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François Bache, Julien Moreau, Jean-Loup Rubino, Christian Gorini, Brigitte van Vliet-Lanoë

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1                   **The Late Palaeozoic glaciation subsurface record,**  
2                   **Chaco Basin (Bolivia)**

3                   F. Bache <sup>1,2</sup> \*, J. Moreau <sup>3</sup>, J.L. Rubino <sup>4</sup>,

4                   C. Gorini <sup>1,2</sup>, B. Van-Vliet Lanoë <sup>5</sup>

5 <sup>1</sup>UPMC Univ. Paris 06, UMR 7193, ISTEP, F-75005, Paris, France

6 <sup>2</sup>CNRS, UMR 7193, ISTEP, F-75005, Paris, France

7 <sup>3</sup>Centre de Géosciences, MINES-ParisTech, 35 rue Saint Honoré 77 300 Fontainebleau, France

8 <sup>4</sup>TOTAL, CSTJF, Avenue Larribau, 64018 Pau Cedex. France

9 <sup>5</sup>Université de Brest, CNRS, UMR 6538 Domaines Océaniques, IUEM & U@B, Place Copernic, 29280  
10 Plouzané, France

11  
12 \*Corresponding author (e-mail: [francois.bache@upmc.fr](mailto:francois.bache@upmc.fr))

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18  
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20                   **ABSTRACT**

21                   Late Palaeozoic glaciation is the longest of the Phanerozoic era. It is recorded in  
22 numerous Gondwanian basins, some having a high petroleum potential like the Chaco Basin.  
23 In this basin, the quality of the available seismic, well and outcrop data permits to characterise  
24 the Late Palaeozoic glacial record. Palaeovalleys >500 m deep and ~7 km wide have here  
25 been analysed. Focusing on the glaciogenic Carboniferous deposits, the seismic data with  
26 well-ties and their outcrop analogues provide new sedimentological insights. The palaeovalley  
27 infill is imaged as a chaotic seismic facies overlain by an aggrading-prograding prism,  
28 interpreted as tillites covered by a fluvio-deltaic system respectively. Tillites form both under  
29 the ice and during rapid ice recession whereas fluvio-deltaic systems can only originate from  
30 a stable ice margin and last until the ice sheets withdraw inland. These two depositional

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\* Corresponding author. Present address : iSTeP. UMR 7193 CNRS/Université Pierre et Marie Curie, 4 place Jussieu, Case 129, 75252 Paris cedex 05. France. E-mail address : [francois.bache@upmc.fr](mailto:francois.bache@upmc.fr). Tel.: +33 675 045 571; fax: +33 144 275 246.

31 modes are repeated several times generating the progressive burial of the Carboniferous  
32 palaeovalleys. This succession of erosions and fills records major glacial stages containing a  
33 series of glacial and interglacial phases from the Late Devonian to the Early Permian.  
34 Depicting the Late Palaeozoic glacial history of the Chaco Basin seems crucial for the  
35 localisation of potential good reservoirs.

## 36 **INTRODUCTION**

37 The Late Palaeozoic Ice Age, developing from the Late Devonian (c. 390 Ma) to the  
38 Mid Permian (c. 270 Ma (Hambrey and Harland, 1981)), generated the largest cyclic  
39 sedimentary deposits in Phanerozoic history (Caputo *et al.*, 2008). It affected a large part of  
40 the supercontinent Gondwana, leaving evidences of ice activity in Australia, Antarctica,  
41 Arabic Peninsula, India, South Africa and South America (Crowell and Frakes., 1975). The  
42 ice masses first developed in South America and South Africa during the Early Carboniferous.  
43 During the Late Carboniferous, the ice sheets were situated in India, Australia and Antarctica.  
44 The peak of the ice age occurred in Antarctica and Australia during the Permian (Crowell and  
45 Frakes., 1975; Caputo and Crowell, 1985). The Late Palaeozoic glaciation coincides with the  
46 greatest episode of coal accumulation on Earth and consequent atmospheric CO<sub>2</sub>  
47 sequestration.

48 In South America, Late Palaeozoic glaciogenic rocks were first observed in the early  
49 19<sup>th</sup> Century (Wegener, 1915; Du Toit, 1937). Ice ages were usually examined by field  
50 studies, based on the occurrence of diamictites containing striated clasts attributed to ice-  
51 rafted debris or on glacial striated pavements recognition. Glacial valleys later became the  
52 main evidence of direct ice activity and, consequently, have been searched for within  
53 glaciogenic successions. Field mapping of the glacial surfaces led to the recognition of  
54 different types of glacial valleys associated with continental ice-sheets: (1) tunnel valleys,  
55 related to the incision of overpressurised meltwater; (2) cross-shelf troughs, related to ice-

56 stream activity and abrasion processes; and (3) fjords which result from melt-water and  
57 abrasion erosion processes. Despite the development of subsurface seismic studies,  
58 palaeofjord incisions have rarely been described for ancient ice ages.

59 This paper aims at describing the seismic signature of the Late Palaeozoic succession  
60 in the Bolivian Chaco Basin which contains some very large-scale glacial incisions. The  
61 seismic stratigraphy provides new insights into the tectonics, the palaeoenvironment and the  
62 palaeoglaciology of the Chaco Basin.

### 63 **REGIONAL SETTING**

64 The Bolivian Chaco Basin is part of foreland basins associated with the Andean  
65 orogenic system and is identified as a backarc flexural intracratonic basin of Cenozoic age  
66 (Sempere *et al.*, 1990; Decelles and Horton, 2003). The basin is bounded to the north and  
67 north-east by the Brazilian craton, and to the west by the subandean fold and thrust belt zone  
68 which constitutes the eastern border of the Andes (Fig. 1). Since the late Oligocene, the  
69 deformation propagated toward the E and NE, uplifting the eastern part of the Andean  
70 depocentre (Sempere, 1995). Consequently, the Phanerozoic strata are well exposed in the  
71 Bolivian Andes. A Precambrian-Tertiary clastic stratigraphic section is exposed in the Andean  
72 and the sub-Andean fold belts of southern Bolivia (Fig. 2), where shallow marine Ordovician-  
73 Devonian clastics are conformably overlain by a Carboniferous to Upper Permian sequence.  
74 The Palaeozoic succession is unconformably overlain by Cretaceous fluvial sediments and  
75 Cenozoic progradational foreland basin deposits (Dunn *et al.*, 1995).

76 In the Chaco Basin, the Izozog High (Fig. 3) is the result of an uplift that occurred prior  
77 to the Cretaceous Period (Gohrbandt, 1992; Uba *et al.*, 2006). Paleozoic units are tilted  
78 toward the W and NW and eroded at the top of the High (Fig. 4). This erosion is in part  
79 responsible for the variation in the thickness of the Paleozoic units (Fig. 5). The  
80 Carboniferous section is characterized by a continuous succession of well-developed massive

81 sandstone units (Tupambi, Chorro, and Escarpment Fms.; Fig. 2) that alternate with thinner,  
82 muddy diamictite intervals (Itacuami, Tarija, Taiguati, and San Telmo Fms.; Fig. 2). This  
83 alternating succession is interpreted to result from episodic tectonic or climatic events  
84 (Helwig, 1972). Deeply incised palaeovalleys, typically 500 m deep and several kilometers  
85 wide, have been described in the Tarija and Escarpment Formations (Fig. 6; (Helwig, 1972;  
86 Salinas *et al.*, 1978; Tankard *et al.*, 1995). The palaeovalley infills have been interpreted as  
87 continental tillites and subaerial meltwater channels, deposited by ice margins advancing and  
88 retreating, respectively (Helwig, 1972; Salinas *et al.*, 1978). The ice masses flowed across the  
89 Chaco Basin and were fed from ice centres to the S and E, situated within the Brazilian  
90 Craton (Helwig, 1972; Salinas *et al.*, 1978). To the contrary, Eyles *et al.* (1995) stress the  
91 importance of marine sedimentation and the paucity of evidence for any direct glacial  
92 influence on sedimentation. The Late Devonian-Early Carboniferous orogeny and Gondwana  
93 glaciations develop simultaneously and therefore, are usually considered to be associated with  
94 each other (Amos, 1972; Eyles and Eyles, 1993; Eyles, 2008).

## 95 **DATA AND METHOD**

96 The dataset consists of 9000 km of 2D seismic lines and 4 wells tied to the seismic  
97 (Fig. 1). Seismic interpretations were carried out based on the principles of seismic  
98 stratigraphy (Vail *et al.*, 1977). Seismic units are identified based on reflection terminations  
99 and the configurations of seismic reflections (Fig. 7). The units can be mapped in 3D  
100 throughout the basin thanks to the extensive coverage of the seismic data.

101 Additional information (datings, e-logs) were obtained from boreholes that sampled  
102 the Carboniferous units (Fig. 8). The gamma ray logging records the radioactivity of a  
103 formation. Shales (or clay-minerals) commonly have a relatively high gamma radioactive  
104 response and, consequently, gamma ray logs are considered to reflect the main grain size.  
105 Sonic logs measures the velocity of sound waves in rock. In complement to the gamma ray,

106 sonic logs help to determine the lithology. The sonic logs have also been used to tie the well  
107 to the seismic lines.

108 The Paleozoic strata have been deformed after their deposition (Izozog deformation).  
109 As the tectonic activity is supposed to have occurred at least after the Devonian, a Silurian  
110 horizon (Figs. 3 and 4) has been used as a datum for the flattening of the seismic lines. At a  
111 regional scale, this method allows restoring the genuine morphology of the seismic  
112 stratigraphic surfaces.

113 This paper focuses on the upper part of the Carboniferous succession where two major  
114 stratigraphic surfaces have been picked and correlated throughout the basin (surfaces 4 and 5;  
115 Fig. 7). The geometric parameters of the observed incisions marked on these surfaces have  
116 been extracted from the studied (1) seismic strike sections for the width and depth, and (2) the  
117 flattened regional maps of the picked surfaces to define their longitudinal extension and  
118 drainage patterns. The described methodology allowed a detailed investigation of the seismic  
119 architecture of the Late Palaeozoic deposits of the Chaco Basin.

## 120 ***IZOZOG DEFORMATION***

121 Glacial activity is commonly considered to be associated with a tectonic trigger  
122 (Eyles, 2008). However, the presence of tectonic activity in the Chaco Basin during the  
123 deposition of the glaciogenic rocks of Late Palaeozoic is debatable. Previous mapping of the  
124 Carboniferous palaeovalleys (Fig. 6) suggested an influence of the Izozog High during their  
125 formation. Eyles *et al.* (1995) attributed the convergent direction of palaeovalleys to their  
126 formation in a confined basin.

127 Two main observations suggest, however, that the Izozog High formed after the  
128 Carboniferous, i.e. after the formation of the palaeovalleys. The first observation concerns the  
129 stratigraphic relationships between the Palaeozoic and the Mesozoic units. A major  
130 unconformity can be recognized on the seismic lines (yellow line, Fig. 3). This unconformity

131 is of a regional extent and separates the Palaeozoic units from the Mesozoic ones (Fig. 8). The  
132 unconformity is deeply incised into the Palaeozoic rocks at the apex of the Izozog High (Fig.  
133 5). The topography of the High is progressively overlapped and concealed by the Mesozoic  
134 deposits (Fig. 3). This erosion/deposition relationship is the evidence of a post-Palaeozoic  
135 tectonic uplift in the Izozog area. The second observation concerns the orientation of the  
136 Carboniferous palaeovalleys. The new maps of the palaeovalleys (Figs. 9 and 10) do not show  
137 any deflection over the Izozog High. On the contrary, the palaeovalleys are progressively  
138 more eroded toward the Izozog apex, indicating that the uplift is postdating the formation of  
139 the incisions.

#### 140 **PALAEOTALLEY MORPHOLOGIES**

141 Ice masses are else flowing from highland areas (mountains) or lowland areas (quiet  
142 basins) and accordingly generate different types of valleys. In the Chaco Basin, the ice centres  
143 are situated onto the Brazilian craton (Helwig, 1972; Salinas *et al.*, 1978). Therefore, the here  
144 analysed glacial palaeovalleys are associated with lowland-ice sheets. Lowland-ice sheets  
145 usually generate three types of glaciogenic incisions visible on the seismic data (Table 1): (1)  
146 the tunnel valleys, (2) the ice stream cross-shelf troughs and (3) the fjords (not restricted to  
147 lowlands). (1) The tunnel valleys are frequently sinuous and are known to be organised in  
148 anastomosing to tributary branching patterns (Huuse and Lykke-Andersen, 2000). They reach  
149 up to 4 km in width, 500 m in depth, 100 kilometres in length (e.g. (O'Cofaigh, 1996; Huuse  
150 and Lykke-Andersen, 2000; Ghiene *et al.*, 2003; Praeg, 2003)). Tunnel valleys have been  
151 mainly observed in unconsolidated sediments but can also incise rocks. It has been assumed  
152 that tunnel valleys originate from subglacial pressurised meltwater incisions (Wingfield,  
153 1990; Brennand and Shaw, 1994; O'Cofaigh, 1996). (2) The ice-stream cross-shelf troughs are  
154 U-shaped as well, they reach extreme widths (100' of km) and lengths (>600 km). Usually,  
155 their depths are subconstant along their flow lines at a regional scale, but they can vary

156 significantly in tectonically active areas. On relatively passive margins like offshore Norway,  
157 they generate incisions between 200 and 500 metres deep and at least 10 km wide (Ottesen *et*  
158 *al.*, 2008). These cross-shelf troughs are preferentially incised into soft unconsolidated  
159 sediments (e.g. the Norwegian channel northern boundary on hard rocks (Ottesen *et al.*,  
160 2005)). (3) As opposed to of (1) and (2), the fjords are deep glacial valleys incised into  
161 bedrock. Their depth reaches several kilometres while they stay relatively narrow in width  
162 (<10 km). Their longitudinal extent is 10's of kilometres but rarely exceeds 100 km (maps in  
163 Ottesen *et al.*, 2008 for comparison). The drainage patterns of fjords are relatively straight,  
164 often guided by faults. They have a tendency to follow the structural grain onto the basement.  
165 Fjords often correspond to the upstream part of ice-streams where they incise crystalline  
166 bedrock (Ottesen *et al.*, 2005; Ottesen *et al.*, 2008).

167         In the Chaco Basin, the seismic analysis of the Late Palaeozoic sedimentary  
168 architecture shows an intricate succession of unconformities bounding the base of  
169 depositional sequences (Fig. 7). The peculiarity of these unconformities is the presence of  
170 large palaeovalleys, predominantly in the upper part of the Carboniferous succession. Both U-  
171 and V-shaped palaeovalleys are observed (Fig. 11). Their width ranges between 3 and 21 km  
172 with a mean width of 7.36 km (n: 24, standard deviation: 4.19 km). The incisions are deep  
173 with 500-700 m between the shoulders and the bottom of the thalweg. Two Upper  
174 Carboniferous surfaces have been mapped in detail (surfaces 4 and 5; Figs. 9, 10) and  
175 compared (Fig. 12). The mapped incisions are visible between the western limit of the dataset  
176 to the West and the Izozog High to the East, where they have been removed by erosion (Figs.  
177 9, 10). They form extremely elongated depressions that were at least >100 km long. The  
178 palaeovalleys of surface 4 are subparallel with a predominant SE-NW direction. The  
179 palaeovalleys of surface 5 present a radial pattern with two different orientations in the North

180 (SE-NW direction) and in the West (E-W direction, Fig. 13) of the Chaco Basin. The surface 5  
181 shows two valleys merging and diverging twice to the South (Fig. 10).

182 The geometric parameters of the Chaco Basin incisions have been summarised and  
183 compared with the three known types of glaciogenic valleys (Table 1). Table 1 highlights that  
184 the studied glaciogenic incisions share characteristics with different types of glacial palaeo-  
185 valleys under lowland-ice sheet conditions:

186 • The section shapes are comparable with fjords, indicating a mixed process abrasion  
187 (U-shape) and hydraulic (V-shape).

188 • The widths are clearly over the width of tunnel valleys but do not permit  
189 discriminating between fjords and cross-shelf troughs.

190 • The depths are similar to fjords and cross-shelf troughs but bigger than tunnel  
191 valleys.

192 • The lengths are comparable with ice stream troughs. Especially knowing that the  
193 lengths are underestimated because of the dataset extent and the Izozog High.

194 • The basement is assumed to be unlithified as in the tunnel valleys and cross-shelf  
195 troughs.

196 • They are straight to slightly sinuous like cross-shelf troughs.

197 • Except for two valleys on surface 5, they show no branching or anastomosing  
198 drainage patterns. This characteristic is also shared with cross-shelf troughs.

199 The size of the Chaco basin incisions rules out their possible interpretation as tunnel  
200 valleys. The anastomosed network to the South of Surface 5 (Fig. 10) is instead interpreted to  
201 result from the cross-cut between two generations of glacial valleys. This cross-cut is not  
202 resolvable with the available seismic data. However, it is difficult to discriminate whether the  
203 incisions represent cross-shelf troughs or fjords. The lengths of the Chaco incisions are an  
204 order of magnitude bigger than fjords. On the other hand, the section shapes and the depths

205 are closer to fjords than to cross-shelf troughs. The Scandinavian ice sheet shows spatial  
206 transition between fjords on crystalline and lithified basements to cross-shelf troughs on  
207 sediments (Ottesen, 2008). The shared characteristics of both cross-shelf troughs and fjords  
208 with the Chaco Basin valleys is therefore, interpreted to be the result of basement variations  
209 probably linked to varying lithification degrees of the subglacial substrate. These lithological  
210 variations are probably favouring abrasion-dominated processes (unconsolidated; cross-shelf  
211 trough type) or hydraulic-dominated incisions (lithified: fjord type).

212 The comparison of the drainage patterns on surfaces 4 and 5 shows a change in the  
213 orientation of the Chaco Basin incisions through time (Fig. 12). This indicates that the  
214 palaeoglaciological setting evolved between the two generations. The first generation (surface  
215 4) is well organised with parallel troughs whereas the second generation of valleys (surface 5)  
216 radiates from a c. NW-SE axis (Fig. 12). This pattern change has been interpreted to reflect  
217 one large ice mass forming surface 4 and individual ice sheets forming surface 5. The  
218 dispersive pattern may alternatively be the result of an ice margin closer during the formation  
219 of the surface 5 than the surface 4. This drainage pattern evolution at a regional scale is  
220 probably the result of a tectono-climatic evolution affecting the ice centres sourcing the Chaco  
221 Basin ice sheets during the Late Carboniferous.

## 222 ***PALAEOVALLEYS INFILL***

223 The most detailed dataset concerns the sediments filling the palaeovalleys of surface 5.  
224 The sediments have been attributed to the Escarpment and the San Telmo Formations (Fig. 2,  
225 8). Consequently, the analysis is focused on this stratigraphic interval based by surface 5 and  
226 topped by the next glaciogenic unconformity. The interval consists of three distinct  
227 sedimentary units with specific seismic facies, wireline log signatures, and sedimentary  
228 environments (Fig. 14). Facies 1 occurs at the base of the palaeovalleys (Fig. 14). It  
229 corresponds to a chaotic seismic facies suggesting an unsorted and unstratified accumulation

230 of sediments. Gamma ray and sonic logs typically associated with diamictites can be observed  
231 (Fig. 14). Facies 2 is overlying Facies 1 (Fig. 14). Facies 2 is made of prograding clinofolds  
232 that can be seen downlapping on Facies 1. Gamma ray logs indicate coarsening-up shale to  
233 sandstone cycles (Fig. 14). On the seismic data, Facies 3 overlays unconformably facies 2.  
234 Facies 3 has a channelised to slightly chaotic seismic facies. It is characterized by fining-  
235 upward cycles of sandy units on gamma ray logs.

236 Facies 1, 2 and 3 have been interpreted as tills, delta progradations and fluvial  
237 deposits, respectively. This interpretation is supported by the field observations of the outcrop  
238 analogue (Fig. 14). Consequently, it is suggested that after the subglacial incision of  
239 palaeovalleys, the sedimentary environment passed through different phases: (1) subglacial to  
240 ice-marginal environment forming the till when ice is in the Chaco Basin, (2) the ice leaves  
241 the basin (3) the remnant glacial topography is progressively buried by an advancing fluvio-  
242 deltaic system. This sedimentary system which concealed the 500-700m deep valleys was  
243 probably fed by ice margins further inland to the SE.

244 Analogues to the palaeovalleys infill patterns in the Chaco Basin can be found within  
245 Upper Ordovician palaeovalleys. The Ordovician valleys are filled by glacial sequences  
246 usually showing a motif with coarse-grained deposits (conglomerates, diamictites) at the base,  
247 passing upsection into prograding deltas and further into aggrading fluvial deposits (Le Heron  
248 *et al.*, 2009). The nature of the fill varies in style depending upon the palaeogeographic setting  
249 (Le Heron *et al.*, 2004). In proximal settings, non-marine glaciofluvial sandstones overlie an  
250 initial fill of ice-proximal deposits. In deeper water settings, the initial, locally developed, ice-  
251 proximal deposits are overlain by a transition from ice-distal diamictites to sand-dominated  
252 underflow fans. A deposition of this fill during deglaciation or marine transgression has been  
253 suggested (Powell *et al.*, 1994; Ghienne and Deynoux, 1998; Le Heron *et al.*, 2004).  
254 Considering the similarities between the successions in the Chaco Basin and the Ordovician,

255 the palaeovalley infill of the Chaco Basin is considered to correspond to a glacial sequence.  
256 As hundreds of metres of deltaic sediments overlay the basal till (Fig. 14), this glacial  
257 sequence is first developed in relatively deep water directly after ice retreat.

258 Terminal moraines are important indicators of former ice-front positions. Studies of  
259 exposed marine moraines have demonstrated that their internal facies architectures bear a  
260 high-resolution record of ice-front evolution, with direct implications for glacier dynamics  
261 and regional paleoclimatic conditions (Lønne, 1995, 1997). Lønne (1995, 2001) and Lønne *et*  
262 *al.* (2001) have synthesized the development of marine ice-contact systems in the form of an  
263 allostratigraphic model. The model has implies a sedimentary architecture comparable to the  
264 sedimentary infill observed in the Chaco Basin palaeovalleys. In the southern part of the  
265 Chaco Basin, deltaic deposits (Facies 2) prograde in opposite directions (Fig. 15). In the  
266 Oslofjorden, the area between two clinoform orientations localise a former ice front (Lønne,  
267 2001). Despite of the difference in the scale, this Quaternary example serves as an analogue;  
268 the pattern of clinoform orientations in the Chaco Basin is interpreted to mark the location of  
269 an ice front of a Late Carboniferous age (Fig. 16). Based on the Oslofjorden analogue, the  
270 glaciological and sedimentary evolution is deduced from the seismic analysis of surface 5 and  
271 its relative glacial sequence is summarised in a conceptual model presented in Fig. 16. The  
272 following multistage formation of the glacial sequence of surface 5 is suggested in the model:  
273 (1) the ice advance and the creation of the valleys; (2) a still stand during ice recession in the  
274 basin and the generation of the southward-dipping proglacial fan-delta; (3) the recession of  
275 the ice from the basin associated with the isostatic uplift of the former ice front, leading to the  
276 reworking of the uplifted area and the creation of the northward-dipping clinoforms; (4) some  
277 minor readvance permitting the development of another fluvio-deltaic system prograding to  
278 the South and blanketing the northward-dipping clinoforms; and (5) the final ice recession  
279 associated with a last advance of the fluvio-deltaic system on top of the glacial sequence. This

280 model honours the observed complexity of the glacial sequence and its potential palaeo-  
281 glaciological record. In addition to ice-flow patterns deduced from the valley orientations, the  
282 localisation of ice-front positions and their consecutive depocentres are good constrains for  
283 understanding the evolution of ancient ice sheets.

## 284 **CONCLUSIONS**

285 The Late Palaeozoic sedimentary architecture of the Chaco Basin (Bolivia) is  
286 characterized by a succession of erosional surfaces and seismic sequences. This sedimentary  
287 architecture records the Late Palaeozoic glaciation events, and the modality of the ice age in  
288 the area. The main results of this study are:

289 • The Izozog High did not influence the Late Palaeozoic palaeovalley orientations.  
290 Considering the progressive onlap of the Late Cenozoic deposits on the High, the Izozog  
291 Uplift is considered to be postdating the ice age and predating the Cretaceous fluvial deposits.

292 • Erosional surfaces present different morphologies from the base to the top of the  
293 succession. These surfaces can be flat (base of Carboniferous) whereas they form very large  
294 palaeovalleys (up to 20 km wide and 700 m deep) in the upper part of the succession.

295 • A lowland glacial environment is suggested, but the erosional processes  
296 responsible for the incisions remain debatable. A coupling between subglacial meltwater and  
297 mechanical abrasion processes is considered as a possible explanation for the observed valley  
298 geometries. In addition, the amount of meltwater at the base of the glacier (cold-/ warm-based  
299 or polythermal ice sheet), the nature and the lithification degree of the incised sediments  
300 probably induced the variability of the glacial erosional surfaces.

301 • The analysis of the glacial surface successions highlights the glacial history of the  
302 area, including ice flow rotations associated with changes in the glaciological parameters of  
303 the ice sheets.

304           • The palaeovalleys are covered by diamictites in the deepest part of the thalwegs  
305 overlain by deltas fed by fluvial depositional systems. As well as the Ordovician glacial  
306 sequences, the sand-prone Chaco Basin sediments present a good reservoir potential. This  
307 succession, corresponding to a glacial sequence, has been interpreted as the effect of glacier  
308 retreat. Depending of the distance to the ice margins, all or parts of the facies can be observed.

309           This paper aims at showing the intricate architecture of the glaciation record in the  
310 Late Palaeozoic sediments of the Chaco Basin. Although the origins of the glaciogenic  
311 features need to be investigated in more detail, this dataset highlights the importance of  
312 constructing a precise seismic stratigraphy for ancient ice ages. This work unravels a part of  
313 the glacial history in the area, built up of distinct events with different glacial settings and,  
314 thus, different climatic and tectonic triggers. This study localises ancient grounding lines of  
315 ice fronts which are palaeohighs containing proximal sandy facies. As they form isolated  
316 coarse-grained clastic depocentres, they represent good targets for hydrocarbon exploration.  
317 Extending the analysis on each glacial depositional sequence is the next step to establish the  
318 context of the Late Palaeozoic ice age and its petroleum potential in the Chaco Basin.

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322 thoughtful comments.

323

324

325 **FIGURE CAPTIONS**

326 Fig. 1. Topographic map of Bolivia and subsurface dataset used for this study. Dotted lines  
327 delimit the major tectonic provinces.

328 Fig. 2. Generalised stratigraphic column of the southern sub-Andean region with the source  
329 rocks, proven sub-Andean reservoirs and local ice sheet development. Modified from Dunn *et*  
330 *al.*1995.

331 Fig. 3. Time-depth of the top of the Silurian unit showing the location of the Izozog High  
332 southeast of the Chaco Basin.

333 Fig. 4. Regional seismic lines showing the deformation of Paleozoic units by the Izozog High  
334 and the onlap of Mesozoic and Cenozoic strata on the High.

335 Fig. 5. Time-thickness maps of Paleozoic and post-Paleozoic units in the Chaco Basin.  
336 Thickness variations of Devonian, Carboniferous and Permian units are the result of erosion  
337 in the Izozog area after their deposition. The N-S strike orientation of the Mesozoic-Cenozoic  
338 depocentre highlights the influence of the Andean deformation.

339 Fig. 6. Palaeovalleys described in the Carboniferous unit of the Chaco Basin Modified from  
340 (Helwig, 1972; Salinas *et al.*, 1978; Tankard *et al.*, 1995).

341 Fig. 7. Erosional surfaces identified in the Carboniferous. Palaeovalleys of surfaces 4 and 5  
342 are well imaged and have been precisely mapped (Fig. 10 and 11). TC: Top of Carboniferous.  
343 BC: Base of Carboniferous. Location of seismic profile on Fig. 1.

344 Fig. 8. Datation of seismic reflectors with boreholes. Location of boreholes on figure 1.

345 Fig. 9. Thickness map (in TWTT, left) between a continuous reference surface (top Devonian)  
346 and surface 4 highlighting palaeovalleys of surface 4 (right).

347 Fig. 10. Thickness map (in TWTT, left) between a continuous reference surface (top  
348 Devonian) and surface 5 highlighting palaeovalleys of surface 5 (right).

349 Fig. 11. Seismic lines showing palaeovalleys of surface 5. TC: Top of the Carboniferous. BC:  
350 Base of the Carboniferous.

351 Fig. 12. Comparison between palaeovalleys directions of surface 4 and surface 5.

352 Fig. 13. Detail of a palaeovalley of surface 5.

353 Fig. 14. Palaeovalleys infill and corresponding seismic facies, sedimentary environment and  
354 electro-facies. GR: Gamma Ray. DT: Sonic.

355 Fig. 15. Seismic profile showing progradational facies (facies 2) in two different directions  
356 (toward the North and toward the South). This sedimentary pattern could indicate the  
357 proximity of an ice front. TC: Top of the Carboniferous. BC: Base of the Carboniferous.  
358 Location of seismic profile on figure 1.

359 Fig. 16. Conceptual model to explain the Carboniferous sedimentary depositional pattern of  
360 the Chaco Basin. Modified from Lønne *et al.* 2001.

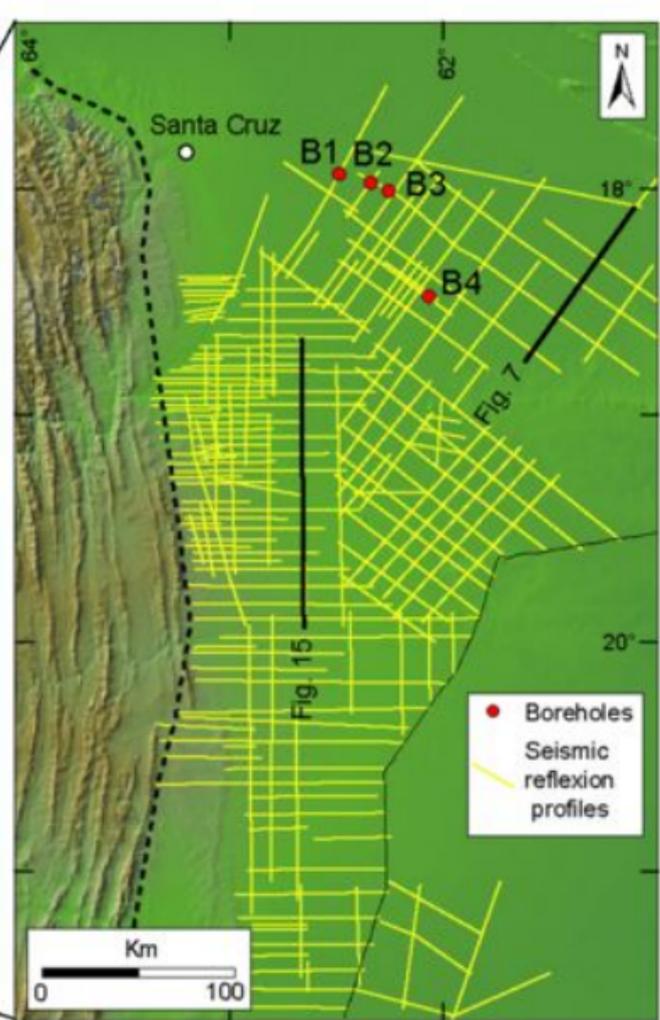
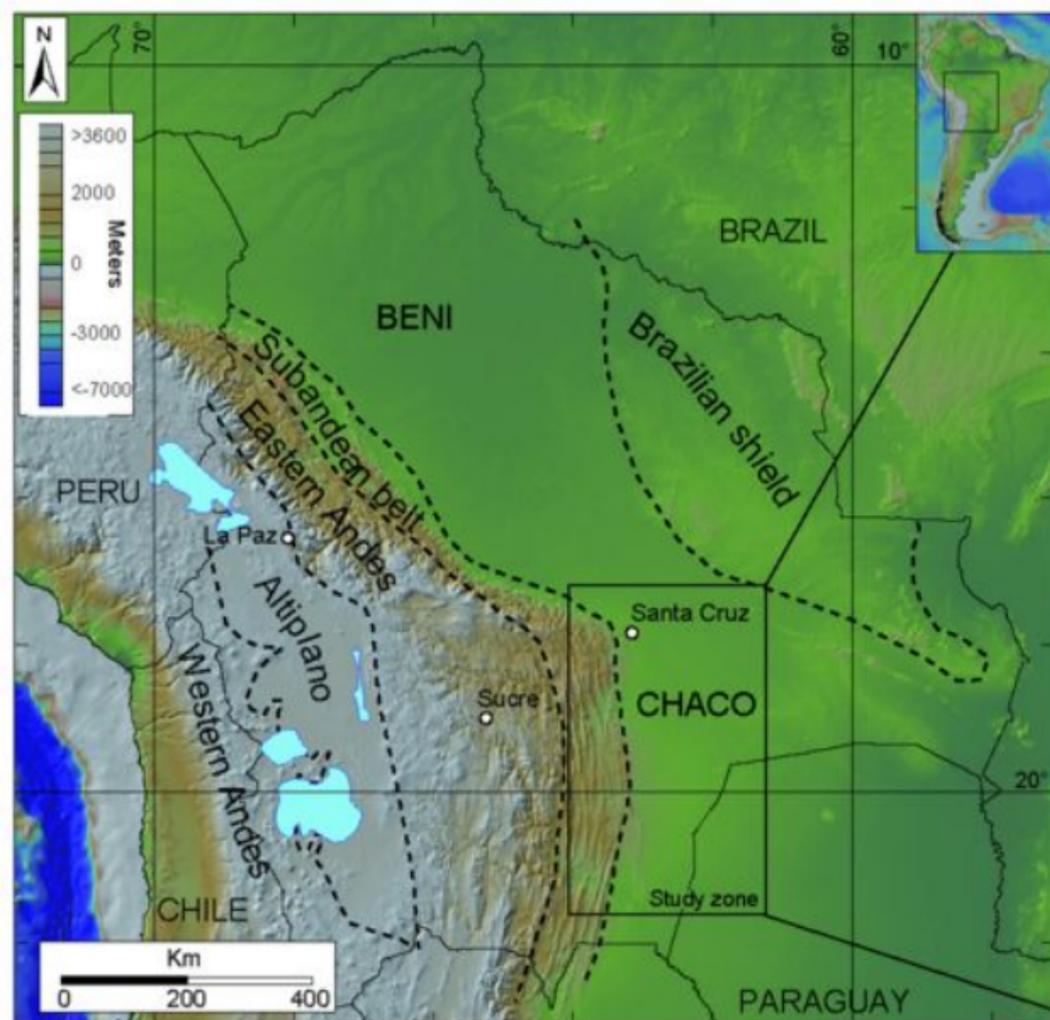
361 Table. 1. Comparison between palaeovalleys observed in the Chaco Basin and different types  
362 of glaciogenic incisions associated with lowland-ice sheets.\* From "pure" ice streams  
363 (Bennett, 2003). M. =Mean.

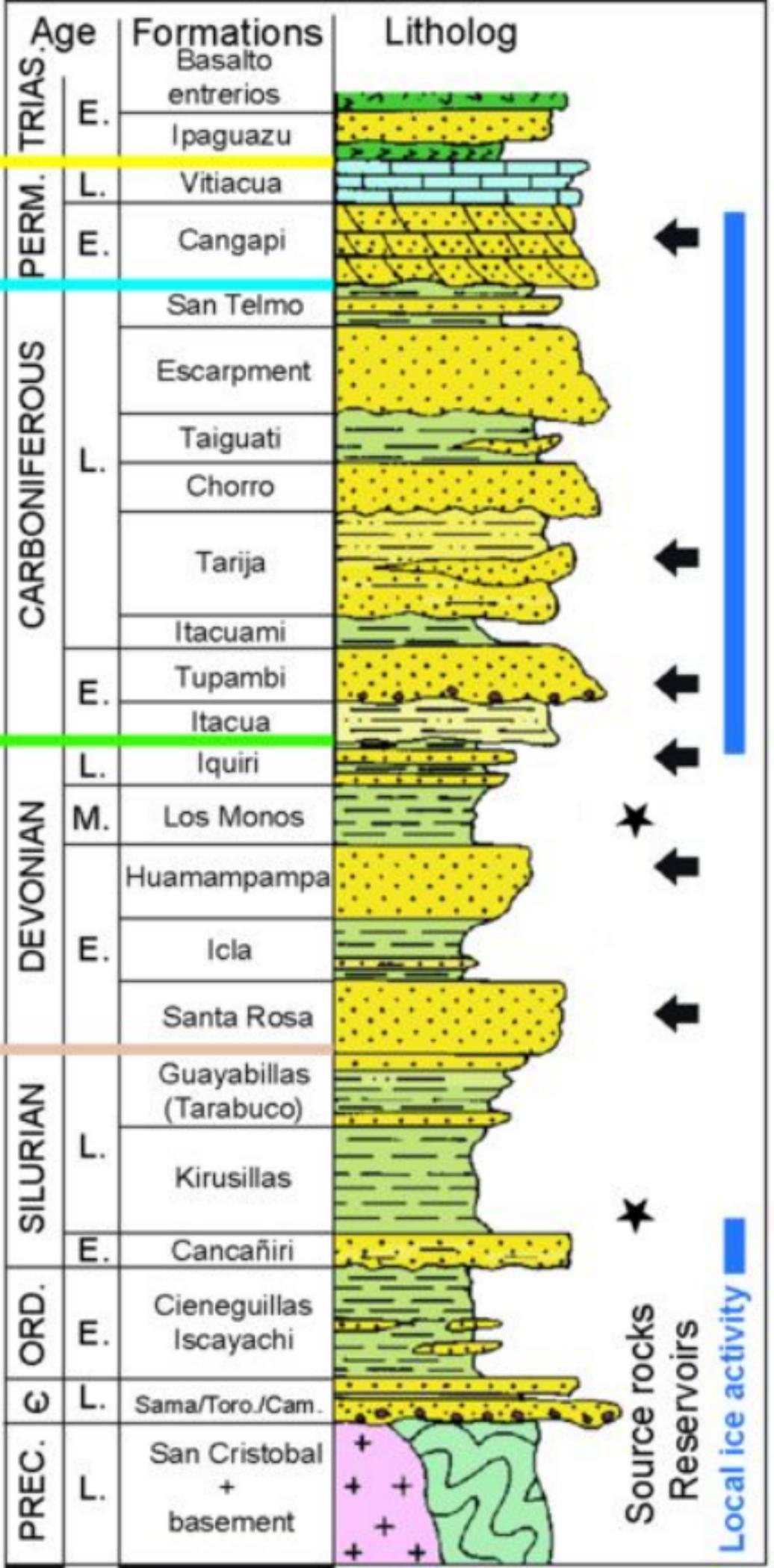
## 364 **REFERENCES**

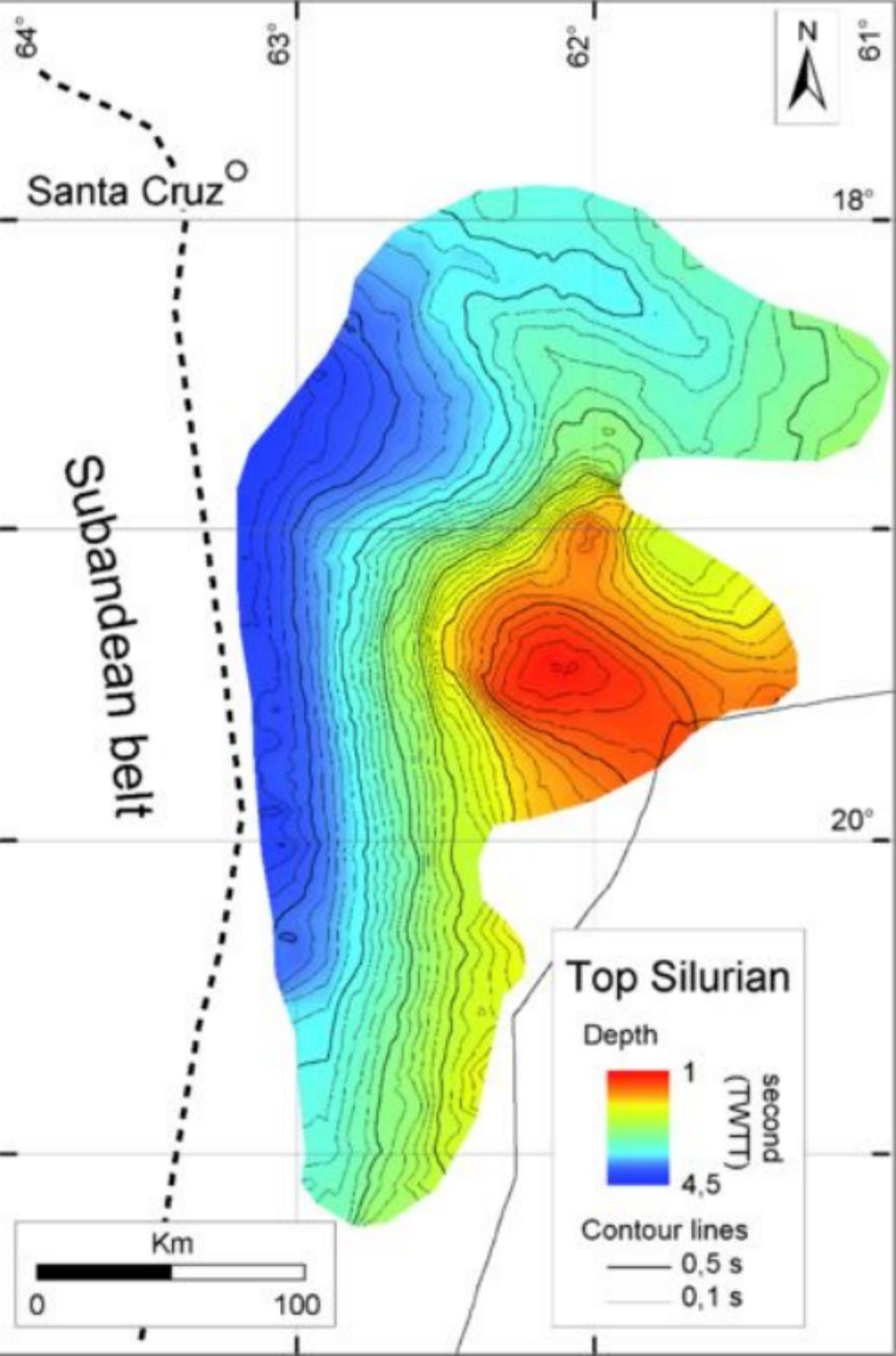
- 365 Amos, A. J., 1972, Las Cuencas Carbónicas y Pérmicas de Argentina: *Anales Brasileños de*  
366 *Ciencias*, **44**, 21-36.
- 367 Bennett, M. R., 2003, Ice streams as the arteries of an ice sheet: their mechanics, stability and  
368 significance: *Earth Science Reviews*, **61**, 309-339.
- 369 Brennand, T. A., & Shaw, J., 1994, Tunnel channels and associated landforms, south-central  
370 Ontario: their implication for ice-sheet hydrology: *Canadian Journal of Earth*  
371 *Sciences*, **31**, 505-522.
- 372 Caputo, M. V., & Crowell, J. C., 1985, Migration of glacial centers across Gondwana during  
373 Paleozoic Era: *Geological Society of America Bulletin*, **96**, 1020-1036.

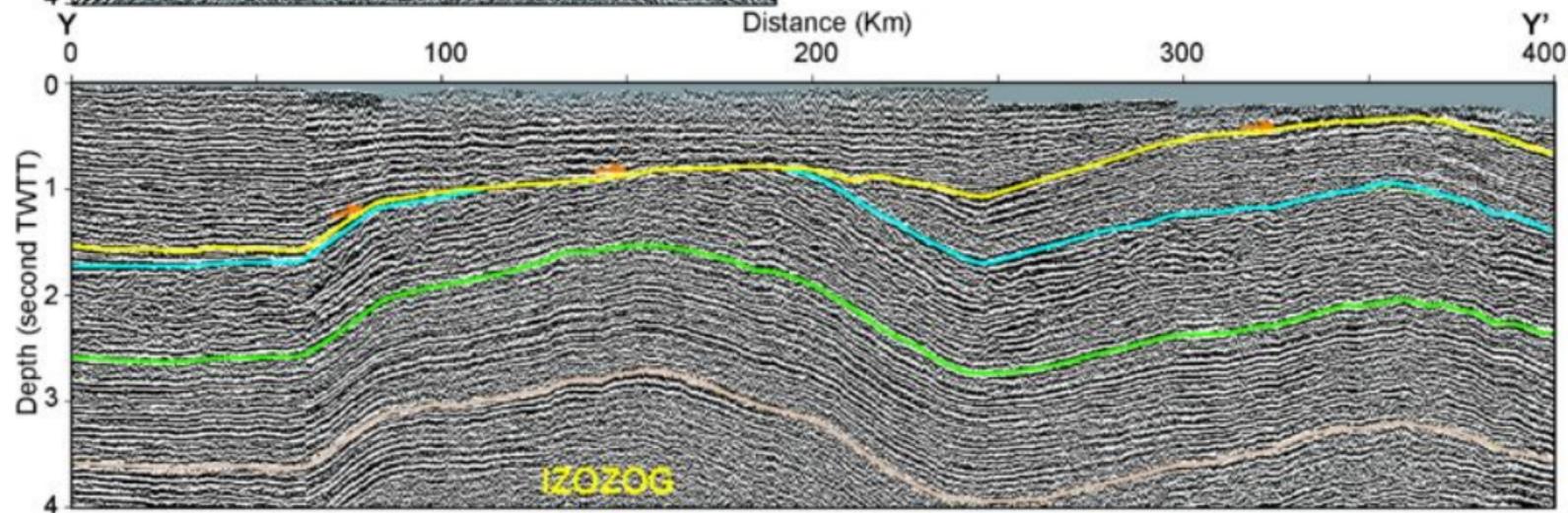
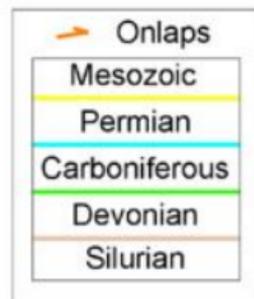
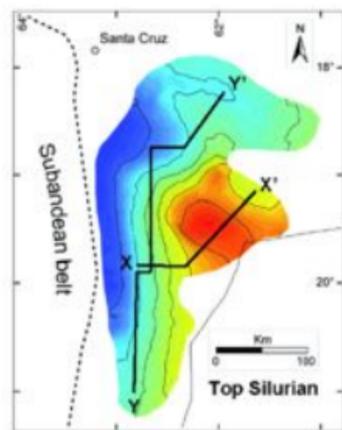
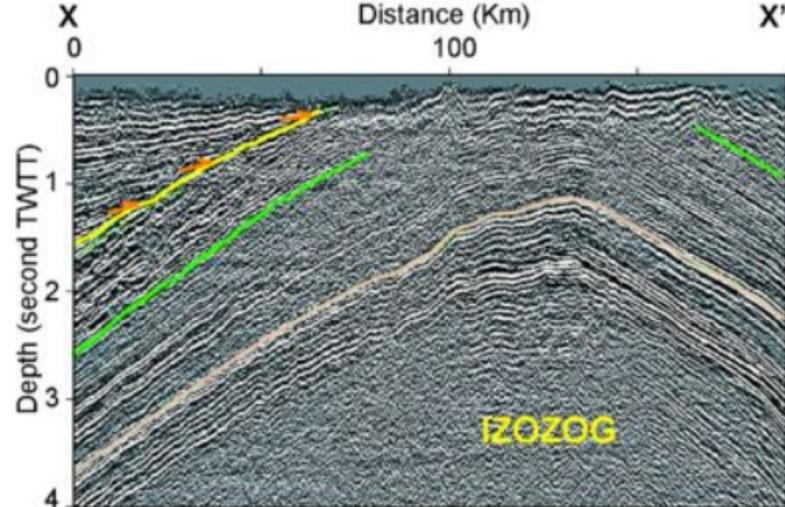
- 374 Caputo, M. V., de Melo, J. H. G., Streef, M., & Isbell, J. L., 2008, Late Devonian and Early  
375 Carboniferous glacial records of South America, *In*: Fielding, C. R., Frank, T. D., &  
376 Isbell, J. L., (eds.), *Resolving the Late Paleozoic Ice Age in Time and Space*:  
377 Geological Society of America Special Paper, **441**, 161-173.
- 378 Crowell, J. C., & Frakes., L. A., 1975, The late Paleozoic glaciation, *In*: Campbell, K. S. W.,  
379 (ed.), *Gondwana Geology*: Australian National University Press, *Canberra*, 313-331.
- 380 Decelles, P. G., & Horton, B. K., 2003, Early to Middle Tertiary foreland basin development  
381 and the history of Andean crustal shortening in Bolivia: *Geological Society of America*  
382 *Bulletin*, **115**, 58-77.
- 383 Du Toit, A. L., 1937, *Our Wandering Continents*: Edinburgh, Oliver and Boyd.
- 384 Dunn, J. F., Hartshorn, K. G., & Hartshorn, P. W., 1995, Structural styles and hydrocarbon  
385 potential of the sub-andean thrust belt of southern Bolivia, *In*: Tankard, A. J., Suárez,  
386 S., & Welsink, H. J., (eds.), *Petroleum basins of South America*: American Association  
387 of Petroleum Geologists, *Tulsa*, **Memoir 62**, 523-543.
- 388 Eyles, N., 2008, Glacioepochs and the supercontinent cycle after ~3.0 Ga: tectonic boundary  
389 conditions for global cooling: *Palaeogeography, Palaeoclimatology, Palaeoecology*,  
390 **258**, 89-129.
- 391 Eyles, N., & Eyles, C. H., 1993, Glacial geologic confirmation of an intraplate boundary in  
392 the Paraná basin of Brazil: *Geology*, **21**, 459-462.
- 393 Eyles, N., Gonzalez Bonorino, G., França, A. B., Eyles, C. H., & Lopez Paulsen, O., 1995,  
394 Hydrocarbon-bearing late Paleozoic glaciated basins of southern and central South  
395 America, *In*: Tankard, A. J., Suárez, S., & Welsink, H. J., (eds.), *Petroleum basins of*  
396 *South America*: American Association of Petroleum Geologists, *Tulsa*, **Memoir 62**,  
397 165-183.
- 398 Ghienne, J. F., & Deynoux, M., 1998, Large-scale channel fill structures in Late Ordovician  
399 glacial deposits in Mauritania, western Sahara.: *Sedimentary Geology*, **119**, 141-159.
- 400 Ghienne, J. F., Deynoux, M., Manatschal, G., & Rubino, J. L., 2003, Palaeovalleys and fault-  
401 controlled depocentres in the Late-Ordovician glacial record of the Murzuq Basin  
402 (central Libya) *Comptes Rendus Geosciences*, **335**, 1091-1100
- 403 Gohrbandt, K. H. A., 1992, Paleozoic paleogeographic and depositional developments on the  
404 central proto-Pacific margin of Gondwana : their importance to hydrocarbon  
405 accumulation: *Journal of South American Earth Sciences*, **6**, 267-287.
- 406 Hambrey, M. J., & Harland, W. B., 1981, *Earth's Pre-Pleistocene Glacial Record*: Cambridge,  
407 Cambridge University Press.
- 408 Helwig, J., 1972, Stratigraphy, sedimentation, paleogeography, and paleoclimates of  
409 Carboniferous ("Gondwana") and Permian of Bolivia: *American Association of*  
410 *Petroleum Geologists Bulletin*, **56**, 1008-1033.
- 411 Huuse, M., & Lykke-Andersen, H., 2000, Large-scale glaciotectonic thrust structures in the  
412 eastern Danish North Sea, *In*: Maltman, A., Hambrey, M., & Hubbard, B., (eds.),  
413 *Deformation of Glacial Materials*: Geological Society Special Publications, *London*,  
414 **176**, 293-305.
- 415 Le Heron, D., Craig, J., & Etienne, J. L., 2009, Ancient glaciations and hydrocarbon  
416 accumulations in North Africa and the Middle East.: *Earth-Science Reviews*, **93**, 47-  
417 76.
- 418 Le Heron, D., Sutcliffe, O., Bourgig, K., Craig, J., Visentin, C., & Whittington, R., 2004,  
419 Sedimentary architecture of Upper Ordovician tunnel valleys, Gargaf Arch, Lybia:  
420 implications for the genesis of a hydrocarbon reservoir: *GeoArabia*, **9**, 137-160.
- 421 Lønne, I., 1995, Sedimentary facies and depositional architecture of ice-contact glaciomarine  
422 systems: *Sedimentary Geology*, **98**, 13-43.

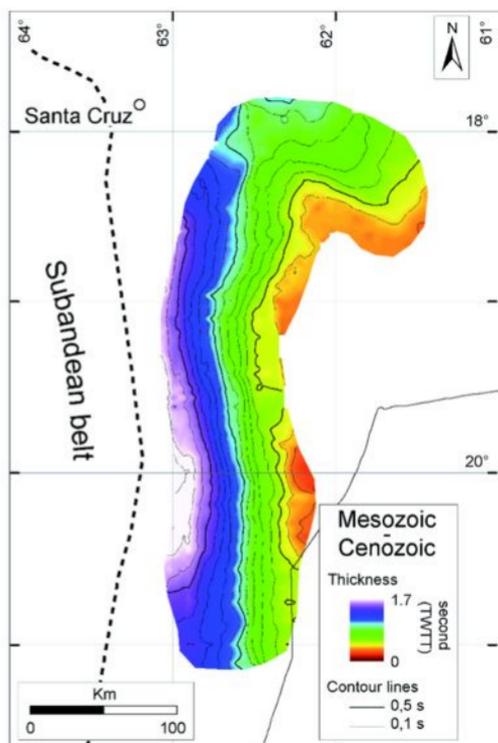
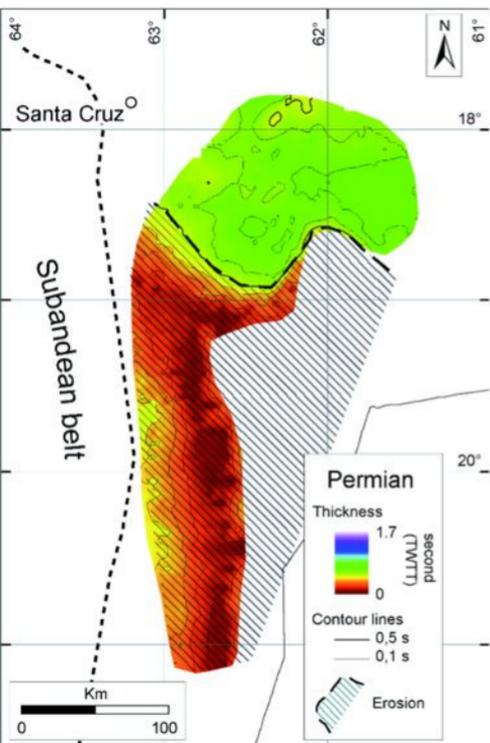
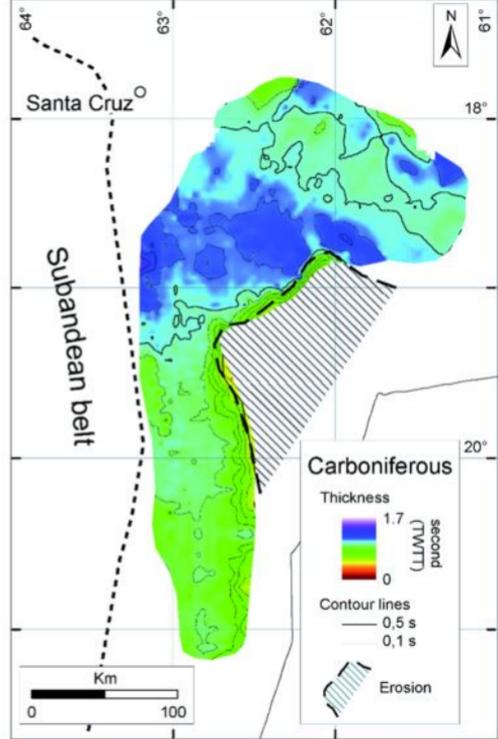
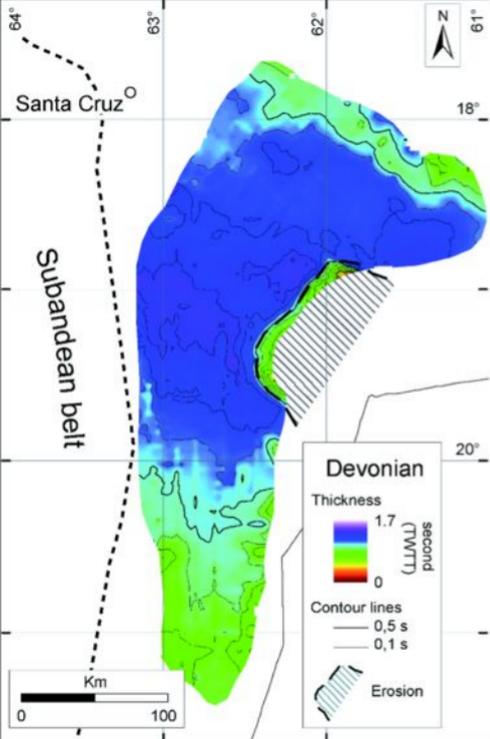
- 423 -, 1997, Facies characteristics of a proglacial turbiditic sand-lobe at Svalbard: *Sedimentary*  
424 *Geology*, **109**, 13-35.
- 425 -, 2001, Dynamics of marine glacier termini read from moraine architecture: *Geology*, **29**,  
426 199-202.
- 427 Lønne, I., Nemeč, W., Blikra, L. H., & Lauritsen, T., 2001, Sedimentary Architecture and  
428 Dynamic Stratigraphy of a Marine Ice-Contact System: *Journal of Sedimentary*  
429 *Research*, **71**, 922-943.
- 430 O'Cofaigh, C., 1996, Tunnel valley genesis: *Progress in Physical Geography*, **20**.
- 431 Ottesen, D., Dowdeswell, J. A., & Rise, L., 2005, Submarine landforms and the reconstruction  
432 of fast-flowing ice streams within a large Quaternary ice sheet: The 2500-km-long  
433 Norwegian-Svalbard margin (57°–80°N). *Geological Society of America Bulletin*, **117**,  
434 1033-1050.
- 435 Ottesen, D., Stokes, C. R., Rise, L., & Olsen, L., 2008, Ice-sheet dynamics and ice streaming  
436 along the coastal parts of northern Norway: *Quaternary Science Reviews*, **27**, 922-940.
- 437 Powell, J. H., Moh'd, B. K., & Masri, A., 1994, Late Ordovician-Early Silurian glaciofluvial  
438 deposits preserved in palaeovalleys in South Jordan.: *Sedimentary Geology*, **89**, 303-  
439 314.
- 440 Praeg, D., 2003, Seismic imaging of mid-Pleistocene tunnel-valleys in the North Sea Basin-  
441 high resolution from low frequencies *Journal of Applied Geophysics*, **53**, 273-298
- 442 Salinas, C., Oblitas, J., & Vargas, C., 1978, Exploración del Sistema Carbonífero en la Cuenca  
443 Oriental de Bolivia: *Revista Técnica Yacimientos Petrolíferos Fiscales Bolivianos*, **7**,  
444 5-49.
- 445 Sempere, T., 1995, Phanerozoic evolution of Bolivia and adjacent regions, *In*: Tankard, A. J.,  
446 Suárez, S., & Welsink, H. J., (eds.), *Petroleum basins of South America*: American  
447 Association of Petroleum Geologists, *Tulsa*, **Memoir 62**, 207-230.
- 448 Sempere, T., Herail, G., Oller, J., & Bonhomme, M. G., 1990, Late Oligocene-Early Miocene  
449 major tectonic crisis and related basins in Bolivia: *Geology*, **18**, 946-949.
- 450 Tankard, A. J., Uliana, M. A., Welsink, H. J., Ramos, V. A., Turic, M., Franca, A. B., Milani,  
451 E. J., de Brito Neves, B. B., Eyles, N., Skarmeta, J., Santa Ana, H., Wiens, F., Cirbian,  
452 M., Lopez Paulsen, O., Germs, G. J. B., De Wit, M. J., Machacha, T., & McG. Miller,  
453 R., 1995, Structural and tectonic controls of basin evolution in southwestern  
454 Gondwana during the Phanerozoic, *In*: Tankard, A. J., Suárez, S., & Welsink, H. J.,  
455 (eds.), *Petroleum basins of South America*: American Association of Petroleum  
456 Geologists, **Memoir 62**, 5-52.
- 457 Uba, C. E., Heubeck, C., & Hulka, C., 2006, Evolution of the late Cenozoic Chaco foreland  
458 basin, Southern Bolivia.: *Basin Research*, **18**, 145-170.
- 459 Vail, P. R., Mitchum, R. M., Jr., & Thompson, S., III., 1977, Seismic stratigraphy and global  
460 changes of sea-level, part 3: Relative changes of sea level from coastal onlap, *In*:  
461 Payton, C. E., (ed.), *Seismic Stratigraphy - Applications to hydrocarbon exploration*:  
462 American Association of Petroleum Geologists, *Tulsa*, **Memoir 26**, 63-81.
- 463 Wegener, A., 1915, Die entstehung der kontinente und ozeane (The origin of continents and  
464 oceans): New-York, Dutton and Co.
- 465 Wingfield, R. T. R., 1990, The origin of major incisions within the Pleistocene deposits of the  
466 North Sea: *Marine Geology*, **91**, 31-52.
- 467
- 468

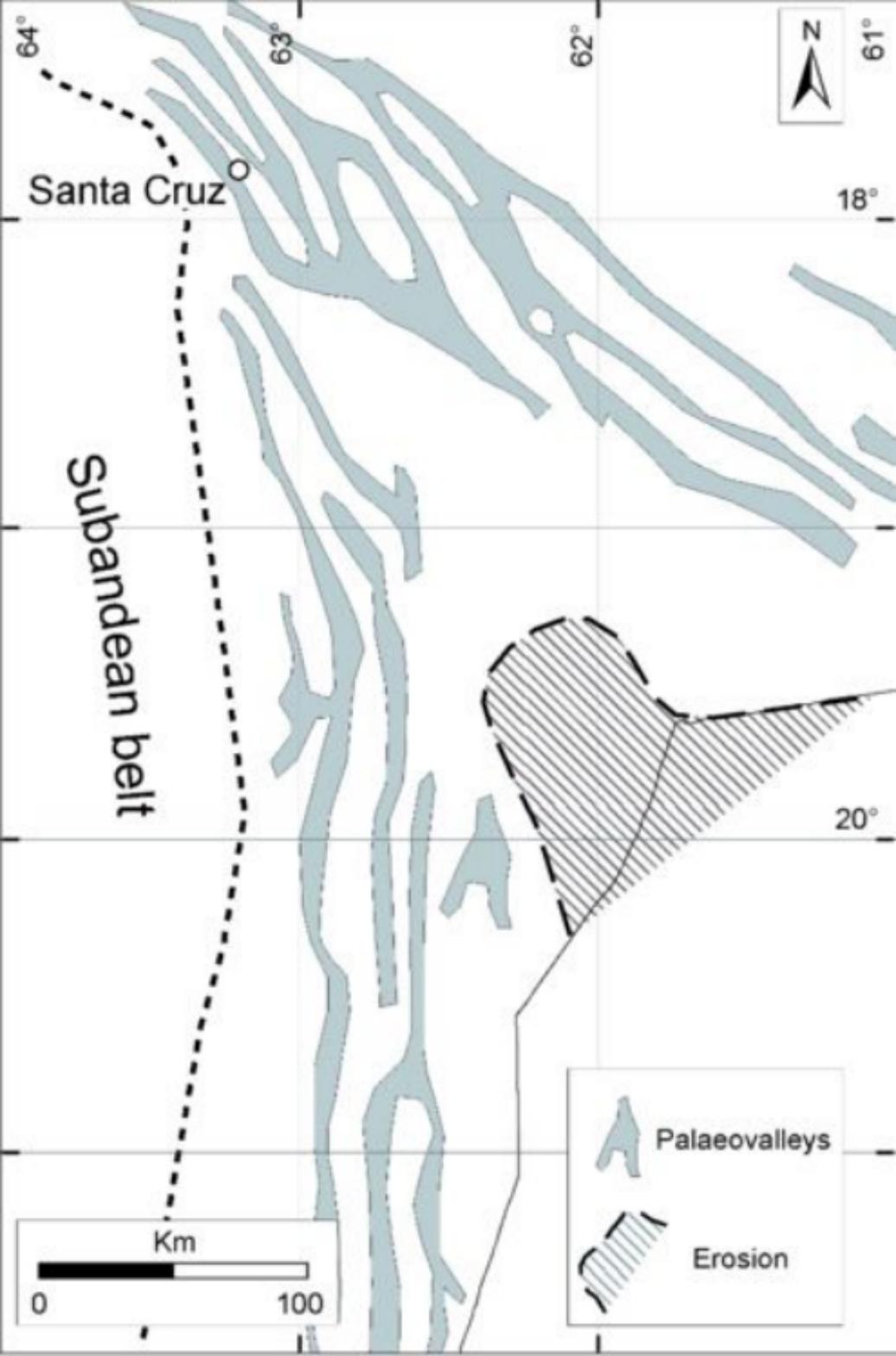


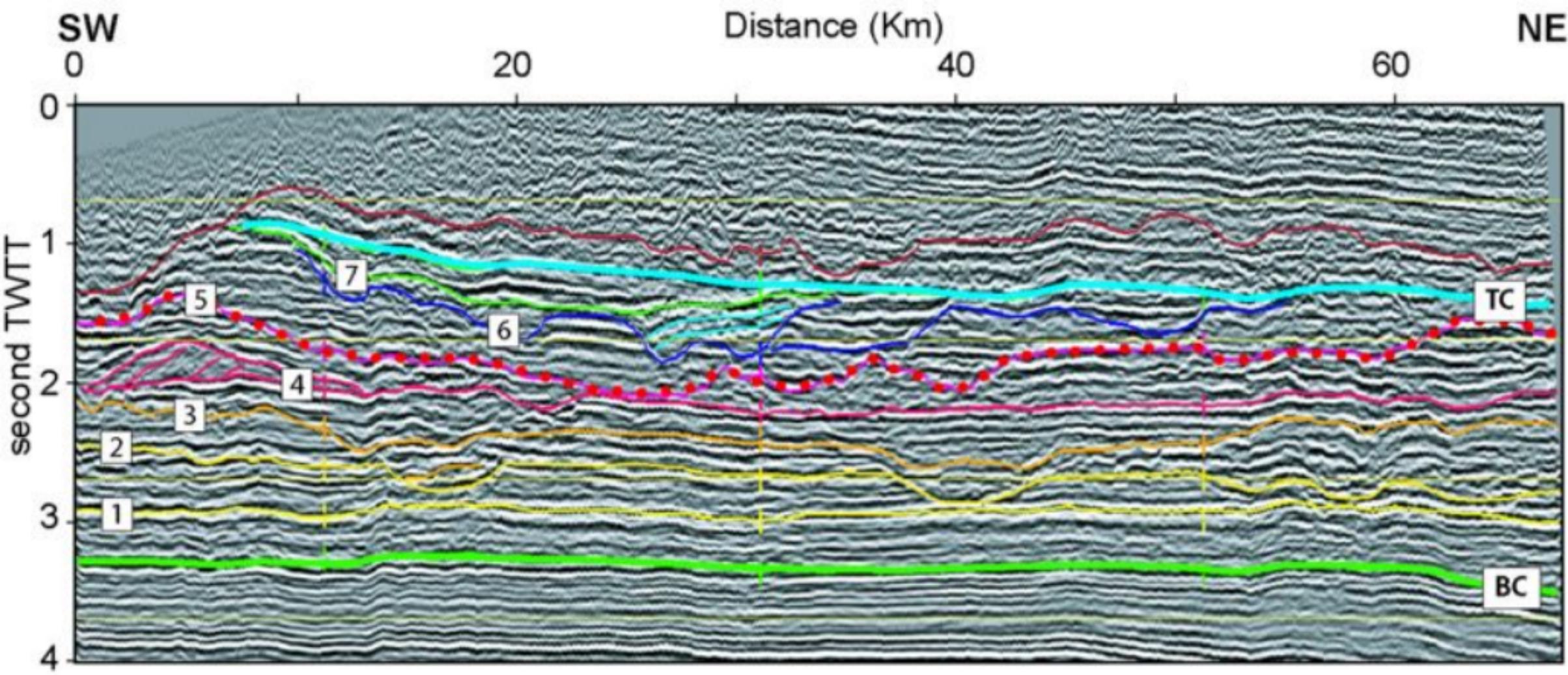


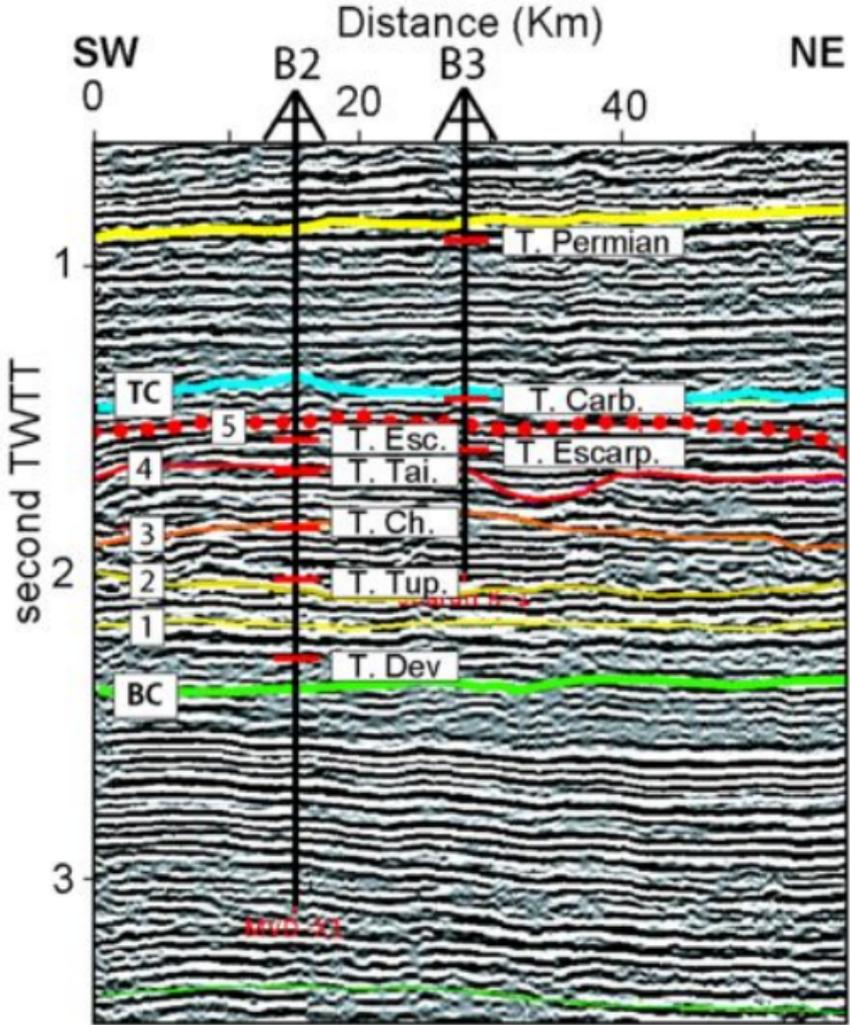
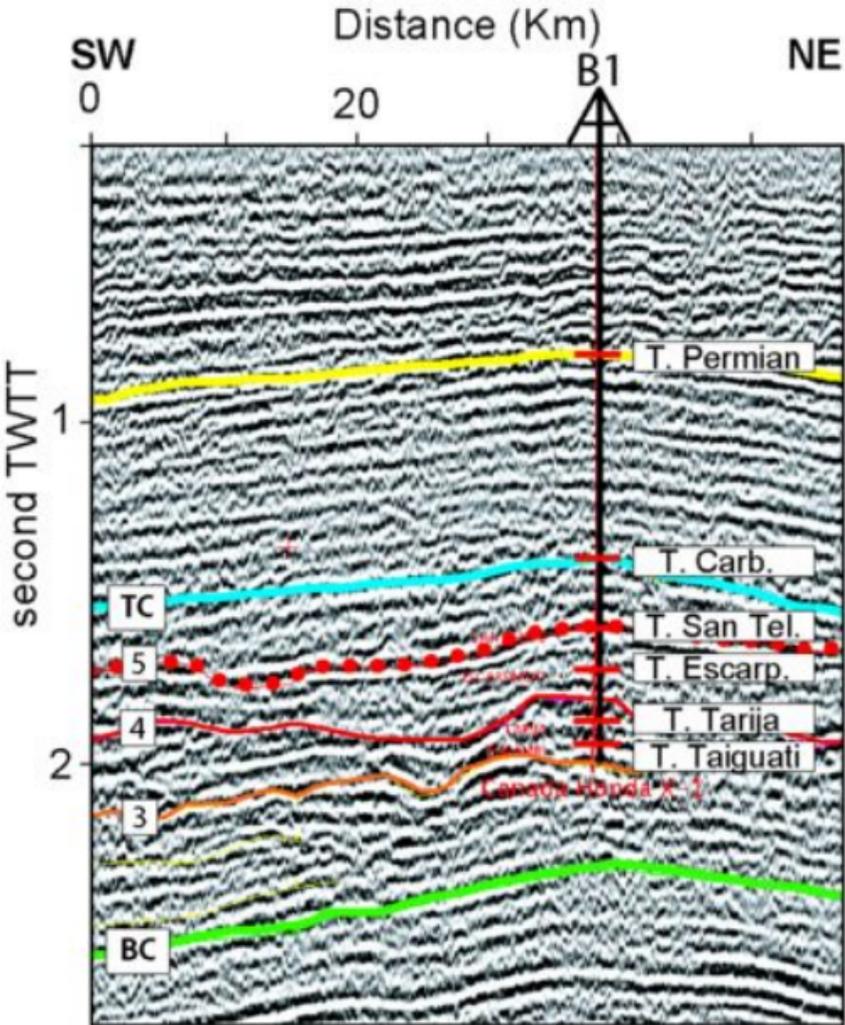


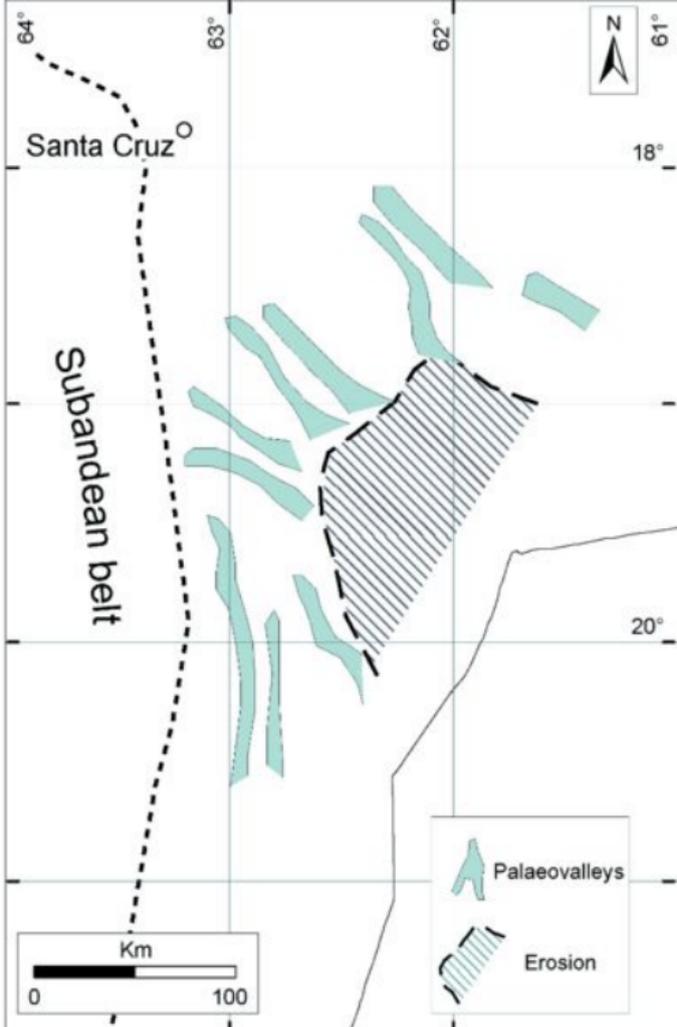
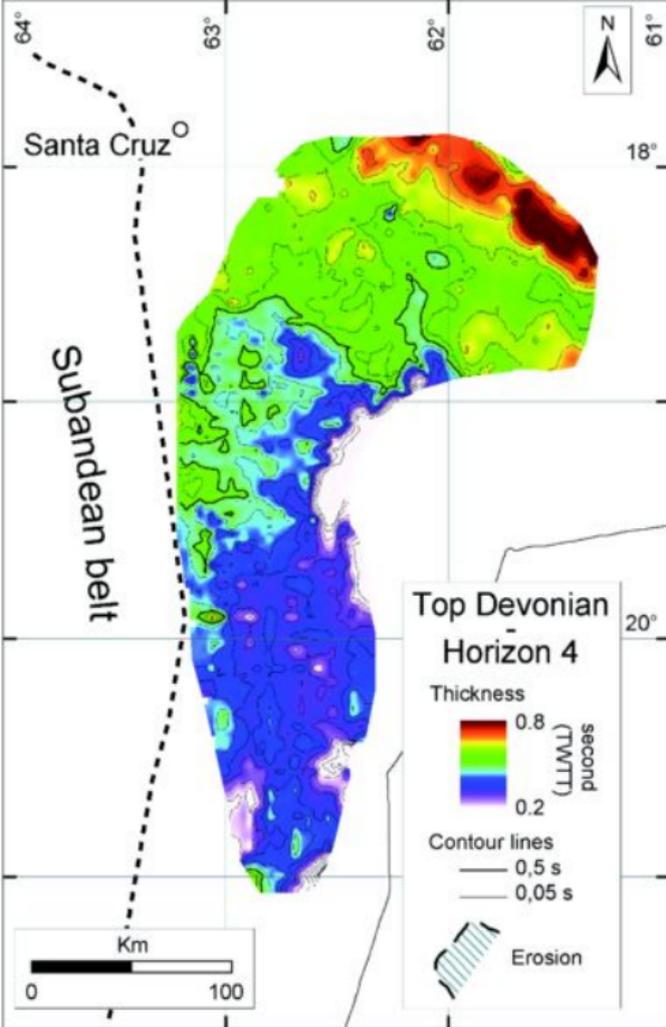


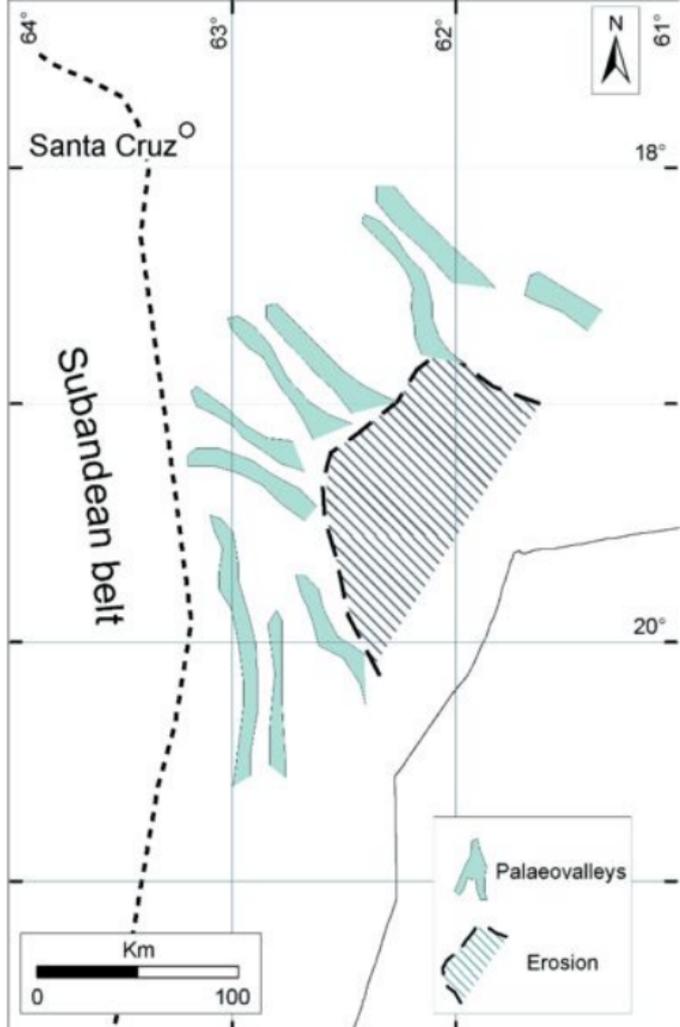
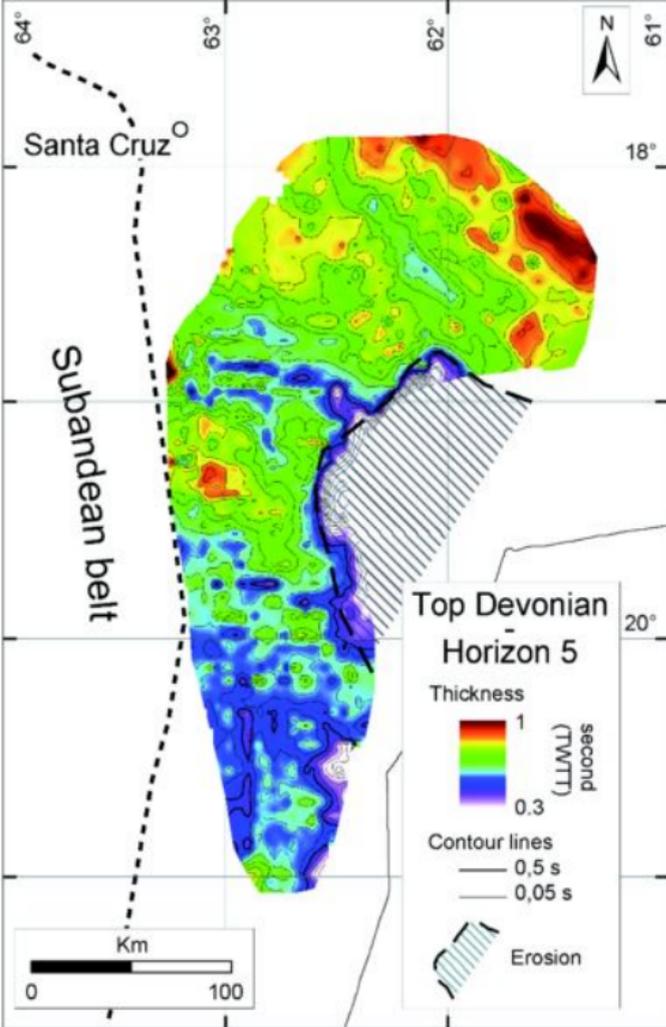


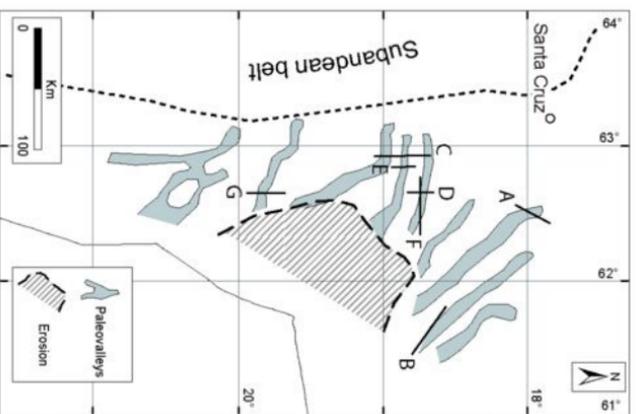
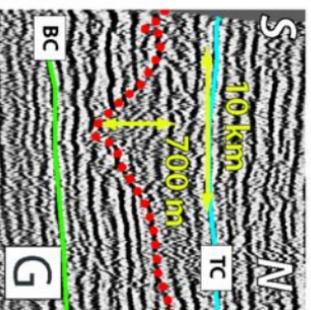
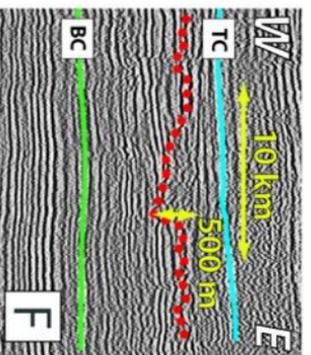
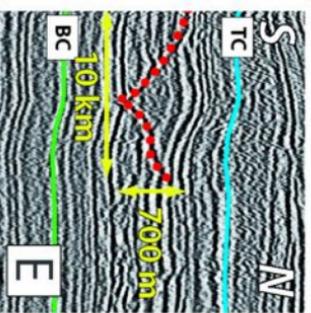
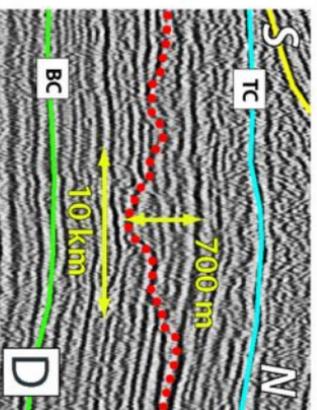
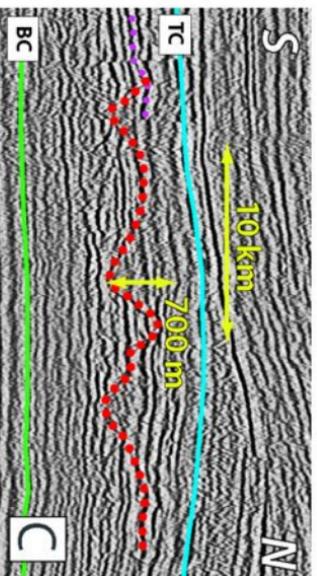
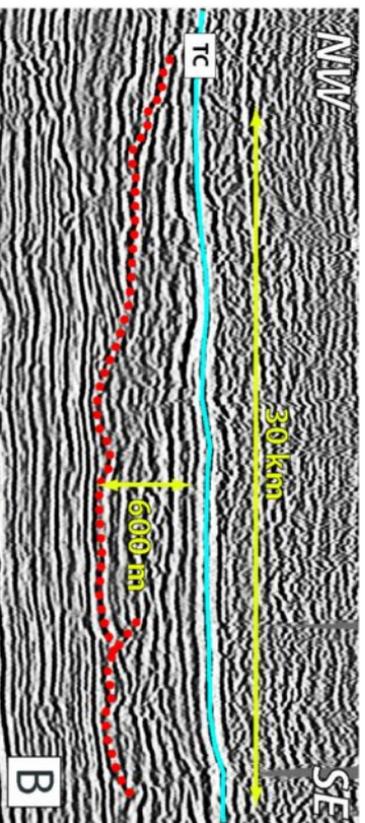
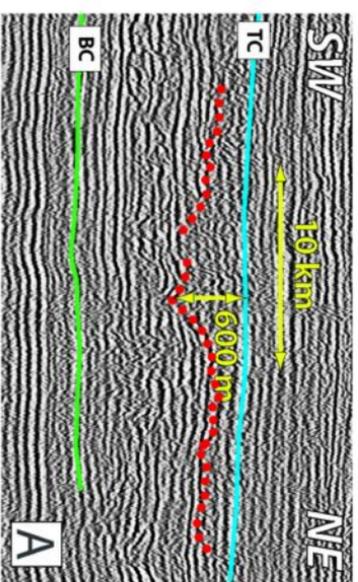


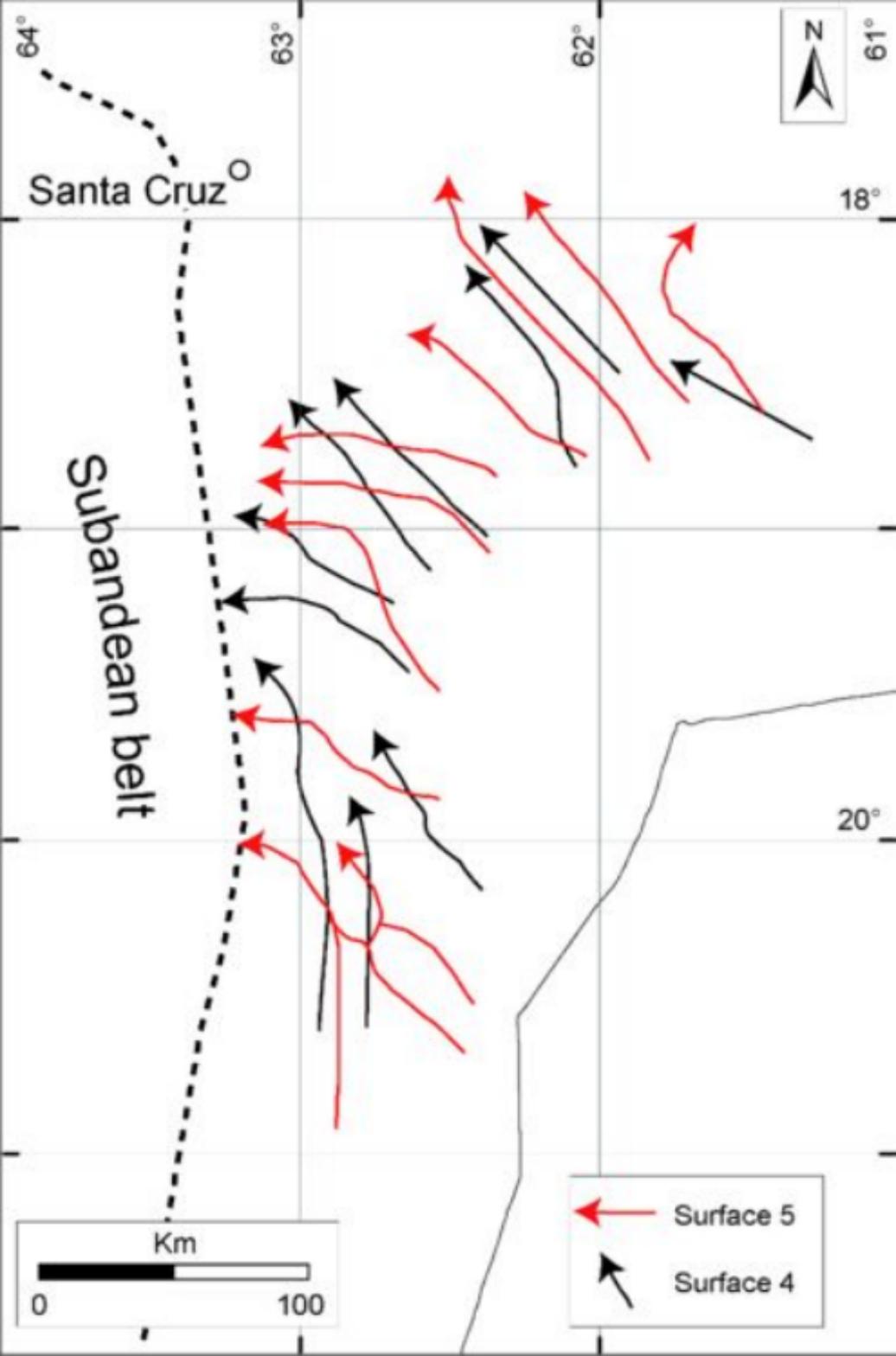


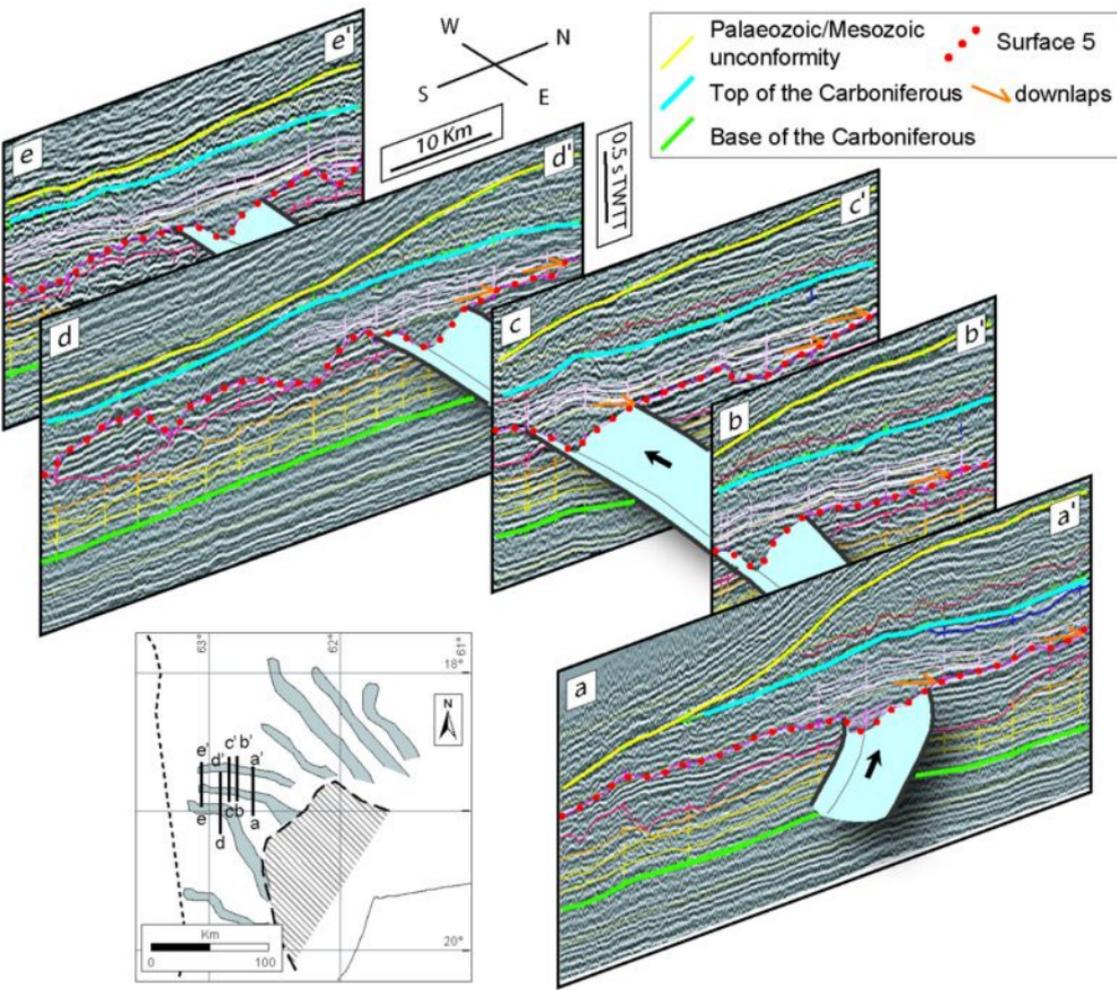






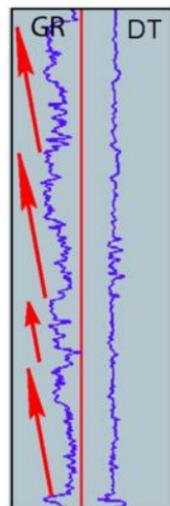
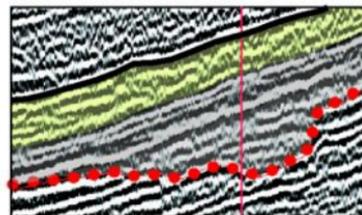
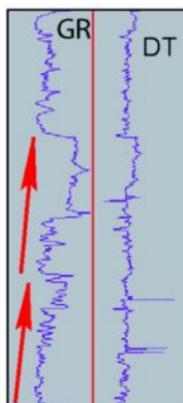
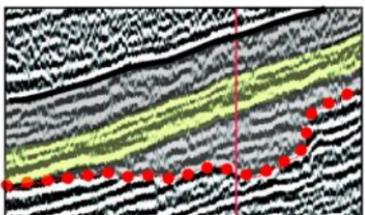




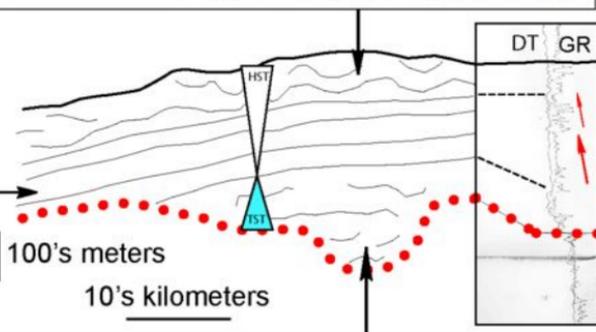




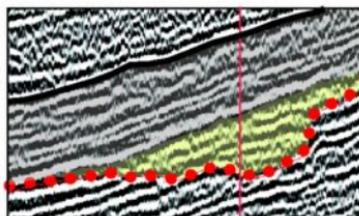
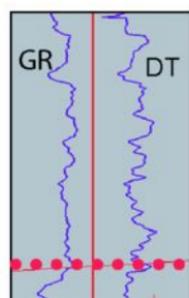
FACIES 3:  
Fluvial facies

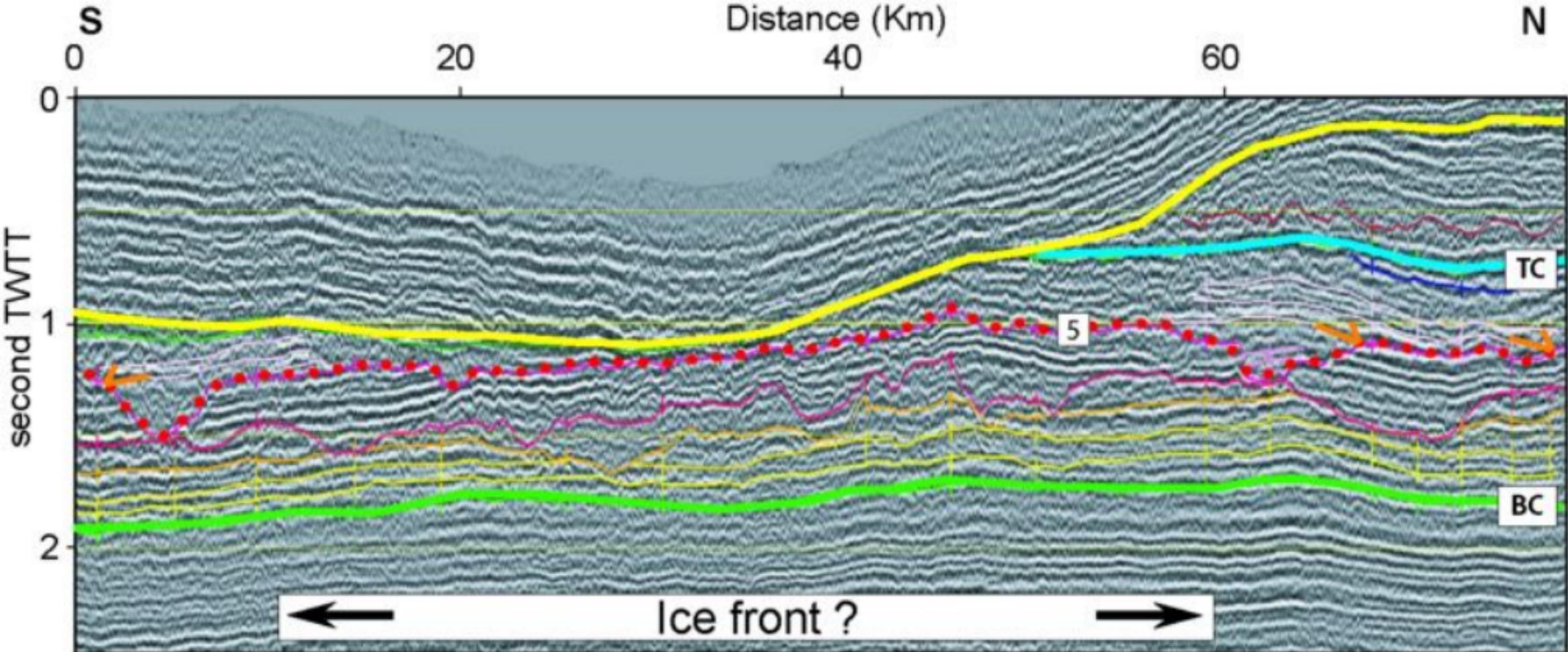


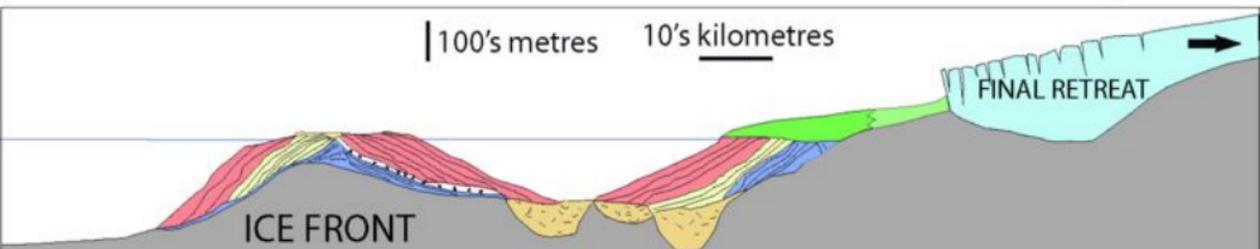
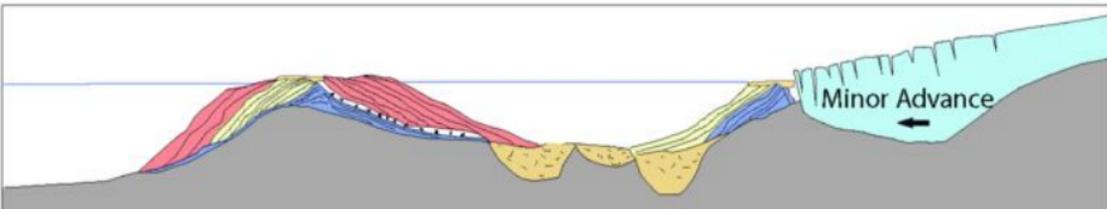
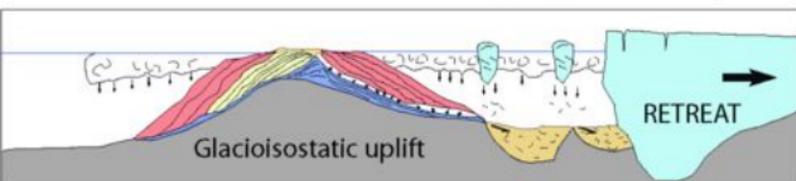
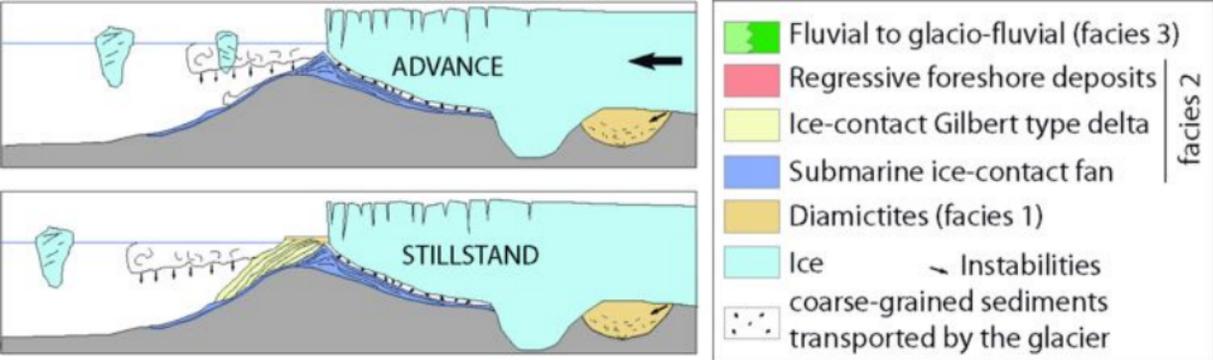
FACIES 2:  
progradational  
delta



FACIES 1: Various tills







Type of incision	Process of incision	Sections	Width	Depth	Length	Basement	Sinuosity	Drainage patterns
Tunnel Valleys	hydraulic	U-shaped	M.= 1km <4 km	M. 250m <500 m	10' of km	rocks & sediments	low	anastomosing to tributary branching
Cross shelf trough*	abrasion	U-shaped	10-100' of km	M. 250m	100' of km	sediments	straight to very low	cross-cutting (no mix)
Fjord	hydraulic + abrasion	U-, V-shaped	1-20 km	< 3km	10' of km	rocks	straight (inherited)	branching to eratic
Chaco incisions	hydraulic + abrasion	U-, V-shaped	M.= 7.3km 3-21 km	500-700 m	>100 km	sediments	straight to very low	one anastomosed network (cross-cut?)