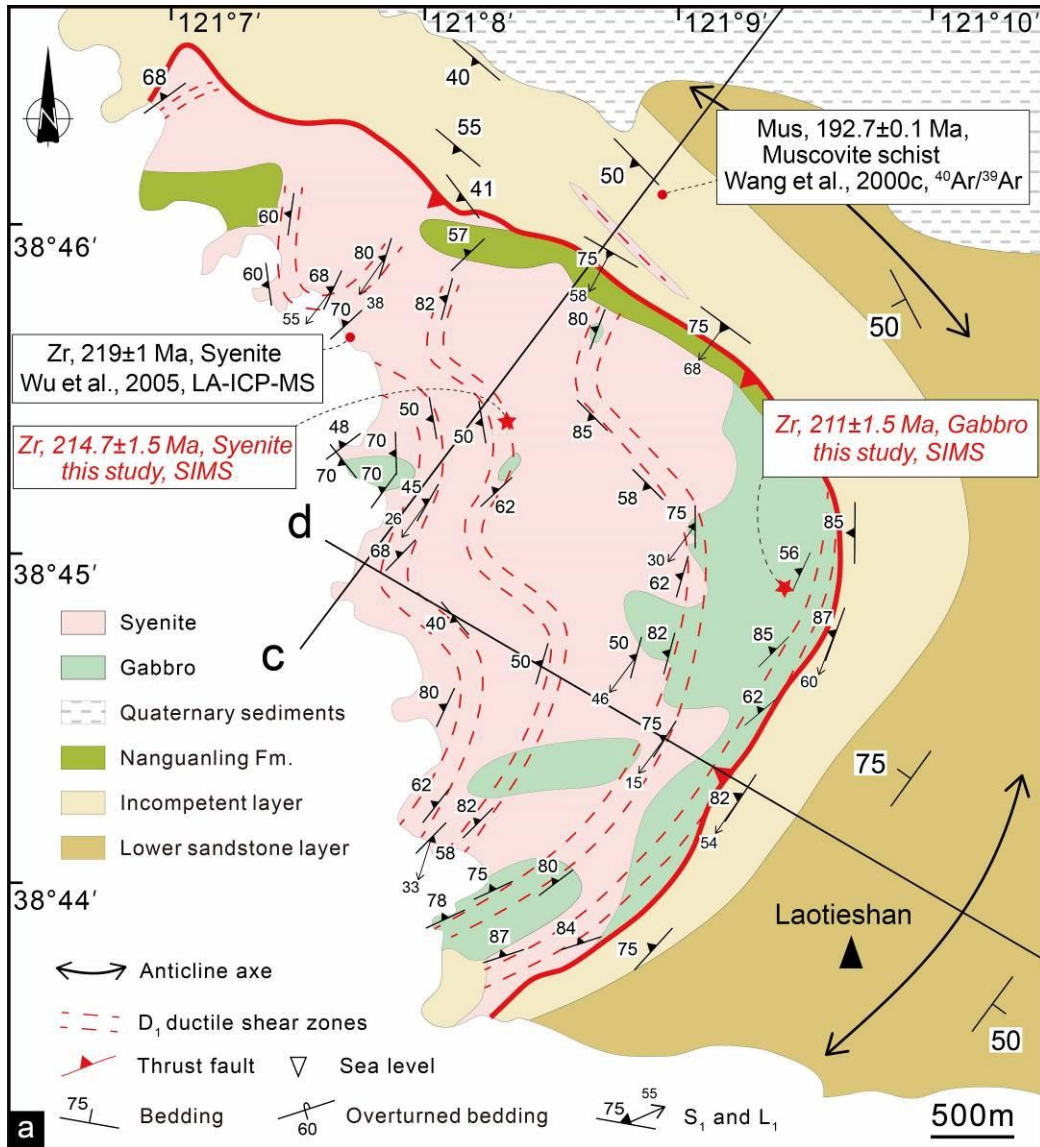


Fig. 8. **a**, Detailed structural map of the Yinjiacun magmatic complex. **b**, Equiareal stereogram (Schmidt net, lower hemisphere) of the S_1 foliation and L_1 lineation in the Yinjiacun complex and its country rocks. **c** and **d**, NE-SW and NW-SE cross-sections of the Yinjiacun complex and its country rocks, respectively.

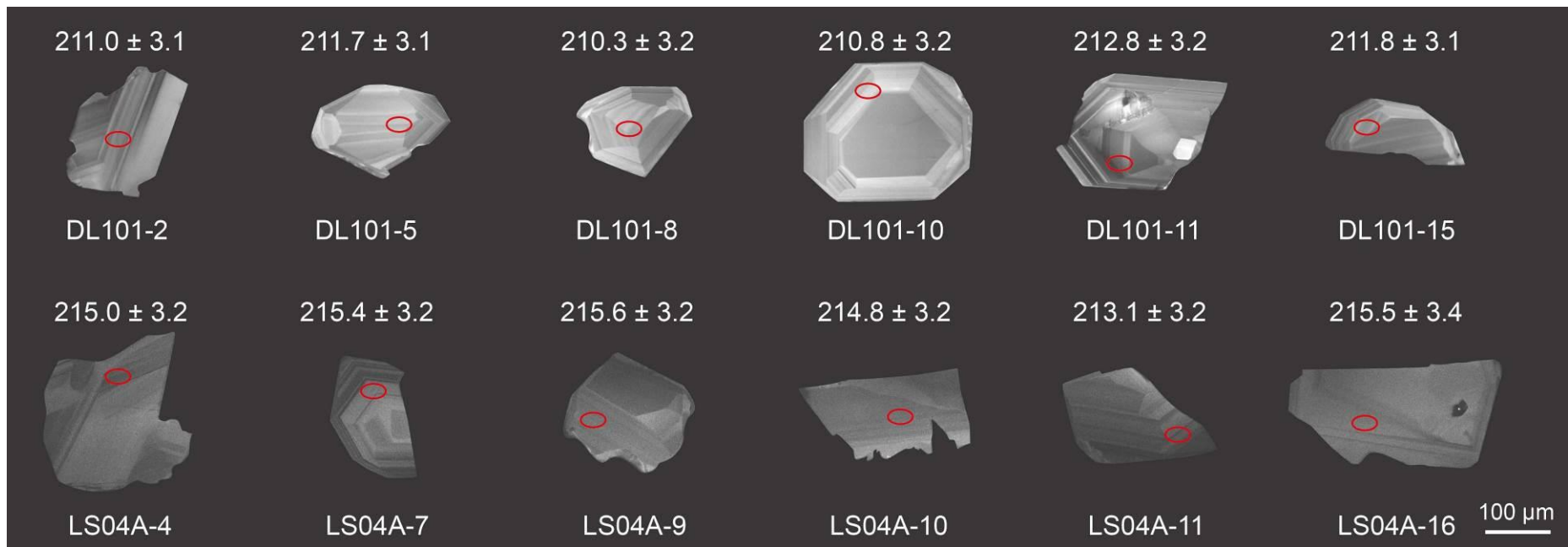


Fig. 9. Cathodoluminescence images of representative zircons from the gabbro and syenite samples. Red ellipses indicate the analytical spots with measured ages.

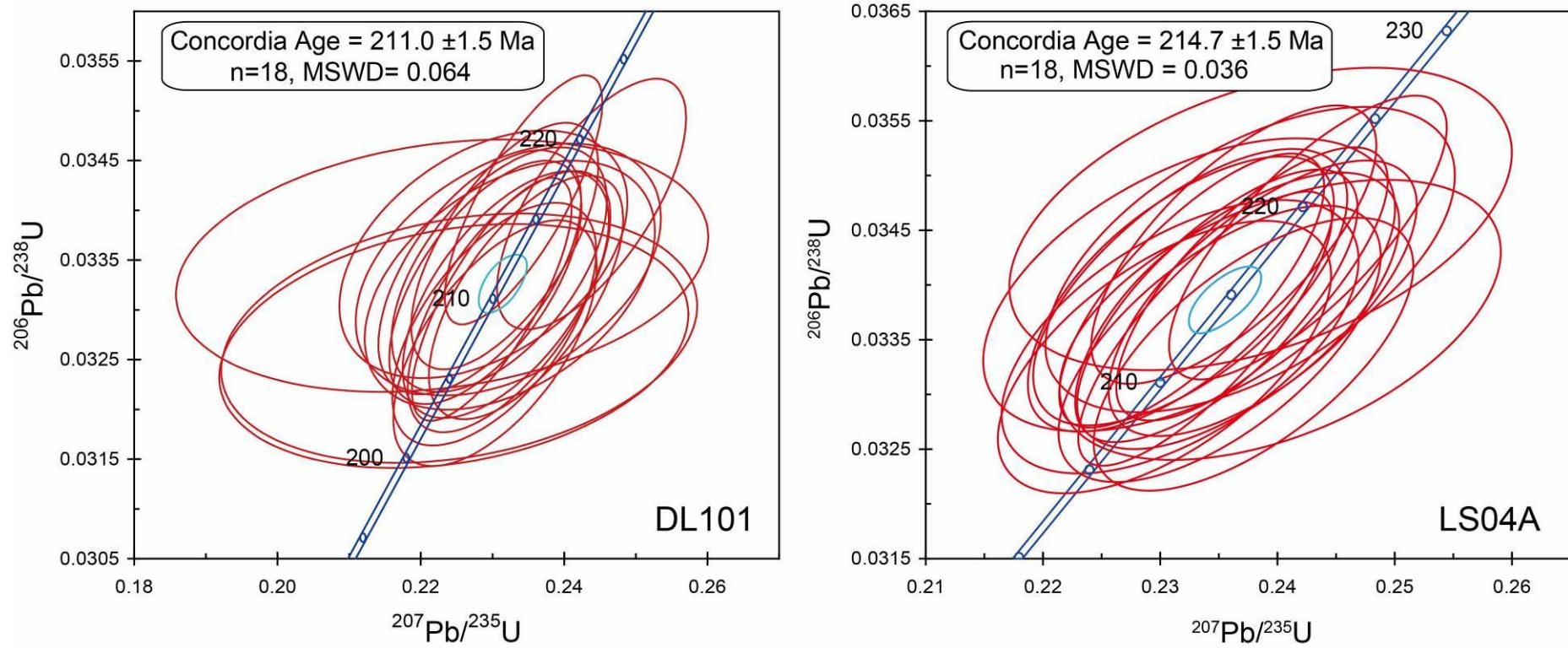


Fig. 10. SIMS U-Pb concordia diagram of the analyzed zircons, sample locations are shown in Fig. 7a.

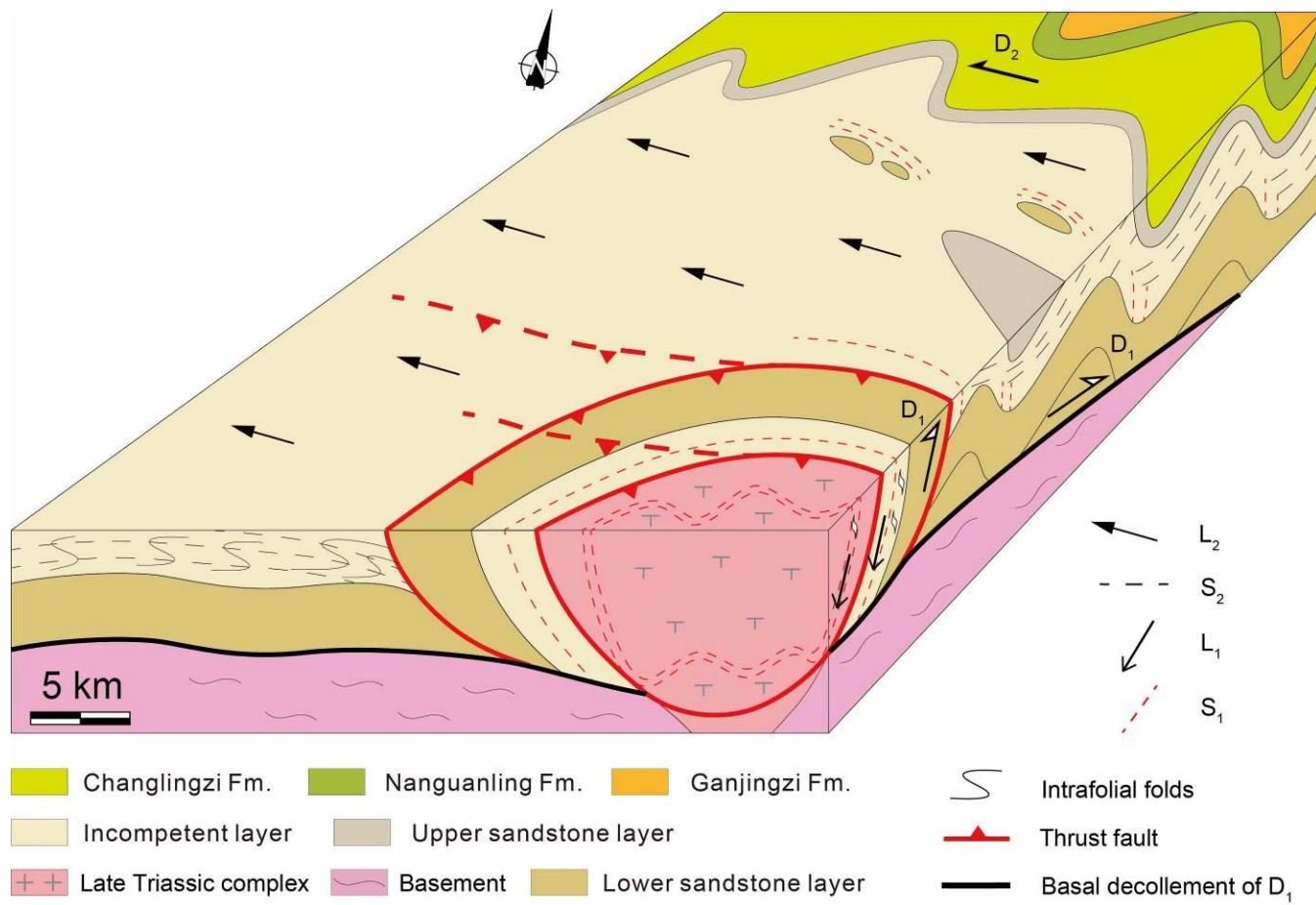


Fig. 11. Schematic block diagram showing the D₁ and D₂ deformation of the Lushun-Dalian area, South Liaodong Peninsula.

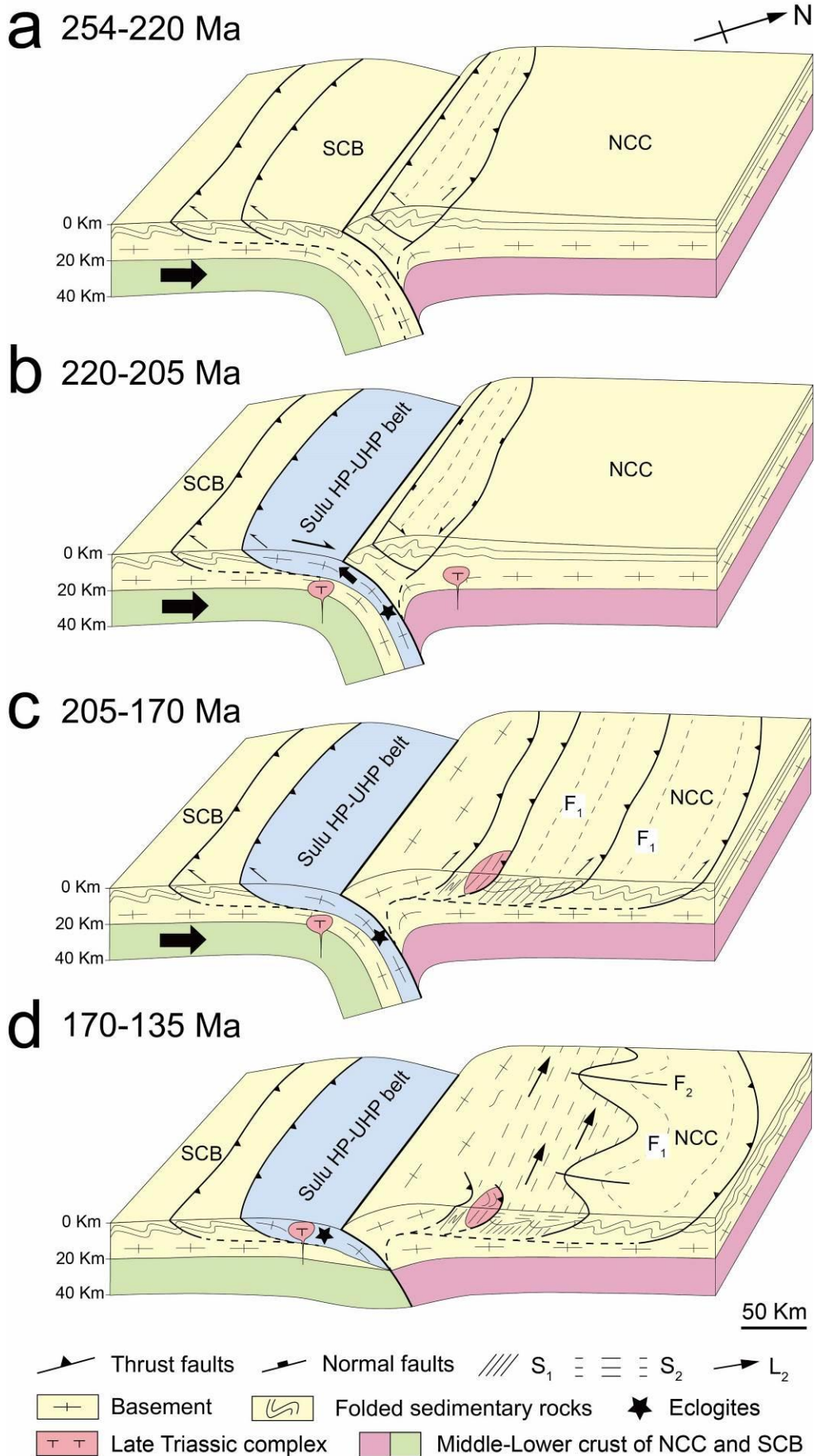


Fig. 12. Tectonic evolution of the Lushun-Dalian area, South Liaodong Peninsula. **a**, NE-verging folds and NE-directed thrusts developed in the southern margin of NCC during the NCC-SCB convergence at 254-220 Ma; **b**, Alkaline magmatic complexes intruding into the middle crust during the extensional exhumation of the UHP metamorphic rocks at 220-205 Ma; **c**, Thrusting and ductile shearing of the Yinjiacun complex in the South Liaodong Peninsula during the post-convergence NE-SW compression at 205-170 Ma; **d**, Reworking of the NE-SW compressional structures. A fold interference pattern developed during the NW-SE compression at 170-135 Ma.

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in sections b c d put the orientation SW-NE; NW-SE, WNW-ESE

Fig. 4. Field photographs of structures associated with the D₁ deformation. **a** Syenite intrusion and country rocks concurrently foliated (38°45'56.63", 121°8'43.91"). **b** Gabbro intrusion and the country rocks concurrently deformed (38°44'16.88", 121°9'7.52"). **c** Stretching L₁ lineation exhibited on the S₁ foliations in slate (38°45'38.16", 121°9'15.48"). **d** Stretching L₁ lineation exhibited on the S₁ foliation of the mylonitized syenite (38°44'7.14", 121°8'8.18"). **e** Delta-type K-feldspar porphyroclast in the mylonitized syenite indicating a top-to-the-NE shear sense (38°45'19.5", 121°7'40.09"). **f** Penetrative SW-dipping S₁ and small intrafolial folds in the slate of the country rocks of the Yinjiacun complex (38°46'3", 121°8'8.77"). **g** Subvertical S₁ in the siltstone of Diaoyutai Formation, east of Lushun city (38°49'51.06", 121°16'47.94"). **h** Fold and thrust in the limestone, north of Jinzhou city (39°15'59.76", 121°37'12.36").

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in sections c d put the orientation SW-NE; NW-SE,

section c not in agreement with the map to the NE, at least indicate the limit of the map by a vertical line

Fig. 7. a Cathodoluminescence images of representative zircons from the gabbro and syenite samples. Red ellipses indicate the analytical spots with measured ages. **b** and **c** SIMS U-Pb concordia diagram of the analyzed zircons, sample locations are shown in Fig. 6a.

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