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Marine Geology

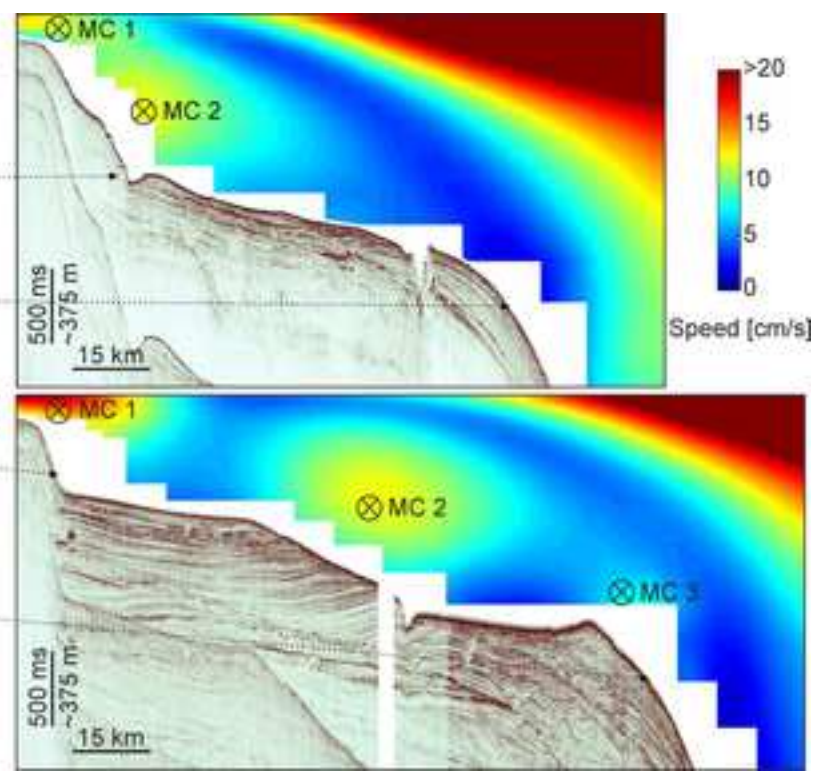
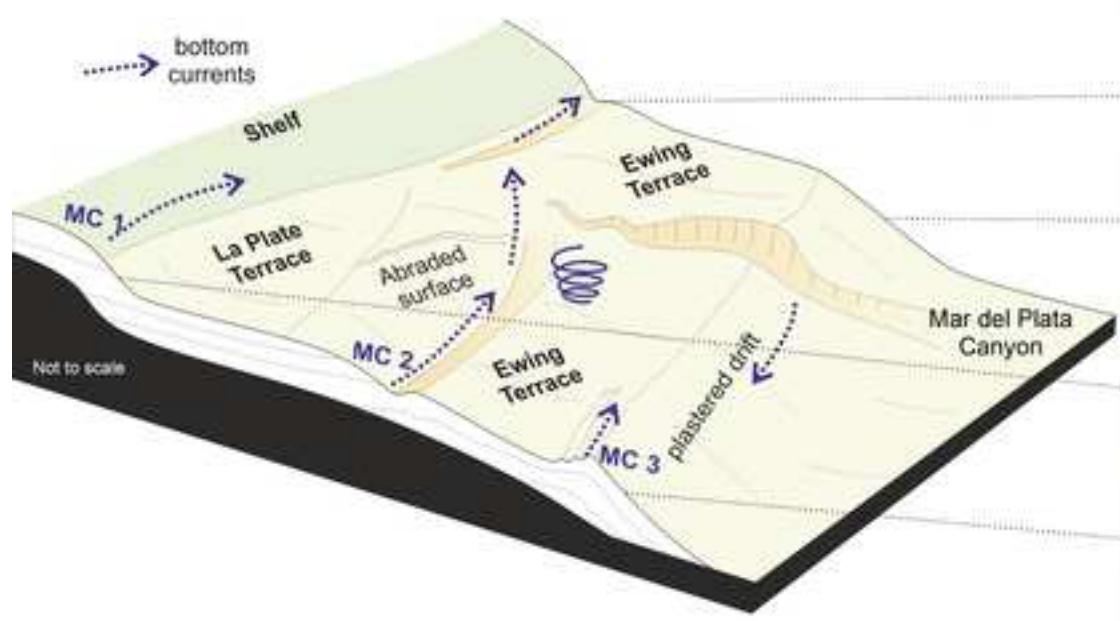
The erosive power of the Malvinas Current: Influence of bottom currents on morpho-sedimentary features along the northern Argentine Margin (SW Atlantic Ocean) --Manuscript Draft--

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Article Type:	VSI:Contourites
Keywords:	Contour current; Deep-water environment; Sediment drift; Contourite Depositional Systems; Sediment transport, Argentine Margin
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Abstract:	<p>Sediment deposits formed mainly under the influence of bottom currents (contourites) are widely used as high-resolution archives for reconstructing past ocean conditions. However, the driving processes of Contourite Depositional Systems (CDS) are not entirely understood. The aim of this study is to establish a clearer link between contourite features and the oceanographic processes that form them. The morphosedimentary characteristics of a large CDS were analysed together with the current dynamics along the continental margin off northern Argentina. This study combines multibeam bathymetry, seismo-acoustic data, sediment cores, vessel-mounted Acoustic Doppler Current Profiler (VM-ADCP) data and numerical modelling of ocean currents.</p> <p>The contouritic features include large contourite terraces (La Plata Terrace, Ewing Terrace) and an abraded surface connecting the terraces, as well as smaller erosional and depositional features like moats, erosion surfaces on the Ewing Terrace, sediment waves and contourite drifts. Measured and modelled near-bottom currents are strong (up to 63 cm/s at 150 - 350 m above the seafloor) where abraded surfaces and moats are present, and weak (below 30 cm/s) on the La Plata Terrace and the Ewing Terrace. Generally, bottom currents follow the upper and middle slope morphology. Decreasing velocity of water masses flowing northward leads to less erosion and finer sediment deposits. ADCP data and the hydrodynamic model show the formation of eddies near the seafloor which probably lead to the small erosion surfaces on the Ewing Terrace, even though it is mainly a depositional environment. Furthermore, modelled data show that a subsurface branch of the Malvinas Current continues flowing northwards (~36°S) beyond the surface confluence zone between the Malvinas Current and the Brazil Current. Overall, this study contributes to a better understanding of the formation of CDS and can help future reconstructions of past ocean conditions based on sedimentary structures.</p>

Suggested Reviewers:	<p>Marta Ribó University of Auckland m.ribo@auckland.ac.nz Marta Ribó is a marine geologist with experience on evaluating sedimentary processes together with their hydrodynamics control. She has previously studied sediment transport and deposition mechanisms in a deep-water environment. Her skillset qualifies her to give constructive feedback in all chapters of our study.</p>
	<p>Amanda Thran UNSW: University of New South Wales m.thran@unsw.edu.au Amanda Thran has expert knowledge about numerical modelling of hydrodynamic and sedimentary processes on passive margins. She worked on the controls on the global distribution of contourite drifts. I would like to suggest her as a potential referee because her previous study aimed in further understanding the same processes as our new study.</p>
	<p>Adriano R. Viana Petróleo Brasileiro SA: Petrobras aviana@petrobras.com.br Adriano R. Viana research include Marine Geology, Margin Geotectonics, Multiphysics Methods and Basin Analysis. His work included analysed of Deep-water contourite systems and their control of bottom currents. I would like to suggest him as a potential referee because of interdisciplinary work and knowledge of contourite systems.</p>
	<p>Dmitrii Borisov FSBIS P P Shirshov Institute of Oceanology of the Russian Academy of Sciences: FGBUN Institut okeanologii imeni P P Sirsova Rossijskoj akademii nauk dborisov@ocean.ru Dmitrii Borisov is an expert in contourites and with knowledge in the working area of South Atlantic. He also has knowledge about Oceanography.</p>
	<p>Leticia Burone Universidad de la Republica Uruguay lburone@fcien.edu.uy Leticia Burone work includes the disciplines of Oceanography, Marine Ecology, Sedimentology. She previously worked on hydrological and morphological controls on surface sedimentation. Furthermore, she previously worked at the South American margin and knows the unique oceanographic setting.</p>
	<p>Tove Nielsen Geological Survey of Denmark and Greenland (GEUS) tni@geus.dk Tove Nielsen work included the analyses of Sedimentary processes and contourites with a focus on Paleontology.</p>

Highlights:

- Near-bottom currents are strong (up to 63 cm/s) over abraded surfaces and moats
- Near-bottom currents are weak (below 30 cm/s) on La Plata and the Ewing Terrace
- Formation of eddies near the seafloor probably lead to small erosion surfaces
- Sediment transport is associated with high-velocity alongslope bottom-current jets
- Model indicates: near the seafloor Malvinas Current splits in 3 branches at $\sim 39^{\circ}\text{S}$



1 **The erosive power of the Malvinas Current: Influence of bottom currents on morpho-**
2 **sedimentary features along the northern Argentine Margin (SW Atlantic Ocean)**

3
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25
26 **Abstract:**

27 Sediment deposits formed mainly under the influence of bottom currents (contourites) are
28 widely used as high-resolution archives for reconstructing past ocean conditions. However,
29 the driving processes of Contourite Depositional Systems (CDS) are not entirely understood.
30 The aim of this study is to establish a clearer link between contourite features and the
31 oceanographic processes that form them. The morphosedimentary characteristics of a large
32 CDS were analysed together with the current dynamics along the continental margin off
33 northern Argentina. This study combines multibeam bathymetry, seismo-acoustic data,
34 sediment cores, vessel-mounted Acoustic Doppler Current Profiler (VM-ADCP) data and
35 numerical modelling of ocean currents.

36 The contouritic features include large contourite terraces (La Plata Terrace, Ewing Terrace)
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38 depositional features like moats, erosion surfaces on the Ewing Terrace, sediment waves and
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40 150 - 350 m above the seafloor) where abraded surfaces and moats are present, and weak
41 (below 30 cm/s) on the La Plata Terrace and the Ewing Terrace. Generally, bottom currents
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44 hydrodynamic model show the formation of eddies near the seafloor which probably lead to
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46 environment. Furthermore, modelled data show that a subsurface branch of the Malvinas
47 Current continues flowing northwards (~36°S) beyond the surface confluence zone between
48 the Malvinas Current and the Brazil Current. Overall, this study contributes to a better
49 understanding of the formation of CDS and can help future reconstructions of past ocean
50 conditions based on sedimentary structures.

51

52 Keywords: Contour current; Deep-water environment; Sediment drift; Contourite

53 Depositional Systems; Sediment transport, Argentine Margin

54

55 **1 Introduction**

56 Continental margins can be shaped by ocean currents, which influence sediment erosion
57 and deposition even at large scales (Heezen, 1959; Heezen and Hollister, 1964; Stow et al.,
58 2009). Sediment deposits formed mainly under the influence of bottom currents (i.e. currents
59 flowing near the seafloor) are classified as contourites (Rebesco and Camerlenghi, 2008;
60 Rebesco et al., 2014). These currents often supply oxygen and nutrients favouring the
61 development of deep-sea ecosystems with high biodiversity, for instance cold-water corals are
62 often found in contourite depositional systems (Hebbeln et al., 2016; Steinmann et al., 2020).
63 Bottom currents that lead to large sediment deposits can also control the distribution of
64 microplastics and lead to hotspots in the same area where biodiversity is high which is a
65 possible threat for marine ecosystems (Kane et al., 2020). Furthermore, contourites are
66 important for several fields including paleoclimatology and palaeoceanography, risk
67 management regarding slope instabilities and hydrocarbon exploration (Rebesco et al., 2014;

68 Hernández-Molina et al., 2018). Many physical oceanographic processes, ranging from low-
69 frequency quasi-steady geostrophic currents, sub-inertial oscillations, tides to high-frequency
70 internal waves, have potentially significant impact on the morphogenesis and evolution of
71 contourites. On a long time scale, the development of contourites is subject to climate-induced
72 change in thermohaline circulation and isostatic movements (e.g. tectonics). However, it is still
73 not clear how these multi-scale processes interact and control the formation and evolution of
74 contourites. Understanding the present deposition mechanisms is necessary for the
75 reconstruction of past ocean conditions based on the geological record (Surlyk and Lykke-
76 Andersen, 2007; Preu et al., 2012; Betzler et al., 2013).

77 A large Contourite Depositional System (CDS) has been recognised along the northern
78 margin of Argentina and Uruguay (Hernández-Molina et al., 2009; 2016a; Preu et al., 2012;
79 2013). The CDS includes three large contourite terraces that have been documented along
80 the continental margin off the Río de la Plata Estuary (northern Argentina) in close proximity
81 to the Mar del Plata (MdP) submarine Canyon (Preu et al., 2012; 2013). The study area is
82 located in the confluence zone of the northward flowing Malvinas Current and the southward
83 flowing Brazil Current (Fig. 1; Artana et al., 2019b; Piola and Matano, 2019). This complex
84 oceanographic setting makes it an interesting study area for analysing the influence of currents
85 on contourite formation. In this study we use a multidisciplinary approach based on multibeam
86 bathymetry, hydroacoustic data, sediment cores, vessel-mounted Acoustic Doppler Current
87 Profiler (VM-ADCP) data, Conductivity, Temperature and Depth (CTD) data and 25 years of
88 high-resolution ocean reanalysis. The main aim of the study is to derive further insights into
89 basic physical oceanographic mechanisms that control the formation of large-scale
90 contourites in such a complex and unique oceanographic configuration. More specifically, this
91 multidisciplinary project has the following three main goals: 1) to report on the characteristics
92 of near-bottom currents in the Brazil-Malvinas Confluence Zone; 2) to discuss differences
93 within the contourite system regarding seafloor morphology, sediment architecture and grain
94 size; 3) to interpret and discuss the oceanographic processes that may contribute to the
95 formation of the observed contouritic features.

96

97 **2 Regional setting**

98 **2.1 Oceanographic framework**

99 Strong ocean currents are present along the continental margin of Argentina and Uruguay
100 from the surface down to 2000 m water depth (Piola and Matano, 2019). The Malvinas Current
101 (MC) transports cold and nutrient rich waters northwards. The Brazil current flows southwards
102 along the continental slope and transports warmer, saltier waters and is shallower than the
103 Malvinas Current (Piola and Matano, 2019). The study area is located in the region where
104 these two boundary currents encounter, forming the Brazil-Malvinas Confluence Zone. On
105 average, the axis of the confluence zone is situated at an approximate latitude of 38°S (Gordon
106 and Greengrove, 1986; Artana et al., 2019b; Piola and Matano, 2019). The confluence shows
107 large migrations at synoptic (800 km) and interannual (300 km) scales compared to rather
108 small seasonal changes (<150 km) (Artana et al., 2019b). Numerical simulations suggest that
109 at the confluence the Malvinas Current splits into two branches at the sea surface (Provost et
110 al., 1995; Artana et al., 2019b). The offshore branch joins the Brazil Current and detaches
111 from the continental slope while the inner branch subducts and continues flowing northward
112 along the upper continental slope (Artana et al., 2019b).

113 Malvinas and Brazil Current refer to the continuous horizontal movement of water, they can
114 be composed of different water masses which are defined by their different chemical
115 composition and can be identified based on the potential temperature, salinity and dissolved
116 oxygen (Maamaatuaiahutapu et al., 1994). The northward flowing water masses at the
117 continental slope from sea surface to bottom are Subantarctic Surface Water (SASW),
118 Antarctic Intermediate Water (AAIW), Circumpolar Deep Water (CDW) and the Antarctic
119 Bottom Water (AABW) (Preu et al., 2013; Piola and Matano, 2019). The southward flowing
120 water masses are Tropical Water, South Atlantic Central Water (SACW), AAIW and North
121 Atlantic Deep Water (NADW) (Preu et al., 2013; Valla et al., 2018; Piola and Matano, 2019).
122 Southward flowing AAIW is an older (saltier and less oxygenated) variety of the AAIW
123 recirculated around the South Atlantic subtropical gyre (Valla et al., 2018). The NADW flows

124 southward between Upper Circumpolar Deep Water (UCDW) and Lower Circumpolar Deep
125 Water (LCDW) (Reid et al., 1977; Piola and Matano, 2019). The depth of the interfaces
126 between the water masses varies with time and between locations. In close proximity to the
127 MdP Canyon the interfaces between AAIW, UCDW, NADW, LCDW and AABW are located at
128 1200, 2000, 3200, 3800 m, respectively (Preu et al., 2013). The zone of interest in this study
129 (located at 450-1400 m water depth) is mainly under the influence of the AAIW (identified with
130 a salinity minimum and a dissolved oxygen maximum) and the UCDW (identified with a
131 dissolved oxygen minimum) (Fig. 1B and 1C, Preu et al., 2013). The interface between the
132 UCDW and the NADW is characterised by an increase of salinity and dissolved oxygen
133 decrease with depth (Fig. 1B and 1C). This modern ocean circulation and stratification pattern
134 was established during the Middle Miocene after the onset of the (paleo-) NADW circulation
135 in the southern hemisphere, which significantly influenced the formation of the CDS (Preu et
136 al., 2012).

137

138 **2.2 Geological setting**

139 The study area is located at the passive volcanic-rifted continental margin of north
140 Argentina, offshore the Río de la Plata estuary formed during the Cretaceous period (Fig. 1A;
141 Hinz et al., 1999; Franke et al., 2007). The rivers flowing into the Río de la Plata, together with
142 the Colorado and Negro rivers that are located further south, are the main sources of
143 sediments to the continental margin (Giberto et al., 2004; Voigt et al., 2013; Razik et al.,
144 2015a). Frenz et al. (2003a) and Razik et al. (2015a) analysed the sediment grain size of
145 surface sediments from the SE South American margin and suggested that sedimentation and
146 grain size distribution on the margins of Argentinian and Uruguayan is strongly controlled by
147 the oceanic circulation. The continental slope is composed of contourites, forming a large
148 Contourite Depositional System (CDS) composed of moats/channels, contouritic terraces,
149 abraded surfaces and sediment drift deposits (Urien and Ewing, 1974; Hernández-Molina et
150 al., 2009; 2016a; Krastel et al., 2011; Preu et al., 2012; 2013; Voigt et al., 2016; Warratz et al.,
151 2017; 2019). At the southern Argentine margin 4 terraces (i.e. relatively flat surfaces) are

152 present: Nágera Terrace at ~500 m depth, the Perito Moreno Terrace at ~1000 m depth, the
153 Piedra Buena Terrace at ~2500 m depth and the Valentin Feilberg Terrace at ~3500 m depth
154 (Hernández-Molina et al., 2009). Nágera Terrace, Perito Moreno and Valentin Feilberg
155 Terrace can be followed further to the north but in the northern part of the margin they are
156 known as La Plata Terrace at ~500 m depth, the Ewing Terrace at ~1200 m depth and the
157 Necochea Terrace at ~3500 m depth (Urien and Ewing, 1974; Preu et al., 2013). Seismic data
158 shows that the La Plata Terrace is much wider south of the MdP Canyon compared to the
159 north (Preu et al., 2013). The La Plata Terrace is deeper (~500 m) south of the MdP Canyon
160 compared to the north where it is located at shallower depth (~400 m) (Preu et al., 2013). Preu
161 et al. (2012) reconstructed the evolution of the internal stratigraphy of the Ewing Terrace in
162 close proximity of the MdP Canyon from Oligocene to modern times. Contourite terraces can
163 show depositional and erosional features and often correspond to the landward part of
164 plastered drifts (Hernández-Molina et al., 2016a; Thiéblemont et al., 2019). Part of the Ewing
165 Terrace is associated with plastered drifts at the basinward side, but at the La Plata Terrace
166 no plastered drifts could be recognised (Hernández-Molina et al., 2009; Preu et al., 2013).
167 Two channels were found in the landward side of the Ewing Terrace that were recently
168 reclassified as moats due to the evidence of sedimentation and its association with a
169 separated mounded drift (Fig. 2; Bozzano et al., 2011; 2020; Preu et al., 2012; 2013; Voigt et
170 al., 2013; Steinmann et al., 2020). Steinmann et al. (2020) described the southern moat for
171 the purpose of analysing cold-water corals in close proximity to this moat. In the moat, current
172 speeds decreasing from south to north between 3 and 52 cm/s have been reported
173 (Steinmann et al., 2020). Bozzano et al. (2020) described several morphological depressions
174 in which dropstones lie, possibly with an origin from the Antarctic Peninsula and Subantarctic
175 islands.

176 The prominent MdP Canyon crosses the Ewing Terrace between 1000 - 4000 m water
177 depth (Krastel et al., 2011). The canyon is disconnected from the continental shelf and it has
178 been excluded that it ever had a direct connection (Krastel et al., 2011). Turbidity currents in
179 the canyon were only active from the Last Glacial Maximum to the late deglacial (Warratz et

180 al., 2019). During sea-level high stands, most of the sediments from the Río de la Plata plume
181 were transported northwards and did not directly reach the zone around the MdP Canyon
182 (Razik et al., 2015a). The MdP Canyon acts in part as a sediment trap for sediments
183 transported along the Ewing Terrace by bottom currents (Voigt et al., 2013; Warratz et al.,
184 2019).

185

186 **3 Materials and methods**

187 **3.1 Oceanographic dataset**

188 Ocean velocities were measured with a 38 kHz vessel-mounted Acoustic Doppler Current
189 Profiler (VM-ADCP) during the R/V SONNE cruise SO260 in January-February 2018 (Kasten
190 et al., 2019). These short-term measurements are used to understand small-scale
191 oceanographic phenomena (e.g. eddies and local acceleration) and changes in bottom
192 currents that can be linked to the underlying morphology. However, these data cannot show
193 seasonal or interannual variations. The data were processed with the Cascade V7.2 software,
194 leading to a horizontal grid cell size of 1 km and vertical grid cell size of 16 m. For analyses of
195 the currents near the sea-surface, the average velocity between 50 and 150 m depth below
196 sea surface was calculated. For analyses of the near-bottom current the average velocity
197 between 150 and 350 m above seafloor was calculated. Below 150 m above seafloor the data
198 quality is too poor to be used with confidence (similar to Steinmann et al. (2020)). However,
199 Steinmann et al. (2020) showed that the selection of this level is a reasonable approximation
200 of bottom currents since, in this particular area, the vertical shear of the along-slope velocity
201 between these depths is low. The maximum range of the 38 kHz VM-ADCP system in this
202 area was about 1500 m. In areas where the seafloor lies below the range of the instrument
203 (e.g inside the MdP Canyon), no analyses of bottom currents is possible.

204 The Conductivity, Temperature and Depth (CTD) data were acquired using a Sea-Bird 9.11
205 plus and were used to identify the different water masses in the study area at the time of the
206 R/V SONNE cruise SO260 (Fig. 1) (Kasten et al., 2019). Typically, the CTD profiles were
207 collected to 50 m above the ocean floor.

208 The direct current observations are only useful to depict the circulation over a limited region
209 at the time of the cruise. To better understand the large-scale and long-term circulation we
210 use high-resolution ocean reanalysis. The Mercator Ocean reanalysis (GLORYS12) delivers
211 daily mean values (temperature, salinity, currents, sea-ice, and sea level) over the period
212 1993-2017 as part of the Copernicus Marine Environment Monitoring Service (CMEMS,
213 <http://marine.copernicus.eu/>) and assimilates measurements (Lellouche et al., 2018; Artana
214 et al., 2019a). The model uses the ETOPO bathymetry (Fig. S1 of the supplementary
215 material). The reanalysis was validated with direct observations including current
216 measurements at depth (Artana et al., 2018). The resolution of the model is $1/12^\circ$ in horizontal
217 and 50 vertical levels. In the 450 and 1400 m water depth range the model vertical resolution
218 varies between 80 and 200 m.

219

220 **3.2 Geological and geophysical dataset**

221 Multibeam bathymetry was acquired during cruise SO260 in 2018 with a hull-mounted
222 Kongsberg Simrad system EM122 operating at a nominal frequency of 12 kHz (swath opening
223 angle across track up to 150° , the opening angle of each beam is $0.5^\circ \times 1^\circ$, equidistant mode)
224 (Kasten et al., 2019). Processing and gridding were carried out using the open-source
225 software MB-Systems. This data set was used to construct a grid with a 25 m cell size for
226 detailed analysis of two moats in the study area. A combined grid with a 100 m resolution was
227 computed with MB-Systems (Fig. 2) using previously collected multibeam data acquired during
228 R/V Meteor cruise M78/3 in 2009 (Kongsberg Simrad system EM120) and R/V Meteor cruise
229 M49/2 in 2001 (Atlas Hydrosweep system DS2) for the analysis of the larger area. Data from
230 the GEBCO grid (General Bathymetric Chart of the Oceans; GEBCO Compilation Group
231 (2020); <https://www.gebco.net/>) at 15 arc-second intervals are used in areas where no
232 multibeam bathymetry is available. The resulting bathymetric grid has been visualised with the
233 open-source software QGIS (QGIS 3.12).

234 For detailed analyses of sub-bottom morpho-sedimentary features, we used sediment
235 echosounder data collected with a hull-mounted narrow-beam parametric PARASOUND P70

236 system during cruise SO260 (Kasten et al., 2019). The PARASOUND system makes use of
237 the parametric effect to produce a secondary low frequency based on two primary high
238 frequencies (for details, see Grant and Schreiber (1990)). For the analyses of the seafloor,
239 the secondary low frequency, which was set to 4 kHz, is used. This results in a vertical
240 resolution of a few decimetres. A despiking algorithm was applied to remove noise bursts from
241 crosstalk with other sounding systems using the software package 'VISTA Desktop Seismic
242 Data Processing Software' (Schlumberger). To enhance reflector coherency, the envelope
243 was calculated and visualised with 'The Kingdom Software' (IHS Markit).

244 The high-resolution multi-channel reflection seismic data set was acquired during R/V
245 Meteor Cruise M49/2 in 2001 (Spieß et al., 2002). The seismic data were previously analysed
246 in Preu et al. (2012) and Preu et al. (2013). In this study, the two longest available seismic
247 profiles on both sides of the MdP Canyon are used for a joint interpretation of the seafloor
248 sedimentary structures together with oceanographic results from model outputs. These
249 profiles are most representative because they cover the entire La Plata Terrace and Ewing
250 Terrace and are perpendicular to the flow direction making it easier to understand the geology
251 and oceanography together. Seismic profiles were acquired with an analogue streamer from
252 the University of Bremen. The streamer has 96 channels over a length of 600 m. As an
253 acoustic source, a 1.7 L GI-Gun (TMSODERA) with a main frequency of 100–500 Hz was
254 used. This results in a vertical resolution of a few metres. The data set was processed with
255 the software package 'VISTA Desktop Seismic Data Processing Software' (Schlumberger)
256 following standard seismic procedures including bandpass filtering and common mid-point
257 (CMP) binning. CMP bin size varies among profiles between 5 and 10 m depending on data
258 quality and coverage. After the CMP stacking a residual static correction and finite-difference
259 time migration was calculated (Preu et al., 2012; 2013). For interpretation of the data, the
260 software package 'The Kingdom Software' (IHS Markit) was used.

261 Sediment samples were collected during the R/V SONNE cruise SO260 and the R/V
262 Meteor cruise M78/3 using different sampling methods: giant box corer, multicorer, grab

263 sampler and gravity corer (Krastel and Wefer, 2012; Kasten et al., 2019). Grain size analyses
264 were performed on bulk sediment samples with a Beckman Coulter Laser LS 13 320 at
265 MARUM laboratories using Sodium hexametaphosphate as a dispersant. We also used grain
266 size measurements from previous studies to get a better understanding of the overall sediment
267 dynamics, which are available on PANGAEA (Frenz et al. (2003b)
268 <https://doi.pangaea.de/10.1594/PANGAEA.95396>; and Razik et al. (2015b)
269 <https://doi.org/10.1016/j.margeo.2015.03.001>).

270 **3.3 Nomenclature**

271 For classifying the different observed contouritic features, we follow the nomenclature of
272 Faugères et al. (1999), Stow et al. (2002b) and Rebesco et al. (2014). Plastered drifts are
273 usually located on a gentle slope and are characterised by a broad, slightly mounded and
274 convex geometry. They are associated with contourite terraces on the landward side, which
275 are relatively flat surfaces. The limits of the contouritic terraces are marked by a significant
276 increase in the slope gradient over a distance of several kilometres. In the seismic and
277 Parasound data the limits are further identified as either an abraded/erosion surface or a
278 transition to a plastered drift. Separated mounded drifts are more mounded than plastered
279 drifts and often associated with steeper slopes, from which they are detached by a distinct
280 erosional contourite channel or a non-depositional moat (Rebesco et al., 2014).

281 For the names of the different features in this region (e.g. terraces and canyons), we follow
282 the widely accepted nomenclature of previous papers that described these structures to some
283 extent (Urien and Ewing, 1974; Hernández-Molina et al., 2009; 2016a; Krastel et al., 2011;
284 Preu et al., 2012; 2013; Voigt et al., 2016; Warratz et al., 2017; 2019). The southern moat in
285 the study area was named Ewing Terrace Moat by Steinmann et al. (2020) and is here
286 referred to as Ewing Terrace Moat 1 (ET-Moat 1). As our study area extends further north and
287 includes a second moat located north of the MdP Canyon that is also up-slope the Ewing
288 Terrace, we named it Ewing Terrace Moat 2 (ET-Moat 2). The ET-Moat 2 was previously
289 named La Plata Terrace Moat (Bozzano et al., 2020). Since this moat is disconnected from

290 the La Plata Terrace by an erosional surface visible in seismic and Parasound data we find it
291 more accurate to name it ET-Moat 2. The term 'bottom current' is used in a general way for all
292 currents flowing near the seafloor and does not refer to any specific origin, flow direction or
293 velocity (Rebesco and Camerlenghi, 2008).

294

295 **4 Results**

296 **4.1 Modelled bottom currents**

297 Simulated bottom currents averaged over 25 years show that the dominant flow direction
298 is towards the N-NE (Figs. 3A and 4). The Malvinas Current affects most of the upper and
299 middle slope down to depths of about 1600 m south of the MdP Canyon and about 1300 m
300 north of the canyon (Figs. 3A and 5). In the model the Malvinas Current splits near the seafloor
301 (SW part of study area) into three branches, here referred to as MC 1, MC 2 and MC 3 (Figs.
302 3A and 5). The strongest mean bottom currents in the study area, reaching up to 25 cm/s, are
303 located at about 1000 m water depth in the zone where the Malvinas Current splits into three
304 branches (Fig. 3A). MC 1 flows along the shelf edge and upper slope (at 200 m water depth),
305 along the La Plata Terrace, with average near-bottom current speeds of 8 cm/s. MC 2 flows
306 along the slope (abraded surface ~700 m) connecting the La Plata Terrace and the Ewing
307 Terrace with an average speed of 8 cm/s (Figs. 3A and 5). MC 1 and 2 remerge downstream
308 of the La Plata Terrace, west of MdP Canyon. These inner branches of the Malvinas Current
309 (MC 1+2) flow in the NE direction to ~36°S. North of this latitude bottom currents are mainly
310 driven by the Brazil Current and flow south-eastwards at the shelf edge and upper slope (Fig.
311 3A). The deepest branch of the Malvinas Current (MC 3) flows northeastward along the Ewing
312 Terrace (~1200 m) and decreases in speed from 25 to 5 cm/s (over 60 km) as the terrace
313 widens and the slope orientation changes to north-south (Fig. 3A). The three Malvinas Current
314 branches observed near the seafloor do not always extend upwards to the sea surface. The
315 two offshore Malvinas Current branches flowing over the abraded surface (MC2) and over the
316 basinward limit of the Ewing Terrace (MC3) have their maximum northeastward velocity at
317 about 500 and 1000 m water depth, respectively, and their velocity sharply decreases towards

318 the sea surface (Fig. 5). Thus, the current velocity of MC2 and MC3 can be higher close to the
319 bottom than at shallower depths.

320 The Malvinas Current affects different water masses in the study area, based on model
321 results of the potential density: the SASW from the surface down to ~500 m water depth, the
322 AAIW from ~500 to ~1100 m and the UCDW below ~1100 m (Figs. 4 and 5). The shallowest
323 branch of the Malvinas Current (MC 1) contains SASW, while the intermediate branch (MC 2)
324 contains AAIW and the deepest branch (MC 3) is at the interface between the AAIW and the
325 UCDW (Figs. 4 and 5). The interface between the AAIW and the UCDW is located at the Ewing
326 Terrace (Fig. 4). On average all water masses (SASW and AAIW) over the La Plata Terrace
327 flow towards the N-NE (Fig. 4). Similarly, the mean bottom currents at the Ewing Terrace also
328 flow towards the N-NE (Figs. 3A and 4). The influence of the Brazil Current, which flows
329 towards the S-SE, is only noticeable close to the sea surface in the region above the Ewing
330 Terrace (Fig. 4). The MdP Canyon influences the bottom current flow direction, leading to
331 redirection of N-NE flowing water to the NE (Fig. 3B).

332

333 The standard deviation of modelled bottom currents over 25 years reaches 16 cm/s over
334 the abyssal plane below 4000 m water depth and is lower over the shelf edge and continental
335 slope, where it is mostly lower than 5 cm/s (Fig. 3B). The variability in flow speed on the La
336 Plata Terrace is lower than 5 cm/s. In contrast, the variability in flow speed over the Ewing
337 Terrace is up to 10 cm/s, being the highest on the offshore part of the terrace near the MdP
338 Canyon (Fig. 3A). High bottom current variability in this part of the Ewing Terrace is related to
339 changes in current direction and speed. Bottom currents modelled over one month (January-
340 February 2012) indicate that the deep branch of the Malvinas Current does not extend north
341 of 39°S. During that time the Ewing Terrace, and especially the offshore part at 1500-2000 m
342 water depth, is affected by southward-flowing bottom currents that exceed 35 cm/s. The
343 interaction of this southward flowing bottom current and of the MC 2 with the seafloor
344 topography results in the formation of a cyclonic eddy centred in the southern part of the Ewing
345 Terrace (Fig. 3C). In contrast, bottom currents over the La Plata Terrace show a similar pattern

346 during January-February 2012 compared the 25-year average, although bottom current
347 speeds are considerably higher during this short period of time, reaching 20 cm/s north of the
348 MdP Canyon (Fig. 3C).

349

350 **4.2 Direct current observations**

351 The VM-ADCP data close to the sea surface show generally a strong (>40 cm/s) northward
352 current in the region over the abraded surface connecting the La Plata Terrace with the Ewing
353 Terrace and the Ewing Terrace south of the MdP Canyon, corresponding to the Malvinas
354 Current (Fig. 6A). In the region above the deeper part of the MdP Canyon surface currents are
355 strong (>50 cm/s) and flow in a southward direction, corresponding to the Brazil Current. Over
356 the Ewing Terrace north of the MdP Canyon, the velocity is generally lower and the flow
357 direction is more variable compared to the region south of the MdP Canyon because it
358 corresponds to the confluence zone between the Malvinas and Brazil currents (Fig. 6A).

359

360 Generally, near-bottom currents are lower than surface currents (Fig. 6). Similar to the
361 reanalysis, stronger near-bottom currents were measured at the abraded surface and slower
362 currents over the contourite terraces (Fig. 6B). The speed over the Ewing Terrace south of the
363 MdP Canyon is higher (16 cm/s) than north of the MdP Canyon (11 cm/s) (Table 1). During
364 the cruise, the average speed over the abraded surface was 26 cm/s. Inside ET-Moat 1 and
365 ET-Moat 2 bottom currents were even higher, reaching average speeds of 30 and 31 cm/s
366 (Table 1). In all three locations, the velocity decreased northeastwards (Fig. 6). The average
367 measured near-bottom current inside the moats is very similar but the standard deviation in
368 ET-Moat 2 is almost twice as high as in ET-Moat 1 (Table 1). The velocity at the SW part of
369 ET-Moat 2 is higher than at ET-Moat 1. The velocity decreases faster in the northward direction
370 in ET-Moat 2 than it does in ET-Moat 1 (Fig. 6B).

371 Over ET-Moat 1 the velocity is higher close to the bottom (800-1000 m) than at mid-depth
372 (400-800 m) (Fig. 7A). In contrast, currents above the abraded surface generally decrease
373 with increasing depth (Fig. 7B). The profile perpendicular to the ET-Moat 1 confirms that the

374 higher velocity at depths is only a local feature within the moat and does not affect the entire
 375 water column (Fig. 8A). Furthermore, this profile shows lower velocities over the Ewing
 376 Terrace (Fig. 8A). The near-bottom flow at 7-15 km distance along the profile turns by 180°
 377 and thus flows southward. This flow reversal occurs only close to the seafloor and does not
 378 reach the sea surface (Fig. 8B). In this turn, the speed increases and is locally up to 20 cm/s
 379 near the seafloor (Fig. 8A).

380

381 Table 1: Average mean speed for different areas: the Ewing Terrace south and north of the
 382 MdP Canyon, the slope connecting the La Plata Terrace with the Ewing Terrace (abraded
 383 surface) and the moats south and north of the MdP Canyon (ET-Moat 1 and 2):

	Mean speed: ADCP measurement [cm/s]	Standard deviation: ADCP measurement [cm/s]
Ewing Terrace South	16	8
Ewing Terrace North	11	6
Abraded surface	26	11
ET-Moat 1 (south)	30	8
ET-Moat 2 (north)	31	15

384

385 **4.3 Seafloor morphology and sediment architecture**

386 The upper and middle slope of the northern Argentine continental margin are characterised
 387 by the presence of two contourite terraces separated by an abraded surface and a plastered
 388 drift associated with the deeper contourite terrace (Ewing Terrace) (Fig. 2). The La Plata
 389 Terrace is the shallowest contourite terrace. South of the MdP Canyon, it is located at 500-
 390 600 m water depth, has a width of ~40 km and an average slope of 0.3°. North of the MdP
 391 Canyon the width of the La Plata Terrace decreases drastically (Fig. 5A). The abraded surface
 392 that separates both terraces has a width of 25 km, an average slope of 0.7° and is
 393 characterised by truncations (Fig. 5B). The characteristics of the Ewing Terrace change north
 394 and south of the MdP Canyon. South of the MdP Canyon, it is located at 1000-1400 m,
 395 between the abraded surface and the plastered drift. The terrace deepens towards the MdP
 396 Canyon. It is ~40 km wide and has a convex morphology due to the presence of a mounded

397 deposit on top of the plastered drift that creates a topographic high. North of the MdP Canyon,
 398 the Ewing Terrace is located at 800-1400 m between the abraded surface landwards and the
 399 plastered drifts basinwards (Fig. 5A). It is ~70 km wide and has an average slope of 0.4°. The
 400 limit of the Ewing Terrace, that transitions into the plastered drift, is marked by an increase in
 401 slope, from 0.4° to >1° (Fig. 5).

402

403 Two moats and parallel separated mounded drifts are located at the landward side of the
 404 Ewing Terrace (Fig. 9). ET-Moat 1 is located in a much deeper water depth (~1150 m) than
 405 ET-Moat 2 (~775 m). Even though the moats are located in different water depths, they show
 406 several similarities regarding length (95 km in ET-Moat 1 and 70 km in ET-Moat 2), max. width
 407 (7 km in ET-Moat 1 and 6 km in ET-Moat 2 m) and max. depth relative to the basinward
 408 mounded drift (100 m in ET-Moat 1 and 90 m in ET-Moat 2) (Table 2). Both moats widen
 409 towards the N-NE and water depth increases in the same direction. However, the depth
 410 between the bottom of the moats and the top of the separated mounded drift increases
 411 northward for ET-Moat 1 and decreases for ET-Moat 2. Internal terraces and scours are only
 412 visible inside ET-Moat 1 (Figs. 9A and 10B).

413

414 Table 2: Key parameters of ET-Moat 1 (south of MdP Canyon) and ET-Moat 2 (north of MdP
 415 Canyon):

	ET-Moat 1	ET-Moat 2
Length (SW-NE direction)	95 km	70 km
Max. width (NW-SE direction)	7 km	6 km
Water depth	1000 - 1300 m	700 - 850 m
Max. depth relative to basinward mounded drift	100 m (deeper in NE)	90 m (deeper in SW)

416

417 South of the MdP Canyon, truncating parallel reflections are visible in the Parasound data
 418 within the abraded surface, as well as in the landward slope and in the deepest point of ET-
 419 Moat 1 (Fig. 10B). In contrast, north of the MdP Canyon, Parasound penetration in ET-Moat 2

420 and on its landward slope is very limited, and no reflections are recognised (Fig. 10A). Small
421 separated mounded drifts are identified associated with the moats and are located
422 basinwards. These contourite drifts become larger towards the N-NE (Figs. 9 and 10). The
423 mounded drift related to ET-Moat 1 shows continuous reflections with a sigmoidal to oblique,
424 landward progradation pattern (Fig. 10B). The bottom boundary of the separated mounded
425 drifts is characterised by a large erosive surface that affected the moat and part of the
426 contourite terrace. The separated mounded drift mainly developed in the space adjacent to
427 the moat previously generated by the erosion. Truncations inside the separated mounded drift
428 are abundant, suggesting frequent phases of erosion and drift construction. Adjacent to ET-
429 Moat 2 the reflections are continuous with a sigmoidal, landward progradation pattern (Fig.
430 10A). Further offshore of the contourite drift, a small unit with continuous reflections is
431 deposited on top of an erosional surface (Fig. 10A). On the Ewing Terrace south of the MdP
432 Canyon continuous reflections are imaged, sometimes interrupted by small erosional surfaces
433 close to the seafloor (Fig. 10B).

434

435 Sediment waves are at the seaward edge of the Ewing Terrace south of the MdP Canyon
436 (Fig. 9A). The crests of the sediment waves are oriented parallel to the slope and migrate
437 basinwards (up-slope). These sediment waves are on top of a drift crest located between the
438 Ewing Terrace and the plastered drift (Fig. 11C). The reflections of the sediment waves have
439 good lateral continuity. They are located on top of an unconformity (showing several truncating
440 reflections; Fig. 11A, B). The reflectivity below the sediment waves is generally low.

441

442 **4.4 Sediment samples**

443 The grain size of surface sediments in general decreases northwards and with increasing
444 depth. All analysed samples on the contourite terraces (excluding the moats) can be divided
445 in three regions with similar sediment grain size: La Plata Terrace, Ewing Terrace south of the
446 MdP Canyon and Ewing Terrace north of the MdP Canyon. The analyses show that the
447 median grain size is coarser on the La Plata Terrace (average median grain size of 78 μm)

448 and on the Ewing Terrace south of the MdP Canyon (average median grain size of 103.2 μm)
449 compared to the Ewing Terrace north of the MdP Canyon (average median grain size of 60.1
450 μm ; Fig. 12A). The grain size distribution on the La Plata Terrace is bimodal with a main mode
451 at 106 μm and a second mode at 27 μm , and it is poorly sorted with a standard deviation of
452 3.67 μm . On the Ewing Terrace south of the MdP Canyon, the grain size distribution typically
453 shows only one mode at 106 μm , and is poorly sorted with a standard deviation of 3.45 μm
454 (Fig. 12B). In contrast, north of the MdP Canyon, the grain size distribution is typically bimodal
455 with a main mode at 88 μm and a secondary mode at 20 μm , and it is poorly sorted with a
456 standard deviation of 3.64 μm . Sediment grain size in the moats is coarser and can reach
457 median values of 168 μm , but its variability is very high (Fig. 12C). Sediment sample 22712-3
458 (inside ET-Moat 1) also contains rock fragments with sizes up to 10 cm. Surface sediments in
459 the plastered drift and inside the MdP Canyon are much finer, with median grain sizes below
460 63 μm and percentages of sand below 60% (Fig. 12A).

461

462 **5 Discussion**

463 **5.1 Bottom current dynamics over the CDS**

464 The Brazil-Malvinas Confluence Zone is a very dynamic area, where southward flowing
465 water from the Brazil Current encounters northward flowing water from the Malvinas Current
466 (Fig. 1; Piola et al., 2018; Artana et al., 2019b; Piola and Matano, 2019). Current velocity
467 measurements can resolve local intensification of the current and the small eddies. This is
468 very important for linking oceanographic processes with sedimentary features. However, they
469 lack large-scale coverage and continuity over long periods of time, which is especially
470 important in a highly variable area like the confluence zone. This gap can be filled by numerical
471 modelling that allows us to extend our observations in space and time, and can thus improve
472 the understanding of long-term mean currents and short-term variability. This is especially
473 important to establish sediment patterns (here the CDS) in geological time scales. The long-
474 term reanalysis covers a period of 25 years, however, contourites are developed over several
475 thousands of years. Still, the model is very useful for understanding current dynamics since

476 the modern ocean circulation and stratification pattern was already established during the
477 Middle Miocene (Preu et al., 2012). Even though the ocean circulation has changed to some
478 extent in terms of strength or position since the Middle Miocene, but the patterns and
479 processes that form the CDS have remained similar.

480 In the present study, we focus our analysis on the near-bottom currents and discuss the
481 differences between currents near the seafloor and at the sea surface in the confluence zone.
482 Numerical simulations indicate that at the sea surface in the confluence zone, the Malvinas
483 Current splits into two branches: the outer branch veers offshore and mixes with the Brazil
484 Current, while the inner branch subducts below the Brazil Current (Artana et al., 2019b). The
485 model results show that on average the Brazil-Malvinas Confluence Zone between the
486 northward flowing and the southward flowing currents is located further south near the surface
487 (Fig. 3; Artana et al., 2019b). The Malvinas Current at 39°S near the seafloor further splits into
488 three branches that flow along the contourite terraces and over the abraded surface located
489 between the terraces, respectively (Fig. 14). The velocity of the two offshore Malvinas Current
490 branches in the confluence zone greatly decreases towards the sea surface (Fig. 5). Direct
491 measurements at 40-41°S indicate that the mean Malvinas Current has an equivalent
492 barotropic structure (Vivier and Provost, 1999). This usually indicates more homogeneous
493 velocities throughout the water column. Thus, the described changes in velocity within the
494 Malvinas Current might be connected to the interaction of the Malvinas Current with the Brazil
495 Current at the confluence and to the interaction with the seafloor morphology. An
496 intensification of near-bottom currents was observed in the VM-ADCP measurements
497 collected above ET-Moat 1 (Fig. 7A). In contrast, the branch of the Malvinas Current located
498 at the shelf edge (MC1) shows higher velocities near the surface and decreases with depth,
499 resulting in less impact on the seafloor morphology and sediment transport of the upper
500 continental slope (Fig. 5).

501 The Malvinas Current affects different water masses (Fig 4). Preu et al. (2013) identified
502 different water masses at the seafloor based on all available historical CTD data. The extent
503 of the NADW interaction with the seafloor based on the historical observations derived by Preu

504 et al. (2013) is in good agreement with the southward near-bottom flow determined by the
505 long-term average circulation derived from the ocean reanalysis (Fig. 13), suggesting that the
506 model depicts a realistic near-bottom circulation.

507 The VM-ADCP measurements show similar flow patterns as the 25-year averaged model
508 result but generally the measured speed is higher (Figs. 3 and 6), which might be expected
509 since it displays instantaneous measurements. Thus, the differences in speed probably reflect
510 the strong flow variability in the confluence zone. The 1-month simulation result (12/01/2012
511 to 14/02/2012) also shows higher bottom current velocity than the 25-year averaged model
512 result (Fig. 3). It highlights the variability not only in current speed but also in current direction.
513 When the Brazil Current is particularly strong, the flow direction over the Ewing Terrace can
514 turn towards the south (Fig. 3C). On a seasonal scale the speed of the Malvinas Current is
515 usually stronger during austral winter (June -Sep.) shifting the confluence further northward
516 (Saraceno et al., 2005), than during summer (Nov. -Feb.). However, Paniagua et al. (2018)
517 demonstrated that this is not always the case. They showed that the Malvinas Current was
518 significantly stronger from early January to mid-April 2015 compared to mid-April to mid-
519 August 2015 period. Even though these variations may not be relevant on a large scale, they
520 may lead to local intensification of bottom currents with important implications for sediment
521 transport (Fig. 3).

522

523 **5.2 Formation of sedimentary features**

524 Sediment dynamics

525 Generally, for a constant seafloor depth a decrease in near-bottom current speed is
526 observed from south to north in both modelled and measured currents (Figs. 3 and 6). This
527 agrees well with the northward decrease in sediment grain size of surface sediments (Fig.
528 12). Erosional surfaces and coarse grain size are generally an indication for strong bottom
529 currents and contourite deposition, whereas fine grain size is rather a sign for weak bottom
530 currents. In order to better understand whether the observed and modelled near-bottom
531 currents would be capable of eroding and transporting sediment, we calculated the bottom

532 shear stress ($\tau = \rho u_*^2$, with seawater density ρ and friction velocity u_*) from VM-ADCP
533 measurements. Observed bottom shear stresses reach critical shear stresses (0.13 -
534 0.17 N/m²) for the observed sediment grain sizes (60-130 μm ; according to critical shield
535 parameter for motion initiation proposed by (Soulsby and Whitehouse, 1997)) along the slope
536 between the La Plata Terrace and the Ewing Terrace, as well as along the moats (Fig. 6). This
537 shear stress corresponds to current velocities at 150 m above the seafloor over 30 cm/s,
538 assuming a logarithmic relation between the friction velocity and the variation of velocity with
539 height, a von Kármán constant equal to 0.4 and bottom roughness length equal to 0.0035 m
540 (Schlichting, 1962). This prediction of sediment erosion based on the bottom shear stress
541 agrees with the erosion visible in the Parasound data at the slope between the La Plata
542 Terrace and the Ewing Terrace as well as along the moats (Figs. 4, 5 and 10).

543

544 Some contouritic features are commonly related to mean flow velocity (Stow et al., 2009)
545 or the corresponding mean bottom shear stress (Schlichting, 1962; Soulsby and Whitehouse,
546 1997). But for further understanding sediment dynamics not only the mean velocity is relevant
547 but also the flow variability and secondary (smaller scale) processes (e.g. eddies) that can
548 increase bottom shear stress on the seafloor and control contouritic processes (Thran et al.,
549 2018; Chen et al., 2019). On the Ewing Terrace south of the MdP Canyon, we observed
550 erosional surfaces in the Parasound data even though the mean speed is low over the terrace
551 (Fig. 10). Internal acceleration due to a sloping morphology can lead to flow instabilities that
552 can lead to generation of waves and eddies (Rebesco et al., 2014; Zhang et al., 2016). This
553 phenomenon possibly occurs at the Ewing Terrace south of the MdP Canyon that is tilted
554 slightly towards the NE (Fig. 2). Furthermore, in this area the terrace width increases and thus
555 the contour current has more space to flow over the flat terrace (Fig. 2). The divergence of
556 isobaths may cause a decrease in the mean flow and also lead to the development of flow
557 instabilities. We propose that this sudden widening can lead to turbulences and eddies at the
558 seafloor, similar to water flowing out of a channel or a river mouth (Falcini and Jerolmack,
559 2010). This is also reflected by a slightly enhanced flow variability on the Ewing Terrace

560 compared to the La Plata Terrace (Fig. 3B). Furthermore, as previously described, during
561 times when the Malvinas Current is relatively weak, the flow direction over the Ewing Terrace
562 can turn towards the south at the basinwards edge (Fig. 3C). On the other hand, one branch
563 of the Malvinas Current (MC 2) flows northward along the abraded surface (landwards of the
564 Ewing Terrace). The opposite flow direction makes the occurrence of clockwise rotating eddies
565 likely. VM-ADCP measurements and hydrodynamic modelling results averaged over one
566 month confirm the presence of a cyclonic eddy on the Ewing Terrace (Figs. 3C and 8B). This
567 suggest that these eddies can lead to local erosion because shear stress can be much higher
568 in turbulent flow compared to laminar flow (Fig. 14; Schlichting and Gersten, 2016). However,
569 this change in flow direction was not observed at all ADCP profiles and is not apparent in the
570 model derived 25-year average bottom currents at the Ewing Terrace. Thus, these eddies may
571 be transient features and there are energetic periods during which the sediment is eroded,
572 alternating with calm periods during which sediment deposition is favoured. This variability in
573 bottom currents may also explain the absence of a clear erosional surface and the presence
574 of several small erosional surfaces at the Ewing Terrace (Fig. 11). These new observations
575 refine our understanding of the sediment dynamics in the vicinity of the MdP Canyon. The
576 depositional system located further south of this study area at $\sim 45^{\circ}\text{S}$ might be different
577 because of a more stable Malvinas Current with its main branch being located over the terrace
578 (Piola et al., 2013).

579

580 Moats and separated mounded drifts

581 Moats and paleomoats and the related separated mounded drifts are commonly used to
582 reconstruct bottom currents because they provide a clear indication for strong bottom currents
583 and their direction (Surlyk and Lykke-Andersen, 2007; Betzler et al., 2013). To make these
584 reconstructions more reliable, it is necessary to study the geomorphology of active moats
585 together with the characteristics of the flow regime. At the landward edge of the Ewing Terrace,
586 two up-slope migrating moats are located, each with an associated separated mounded drift
587 (Fig. 10). The separated mounded drifts have a sigmoidal reflection pattern. The morphology

588 of the observed separated mounded drifts is not typical for a drift associated with a moat
589 (Faugères et al., 1999; Stow et al., 2002a; Rebesco et al., 2014). In the separated mounded
590 drifts described here; the sigmoidal reflections terminate at the seaward side at one point.
591 Typically, the units between the reflectors become thinner leading to almost parallel, uniform
592 reflectors at the basinward side of the drift (Faugères et al., 1999; Stow et al., 2002a; Betzler
593 et al., 2013; Rebesco et al., 2014). The unusual depositional character is possibly connected
594 to the strong bottom currents, making it an erosive and very sandy and even gravelly moat,
595 and a silty-sandy separated mounded drift (Bozzano et al., 2011), while separated mounded
596 drifts related to moats are typically mud dominated (Rebesco et al., 2014; Miramontes et al.,
597 2016). The initiation for developing a moat might be connected to local eddies, as discussed
598 earlier. However, it is not clear yet how the development of moats initially starts and further
599 investigation is needed. Possibly, there are turbulences and small eddies occurring in the
600 moats that lead to erosion but these cannot be resolved by the presented model because of
601 a lack of higher resolution. For detailed understanding of flow patterns inside of the moat very
602 high-resolution numerical modelling of bottom currents is needed or extensive ADCP
603 measurements.

604 The available ADCP data show that bottom currents inside the moat increase locally (Fig.
605 8). Along and cross slope ADCP sections confirm that this increase in flow velocity is restricted
606 to the near-bottom currents inside the moat (Fig. 7). Thus, after the moat started to form it
607 affected the bottom currents, probably focusing bottom currents and leading to an increase in
608 velocity. Current speed standard deviation in ET-Moat 2 is almost twice as high as in ET-Moat
609 1 which could be due to a stronger decrease of speed in ET-Moat 2 and larger flow fluctuation
610 in shallower environments. Taking velocity fluctuations in turbulent flow into account (Inman,
611 1949), this may explain why the sediment is less sorted. ET-Moat 2 progressively widens
612 northwards, while ET-Moat 1 shows a sudden widening in its central zone towards the abraded
613 surface (Fig. 9). A scour is located at the edge where the moat suddenly widens (Fig. 9A). The
614 interaction of bottom currents with the edge on the slope possibly leads to the formation of
615 vortices and eddies that may have formed the observed scour inside the moat (Fig. 9A). This

616 process of cutting back of the slope can be an important factor responsible for widening the
617 contourite terrace. Furthermore, the ADCP data also show that as the moats widen northwards
618 the flow velocity decreases (Figs. 6 and 7). This has implications for the along-slope sediment
619 transport. Sediment transported in close proximity to ET-Moat 1 by the MC2 current branch
620 can be deposited at the MdP Canyon head and subsequently transported down the canyon
621 by turbidity currents (Warratz et al., 2019).

622

623 Drift crest

624 The modelled bottom currents averaged over 25 years show that the flow variability over
625 the La Plata Terrace is lower than over the Ewing Terrace. The highest flow variability is at
626 the basinward edge of the Ewing Terrace south of the MdP Canyon where MC3 drastically
627 decreases in speed (from 25 to 5 cm/s over 60 km) (Figs. 3B, 5B, 11E). The maximum
628 northward extent of MC3 fluctuates and is dependent on the strength of the Malvinas Current,
629 which can explain the higher variability in speed compared with the rest of the Ewing Terrace
630 (Fig. 3B). In this area a drift crest or morphologic high developed on the upper part of the
631 plastered drift (Figs. 9A, 11A, 14), possibly as a result of a weakening bottom current with
632 reduced sediment transport capacity, allowing deposition along its path. The decrease in
633 bottom current speed towards the north may also inhibit the transport of coarse sediment,
634 favouring its deposition and forming the observed drift crest, which is mainly composed of
635 sand, with a median grain size of 103 μm .

636

637 Sediment waves

638 The drift crest on the basinward edge of the Ewing Terrace is covered in part by several
639 sediment waves that migrate basinwards up-slope of the drift crest (Fig. 11). Sediment waves
640 can be formed by downslope flowing turbidity currents and along-slope flowing bottom
641 currents. The sediment waves discussed here are not associated with any downslope
642 submarine channel and they are thus not formed by turbidity currents. They are contouritic
643 sediment waves and part of the CDS. Flood (1988) proposed that the lee-wave mechanism

644 can form sediment waves under bottom currents. Lee-waves can develop within a bottom
645 current that flows over a wavy topography (Flood, 1988), but the sediment waves initiation
646 process is not well understood. In agreement with this theory, the sediment waves discussed
647 here are located at the lee side of the drift crest described before. This drift crest could possibly
648 lead to the development of the lee-waves. Flood (1988) assumed that the sediment waves are
649 perpendicular to the current direction. However, further theoretical analyses taking the Coriolis
650 force into account indicate that sediment waves under bottom currents can be oblique to the
651 flow direction (Blumsack and Weatherly, 1989; Hopfauf and Spieß, 2001). Oblique sediment
652 waves have been observed at several places (McCave, 2017). In this study we report on
653 sediment waves that are parallel to the direction of currents (Figs. 9, 11). This parallel
654 orientation to the flow direction seems unlikely to be explained by lee-waves alone. Thus, other
655 processes have to be taken into consideration. Previous research reported that internal waves
656 can form sediment waves and dunes (Hand, 1974; Reeder et al., 2011; Droghei et al., 2016;
657 Ribó et al., 2016; Reiche et al., 2018; Yin et al., 2019; Miramontes et al., 2020). Internal waves
658 can propagate at density discontinuities and have been previously proposed as a cause for
659 the development of the Ewing Terrace and the La Plata Terrace (Hernández-Molina et al.,
660 2009; Preu et al., 2013). The suggested mechanism is that the internal waves can propagate
661 at the interface of AAIW, UCDW and NADW, respectively. The sediment waves discussed
662 here are located slightly below the interface between the AAIW and the UCDW (Fig. 14).
663 Internal waves with an amplitude of up to 250 m have been reported in deep-sea environments
664 (Van Haren and Gostiaux, 2011). Possibly, part of the energy from the internal wave
665 propagating at the interface of AAIW/UCDW interacts with the northward bottom flow which
666 influences the deposition of sediment waves. The formation of these sediment waves was
667 initiated several thousands of years ago likely during times when the Malvinas Current was
668 stronger, for example during glacial times when the current was presumably stronger (e.g.
669 Voigt et al., 2013). However, the processes leading to the formation of sediment waves are
670 still not well understood.

671

672 Terrace formation

673 The initiation of the formation of the contouritic terraces was suggested by some authors to
674 be related to internal waves propagating at water mass interfaces (Hernández-Molina et al.,
675 2009; 2016b; Preu et al., 2013; Ercilla et al., 2016; Yin et al., 2019; Llave et al., 2020). Other
676 authors proposed that internal waves may be secondary processes that can form channels
677 and dune fields on contourite terraces, but are not responsible for the original formation of the
678 contourite terrace, which they argued is probably related to strong currents (Miramontes et al.,
679 2019; Miramontes et al., 2020). The model derived 25-year average bottom currents and the
680 near-bottom water mass distribution derived from CTD measurements confirm that the
681 contouritic terraces in the northern Argentine margin are roughly located at water mass
682 interfaces (Figs. 4 and 13; Preu et al., 2013). However, the modelled bottom currents averaged
683 over 25 years indicate that the La Plata Terrace is not located at the interface of Brazil Current
684 and AAIW as suggested by Preu et al. 2013, but at the interface of SASW and AAIW (Fig. 4).

685 It has also been suggested that contourite terraces in the Mediterranean Sea are located
686 in zones of relatively high geostrophic bottom currents, while plastered drifts are located in the
687 adjacent zone of less intense bottom currents (Miramontes et al., 2019). Strong currents are
688 observed and modelled only in the inner (landward) part of the contourite terraces, while the
689 central and external (basinward) parts are affected by weaker bottom currents, although with
690 a higher variability at the external (basinward) edge of the terrace (Figs. 3, 5 and 6). Modelled
691 and observed bottom currents are the weakest over the plastered drifts (Figs. 3, 5 and 6). This
692 current regime is also reflected in the general sediment stratigraphy of the Ewing Terrace
693 (Preu et al., 2012). The landward part, where high currents are present, shows more evidence
694 of erosion. As the water movement weakens towards the basinward side, more deposition is
695 possible and large plastered drifts form. On top of this general stratigraphy, secondary
696 deposits like separated mounded drifts, drift crests and sediment waves were deposited as
697 discussed before. We suggest that contourite terraces may have been initiated by erosion on
698 the slope generated by the (paleo) Malvinas Current that progressively cut the slope
699 landwards, widening the contourite terrace with time. The fact that the Argentine contourite

700 terraces are much wider and flatter than other terraces observed for instance in the
701 Mediterranean Sea (Ercilla et al., 2016; Miramontes et al., 2019), along the Mozambican
702 margin (Thiéblemont et al., 2019; Miramontes et al., 2020) and in the Makassar Strait
703 (Brackenridge et al., 2020) could be related to the higher speed of near-bottom currents as
704 part of the Malvinas Current. The particular flat morphology with an abrupt edge of the terraces
705 along the Argentine margin may favour the formation of internal waves at the terrace edge, in
706 a similar way as at the shelf break (Jackson et al., 2012) that could also favour sediment
707 transport and erosion along the terrace. These processes are however expected to be weaker
708 than on the upper slopes and at the shelf break because of the weaker density gradient (Fig.
709 1B). Up to date, no internal waves could be directly identified near the seafloor in the study
710 area. Magalhaes and da Silva (2017) analysed internal waves along the Malvinas Current with
711 multispectral satellite imagery and found that most of the internal waves are located south of
712 the study area in areas of submarine canyons. These internal waves propagate upstream of
713 the Malvinas Current (Magalhaes and da Silva, 2017) and are thus not perpendicular to the
714 slope. New *in situ* measurements and modelling studies would be necessary to determine the
715 role of internal waves in the formation of contourite terraces.

716

717 **5.3 Sediment origin and submarine transport**

718 The primary origin of sediment deposits in the study area was linked to a mountainous
719 origin and igneous source rock lithology from the Andes, transported by the Colorado and
720 Negro Rivers to the ocean (Razik et al., 2015a). The sediment is then transported northward
721 by along-slope bottom currents (Malvinas Current) and is finally deposited in the study area
722 forming the observed contourite depositional system. Part of the sediment transported along
723 the Ewing Terrace may reach the head of the MdP Canyon. The general decrease in
724 northward bottom current speed towards the MdP Canyon (Figs. 3 and 7) would favour the
725 accumulation of sediments at the canyon head that could be transported down canyon by
726 turbidity currents, in a similar way as longshore currents feeding shelf-incised submarine
727 canyons like the Monterrey Canyon (Paull et al., 2005) and the Cap Breton Canyon (Mazières

728 et al., 2014). Voigt et al. (2013) and Warratz et al. (2019) reported the absence of turbidites
729 during the Holocene and the presence of turbidites during deglacial and glacial periods, which
730 have the same composition as the sediments from the Ewing Terrace (Warratz et al., 2019).
731 This was previously linked to a variability in the nepheloid layer depending on the current
732 strength (Voigt et al., 2013; 2016; Warratz et al., 2019). Since sandy sediment is transported
733 mainly as bedload under the observed and modelled bottom current velocities and is not part
734 of the nepheloid layer, we propose that sediment transport associated with high velocity along-
735 slope bottom-current jets (here MC2) plays an important role in the sediment input to the MdP
736 Canyon head and is then transported downslope by turbidity currents. The presence of only
737 one major tributary to the MdP Canyon (Fig. 2; Krastel et al., 2011) also indicates a sediment
738 input coming from the canyon head rather than from the southern lateral side of the canyon.

739 Some previous studies focused more on the variability of the latitude of the confluence zone
740 and on the reconstruction of the strength of the Malvinas Current based on geological,
741 geophysical data and oceanographic data (Lumpkin and Garzoli, 2011; Preu et al., 2012;
742 2013; Voigt et al., 2013; 2016; Razik et al., 2015a; Artana et al., 2018; 2019a). It is important
743 to consider that the mean latitude of the confluence zone is not the same at the sea surface
744 and near the seafloor (Fig. 6). The reanalyses from Artana et al. (2019a) showed that the
745 strength of the Malvinas Current has not changed over the period of 1993-2017. A southward
746 shift of the mean confluence zone of 0.6 to 0.9° per decade was observed in recent times
747 (1992-2007) (Lumpkin and Garzoli, 2011). Thus, the shift in the confluence might be more
748 controlled by the Brazil Current. This southward trend of the confluence zone is expected to
749 continue with the present global warming due to anthropogenic climate change (de Souza et
750 al., 2019). This shift could possibly threaten the cold-water coral ecosystem on the Ewing
751 Terrace (Hebbeln et al., 2016; Steinmann et al., 2020).

752 The frequency of turbidity currents in the MdP Canyon is linked to the strength of the
753 Malvinas Current. After the last glacial maximum, when the climate became generally warmer
754 and sea level rose, the Malvinas Current became weaker on average (Preu et al., 2013; Voigt
755 et al., 2013; Warratz et al., 2019). These weaker currents can only transport finer sediment

756 and thus probably transported less sediment into the study area leading to a lower
757 sedimentation rate and fewer turbidites in the MdP Canyon (Voigt et al., 2013; 2016; Warratz
758 et al., 2019). The described onset of sediment wave deposition on the Ewing Terrace possibly
759 started in this calmer environment (Fig. 11).

760

761 **6 Conclusions**

762 This study represents a step forward in understanding the sediment dynamics in proximity
763 to the Mar del Plata (MdP) submarine Canyon at the northern Argentine Margin by combining
764 geophysical and sedimentological datasets (multibeam bathymetry, seismo-acoustic data and
765 sediment cores) with oceanographic datasets (vessel-mounted ADCP measurements, CTD
766 data and ocean reanalysis). Overall, this study contributes to a better understanding of the
767 formation of contourite depositional systems and can help future reconstructions of past ocean
768 conditions based on sedimentary structures. The main conclusions can be summarized as
769 follows:

- 770 • Measured and modelled current data show that in close proximity to the MdP Canyon,
771 the Malvinas Current dominates the sediment dynamics at the seafloor. We propose
772 that sediment transport associated with high-velocity along-slope bottom-current jets
773 plays an important role in supplying sediments to the MdP Canyon head similarly to
774 longshore currents feeding shelf-incised submarine canyons. The moat of the Ewing
775 Terrace is possibly also a pathway for sediment transport to the MdP Canyon head.
- 776 • ADCP measurements together with the 25-year reanalysis of ocean currents show a
777 northward decrease of the northward-flowing waters. This decrease in speed leads to
778 less erosion and the accumulation of finer sediment deposits north of the MdP Canyon,
779 as observed in the surface sediment samples.
- 780 • Modelling results indicate that near the seafloor the Malvinas Current splits into 3
781 branches (at ~39°S). The shallowest branch (MC1) flows along the upper slope of the
782 La Plata Terrace and continues flowing below the Brazil Current until ~36° S. MC2 flows

783 along the abraded surface connecting the La Plata and Ewing Terrace. The offshore
784 branch (MC3) flows at the basinward edge of the Ewing Terrace and drastically
785 decreases in speed south of the MdP Canyon.

786 • The decrease in speed of branch MC3 reduces sediment transport capacity, which
787 therefore allows deposition along its path and possibly leads to the formation of the
788 observed drift crest. Downstream of the drift crest sediment waves with a parallel
789 orientation to the flow direction are deposited.

790 • Measured and modelled near-bottom currents are strong (up to 63 cm/s at 150 - 350 m
791 above the seafloor) where abraded surfaces and moats are present, and weak (lower
792 than 30 cm/s) on the La Plata Terrace and the Ewing Terrace. The strong bottom
793 currents generate the moats located at the landward slope of the Ewing Terrace that
794 are very sandy and even gravelly. In the moats, an intensification in flow velocity was
795 measured and an up-slope migration observed. We suggest that contourite terraces
796 may have been initiated by erosion on the slope generated by the (paleo) Malvinas
797 Current that would progressively cut the slope landwards, widening the contourite
798 terrace with time.

799 • The divergence of isobaths at the terraces possibly explains the measured and
800 modelled weaker near-bottom currents on the La Plata Terrace and the Ewing Terrace.
801 Together with the sloping morphology of the Ewing Terrace this can lead to flow
802 instabilities near the seafloor. We suggest that this effect leads to local cyclonic eddies
803 near the seafloor, which have also been measured and modelled. We propose that
804 these eddies are transient and can cause local erosion only during energetic periods.
805 The alternation between sediment deposition and erosion may also explain the absence
806 of a clear large-scale erosional surface and the presence of several small erosional
807 surfaces at the Ewing Terrace.

808

809

810 **7 Data Availability**

811 The ADCP data and surface grain size analyses used in this paper will be made available at
812 PANGAEA database (www.pangaea.de). Modelled data is freely available from the
813 Copernicus Marine Environment Monitoring Service (CMEMS, <http://marine.copernicus.eu/>).

814

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828

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1096

1097 **Figure captions**

1098

1099 Fig. 1. (A) Regional bathymetric map showing the SE American margin. The arrows indicate
1100 the general circulation pattern of the cold Malvinas Current, the warm Brazil Current and
1101 their confluence. (B/C) Potential temperature versus Salinity/Oxygen based on CTD data
1102 collected during Cruise SO260 that allowed the identification of different water masses:
1103 SASW: Subantarctic Surface Water, SACW: South Atlantic Central Water, AAIW: Antarctic
1104 Intermediate Water, UCDW: Upper Circumpolar Deep Water. σ_0 : potential density anomaly.

1105

1106 Fig. 2. Bathymetric map of the study area showing the location of the main morphological
1107 and contouritic features, sediment cores, CTD stations, seismic and Parasound profiles. The
1108 first contour line at 200 m indicates the approximate location of the continental shelf break.
1109 The deeper contour lines are every 500 m. (See Fig. 1 for location)

1110

1111 Fig. 3. (A) Modelled mean bottom velocity; (B) model standard deviation $\underline{\sigma} (= \sqrt{EKE})$ of over 25
1112 years; and (C) Modelled mean bottom velocity from 12/01/2012 to 14/02/2012. Note that the scale
1113 for the speed and the standard deviation is not the same. MC 1-3 refers to three branches of the
1114 Malvinas Current near the seafloor.

1115

1116 Fig. 4. Cross-sections of the hydrodynamic model showing the 25-year mean flow direction
1117 in combination with seismic sections. The white dashed lines indicate the interface of water
1118 masses calculated based on the potential density anomaly (SASW: Subantarctic Surface
1119 Water, SACW: South Atlantic Central Water, AAIW: Antarctic Intermediate Water, UCDW:

1120 Upper Circumpolar Deep Water). The location of the cross-sections is shown in Figs. 2 and
1121 4. (A) Seismic section GeoB01-141 located north of MdP Canyon and (B) GeoB01-135
1122 located south of MdP Canyon (modified from Preu et al. (2012; 2013)).

1123

1124 Fig. 5. Cross-sections of the hydrodynamic model showing the 25-year mean speed in
1125 combination with seismic sections. The white dashed line indicates the border between
1126 southward and northward-flowing currents (see Fig. 5). The location of the cross-sections is
1127 shown in Figs. 2 and 4. (A) Seismic section GeoB01-141 located north of MdP Canyon and
1128 (B) GeoB01-135 located south of MdP Canyon (modified from Preu et al. (2012; 2013)).

1129

1130 Fig. 6. (A) Near-surface velocity from ADCP data averaged between 50 to 150 m below sea
1131 surface. (B) Near-bottom velocity from ADCP data averaged between 150 to 350 m above
1132 the seafloor. Yellow arrows indicate the modelled mean bottom current velocity over 8 cm/s.

1133

1134 Fig. 7. (A) ADCP cross-section showing the speed over and parallel to ET-Moat 1 and (B)
1135 ADCP cross-section parallel to the slope connecting the La Plata Terrace with the Ewing
1136 Terrace. The sections are parallel to each other. See Fig. 2 for location.

1137

1138 Fig. 8. (A) ADCP cross-section showing the speed across the southern Ewing Terrace in
1139 combination with Parasound data. Note that ADCP data and Parasound data are not in the
1140 same vertical scale (B) ADCP cross-section showing the current flow direction with arrows.
1141 The speed corresponds to the length of the vectors. An average mean velocity over 50 m is
1142 shown every 100 m below the sea surface. See Fig. 2 for location.

1143

1144 Fig. 9. Bathymetric map of the Ewing Terrace showing the main small-scale features: moats,
1145 separated mounded drifts, sediment waves and drift crest (A) south and (B) north of the MdP
1146 Canyon.

1147

1148 Fig. 10. Parasound data showing (A) Ewing Terrace Moat 2 north of MdP Canyon and (B)
1149 Ewing Terrace Moat 1 south of MdP Canyon. See Fig. 10D for location. (C) Mean speed and
1150 (D) standard deviation of modelled bottom currents.

1151

1152 Fig. 11. (A)(B)(C) Parasound data showing S-SE edge of southern Erwin Terrace (south of
1153 MdP Canyon). See Fig. 11E for location. (D) Mean speed and (E) standard deviation of
1154 modelled bottom currents.

1155

1156 Fig. 12. (A) Median grain size of all the bulk sediment samples collected in this study
1157 (circles), median grain size of the terrigenous fraction (diamonds, Razik et al., 2015) and
1158 percentage of sand of the bulk surface sediment (triangles, Frenz et al., 2003). (B) Grain
1159 size distribution of three samples located on the contourite terraces. (C) Grain-size
1160 distribution of two samples located inside of the two moats.

1161

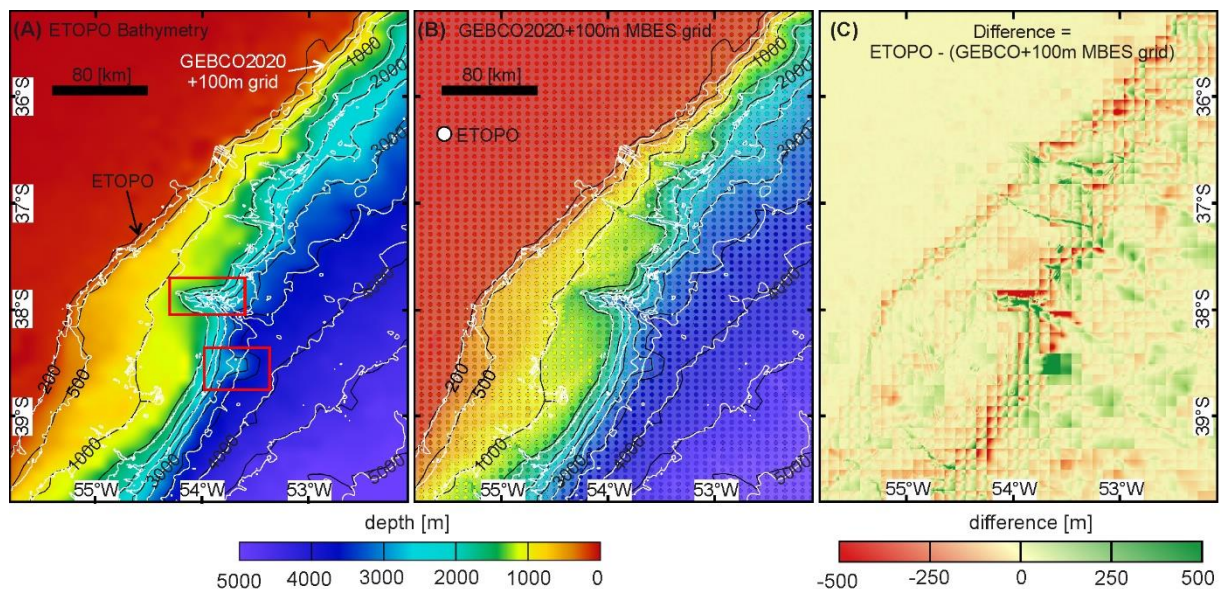
1162 Fig. 13: Modelled bottom current velocity (over 25 years) together with an illustration of the
1163 water masses (identified from CTD data) at the seafloor (adapted from Preu et al. (2013)).

1164

1165 Fig. 14. Conceptual model of the main bottom currents and associated contouritic features in
1166 the study area. The approximate water mass interfaces in this region are indicated (after
1167 Preu et al., 2013; Kasten et al., 2019; Piola and Matano, 2019). MC: Malvinas Current, SW:
1168 Surface Water, AAIW: Antarctic Intermediate Water, UCDW: Upper Circumpolar Deep
1169 Water, NADW: North Atlantic Deep Water.

1 Supplementary material

2 For the analyses of model bottom currents, the underlying bathymetry plays a vital part because the
 3 currents interact with the seafloor morphology. There are generally no major differences between the
 4 ETOPO Bathymetry used for the Model (Fig. S1 A) and the GEBCO Bathymetry combined with the 100-
 5 m grid measured with a Multibeam Echosounder (MBES) used for the geomorphological analysis (Fig.
 6 S1 B). The comparison of the isobaths calculated from the different grids shows generally the same
 7 structure. On the shelf, both grids are similar, and in the study area (450 to 1400 m water depth), the
 8 differences are only minor. Because of the lower resolution of the ETOPO grid, the steep slopes cannot
 9 be resolved with the same details and the canyons are slightly wider (Fig. S1 C).



10

11 Fig. S1: (A) ETOPO Bathymetry used for the Model. The red boxes indicate differences between
 12 isobaths calculated from ETOPO Bathymetry and of GEBCO Bathymetry combined with the 100-m grid
 13 measured with a Multibeam Echosounder (MBES). (B) Comparison between the GEBCO Bathymetry
 14 combined with the 100 m grid and ETOPO Bathymetry (coloured dots). (C) Difference between the
 15 ETOPO Bathymetry and the GEBCO Bathymetry combined with the 100-m grid.

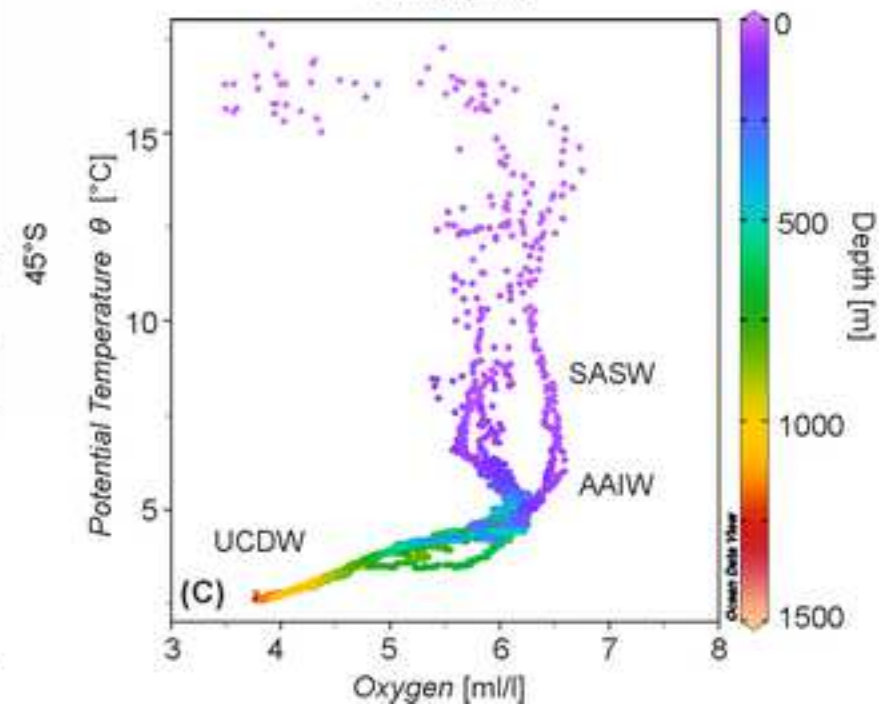
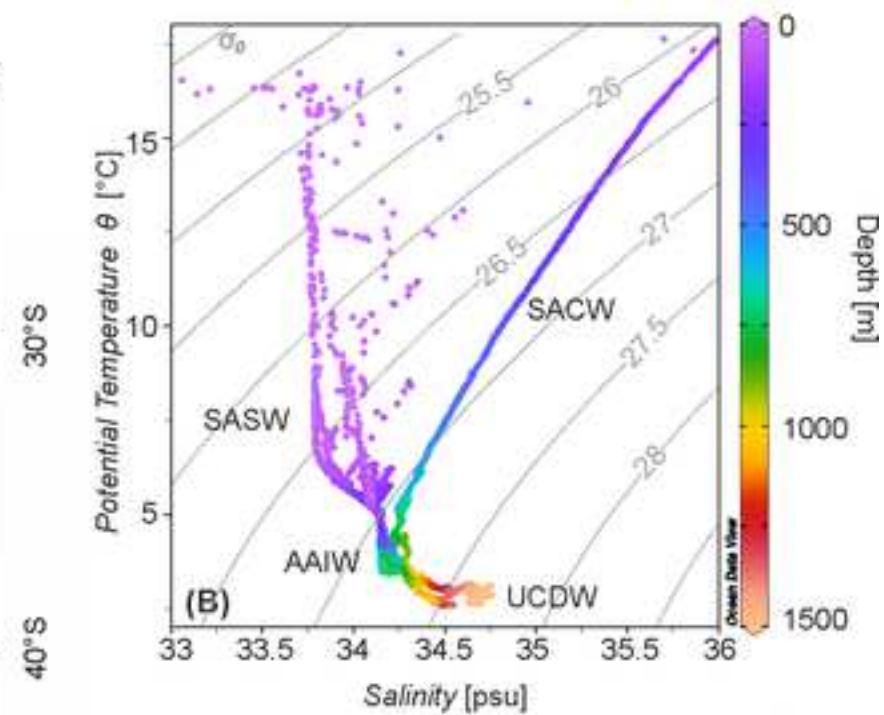
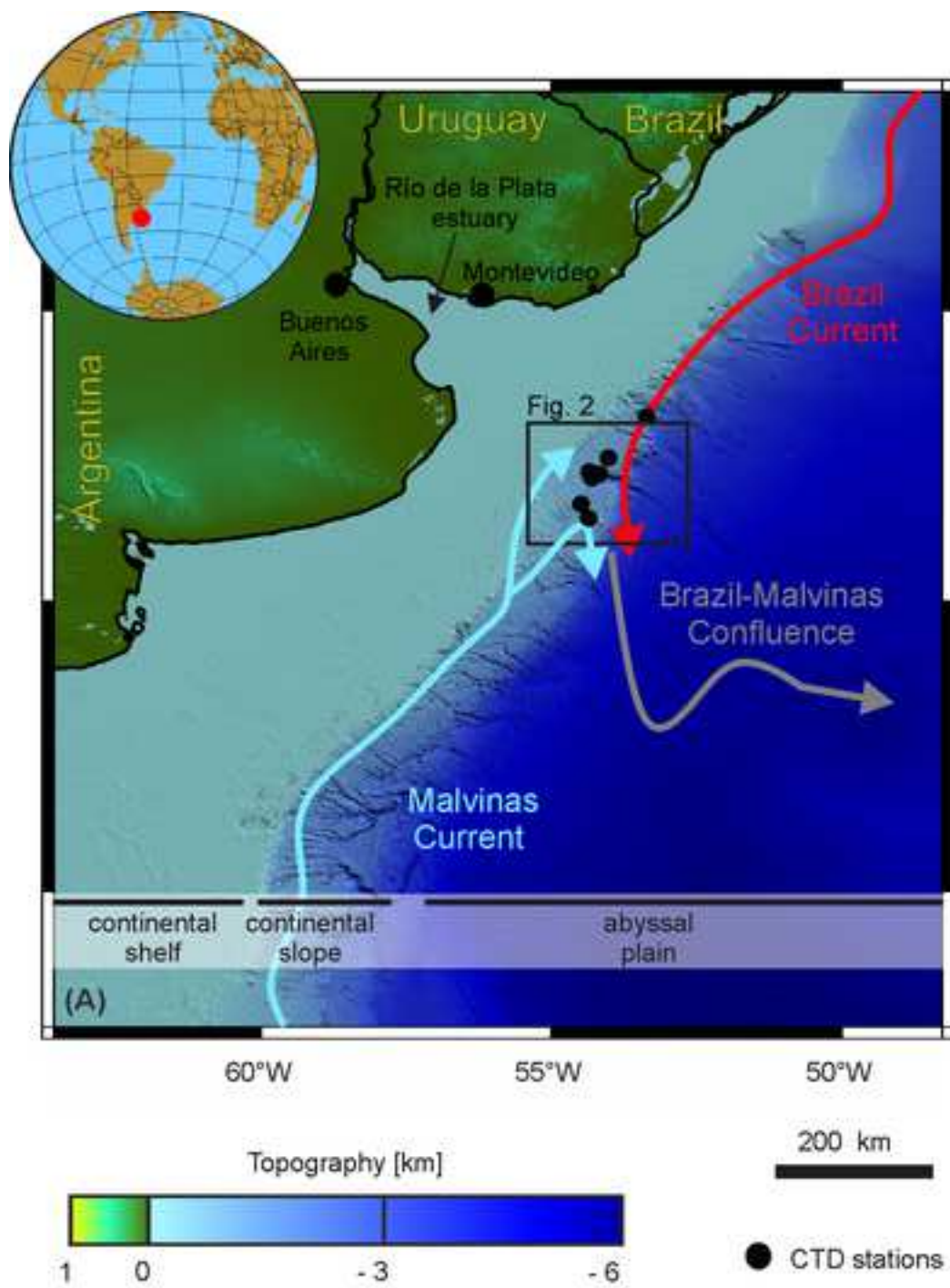
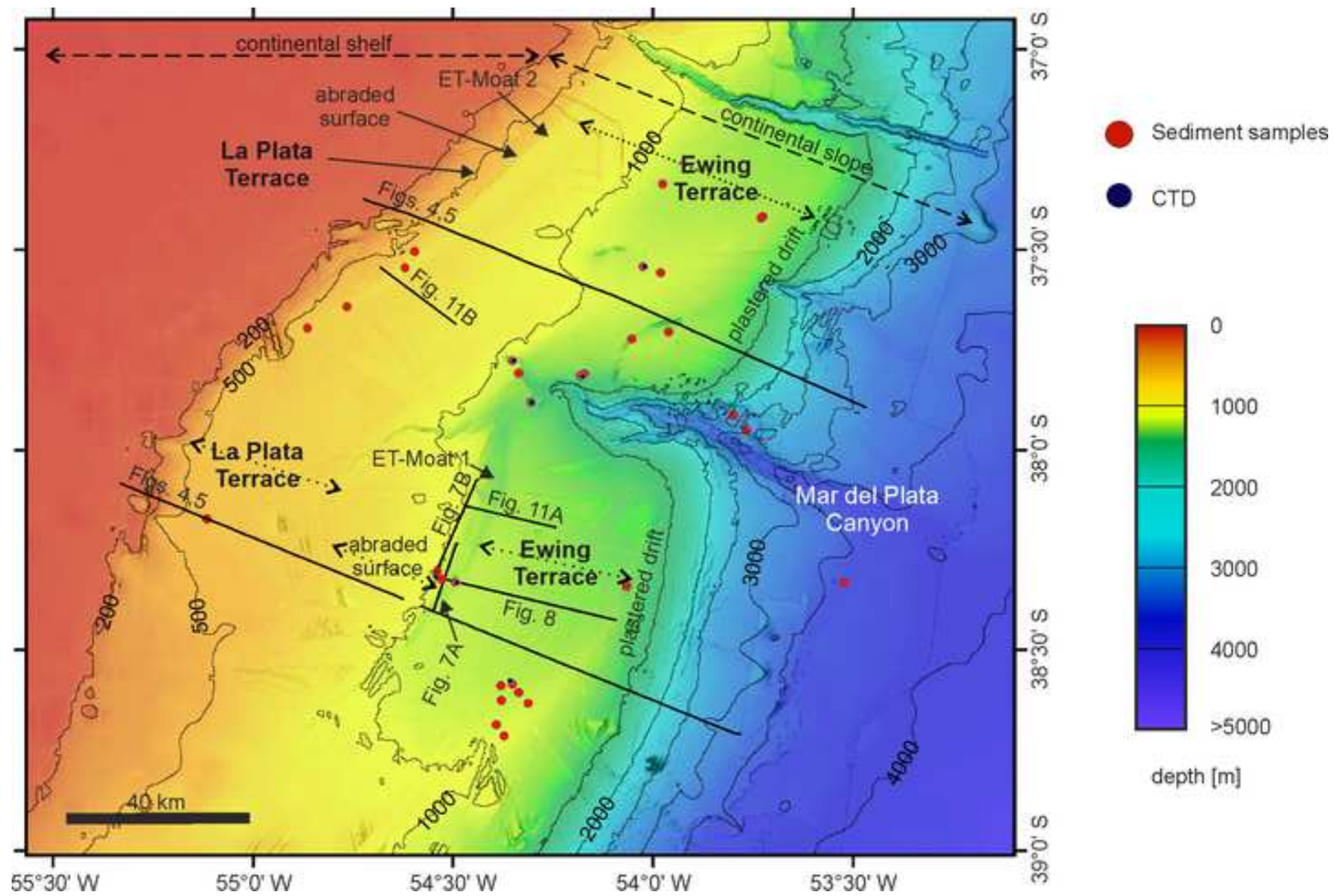
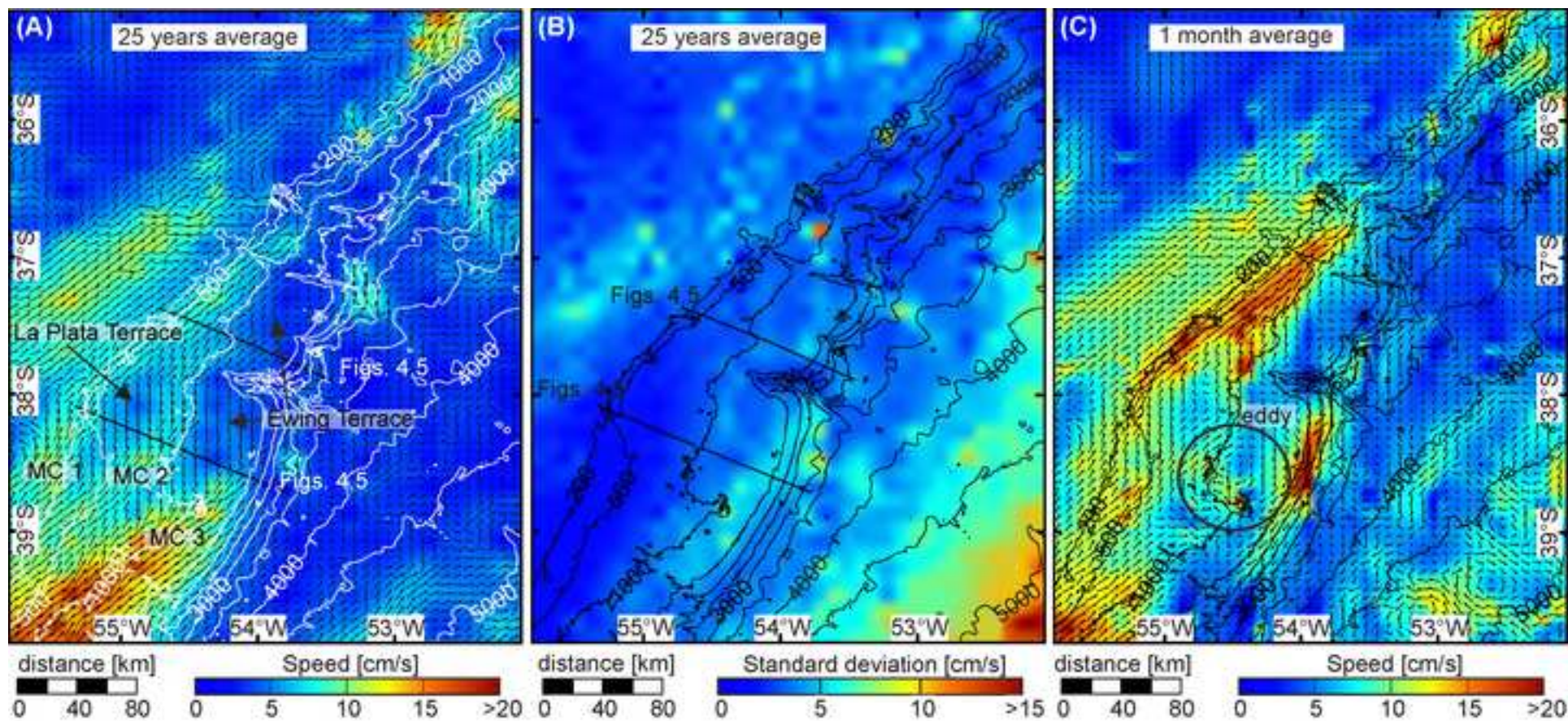
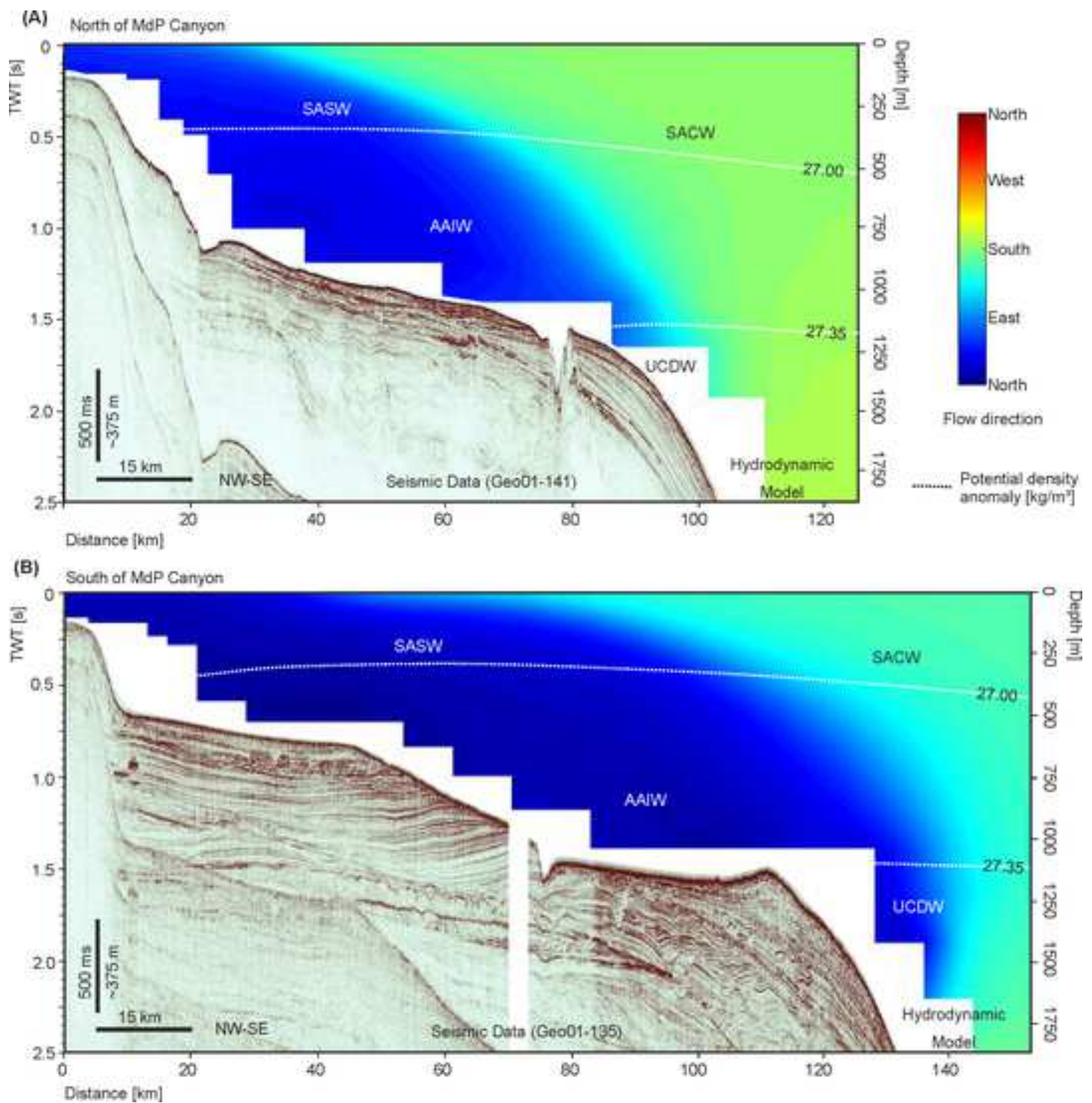


Figure 2

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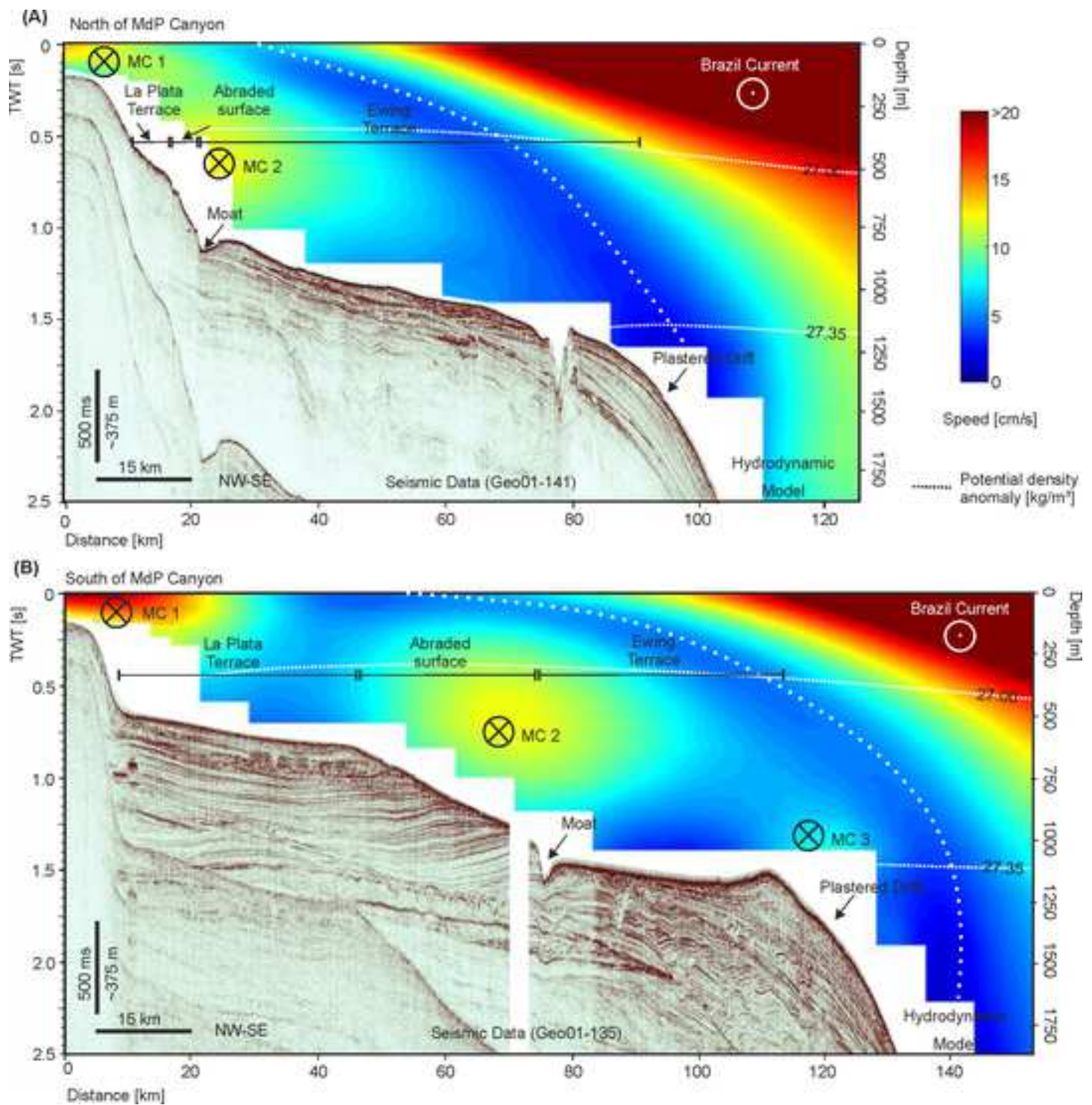
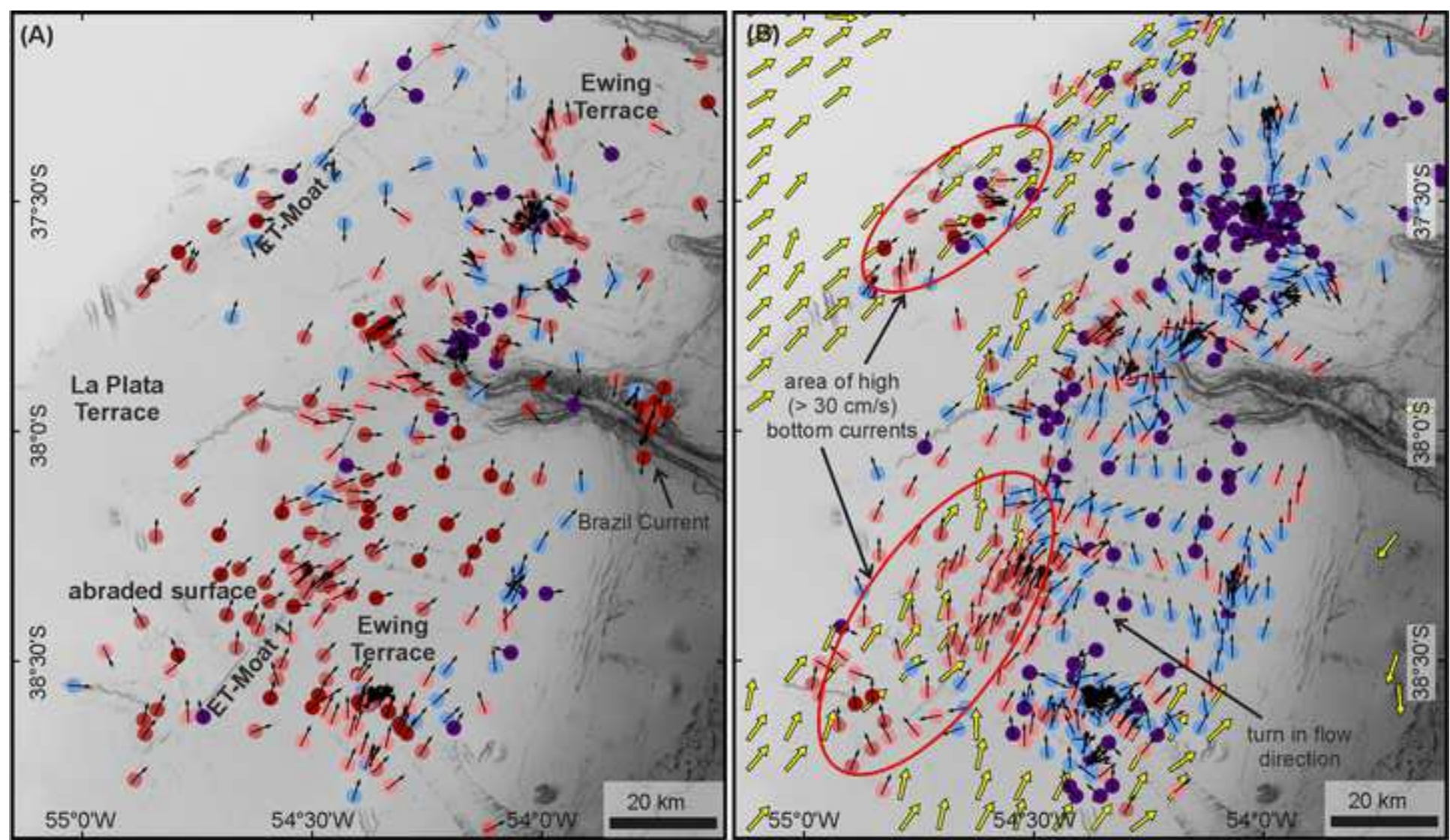


Figure 6



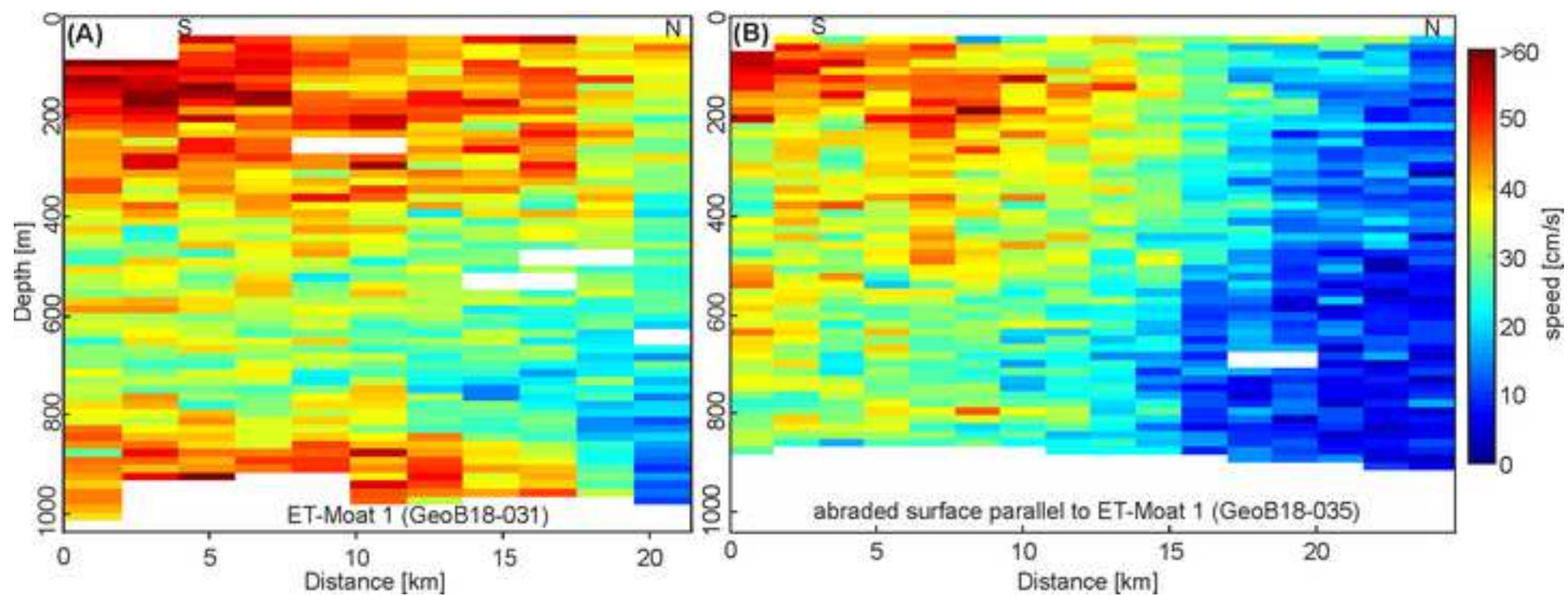
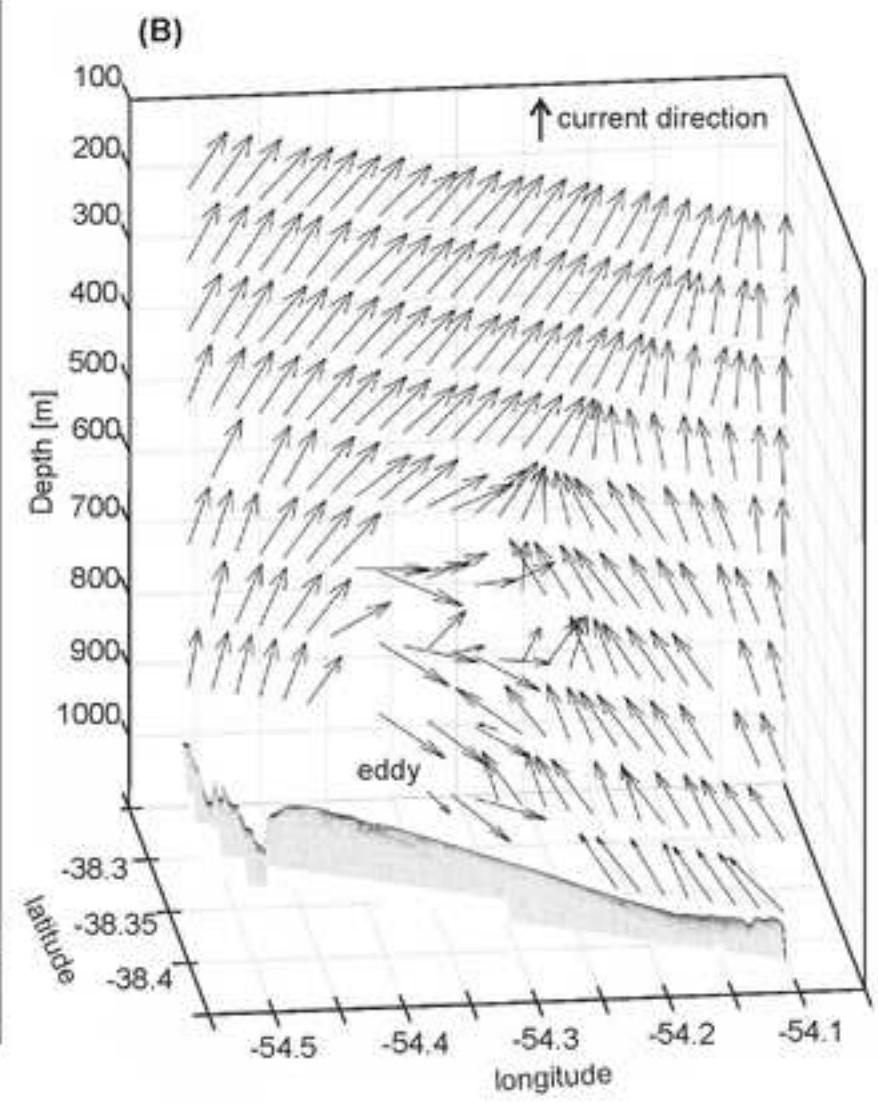
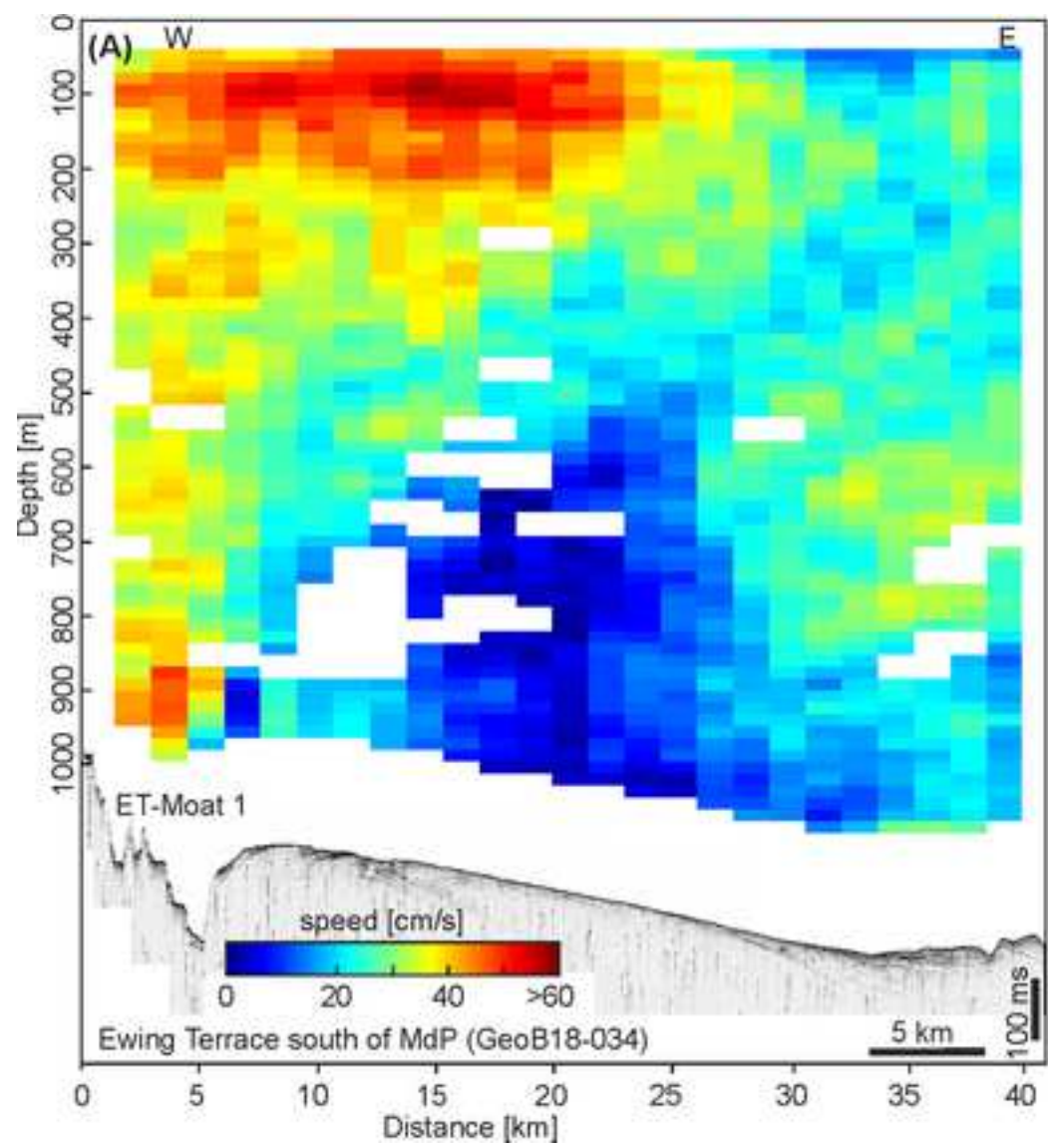


Figure 8



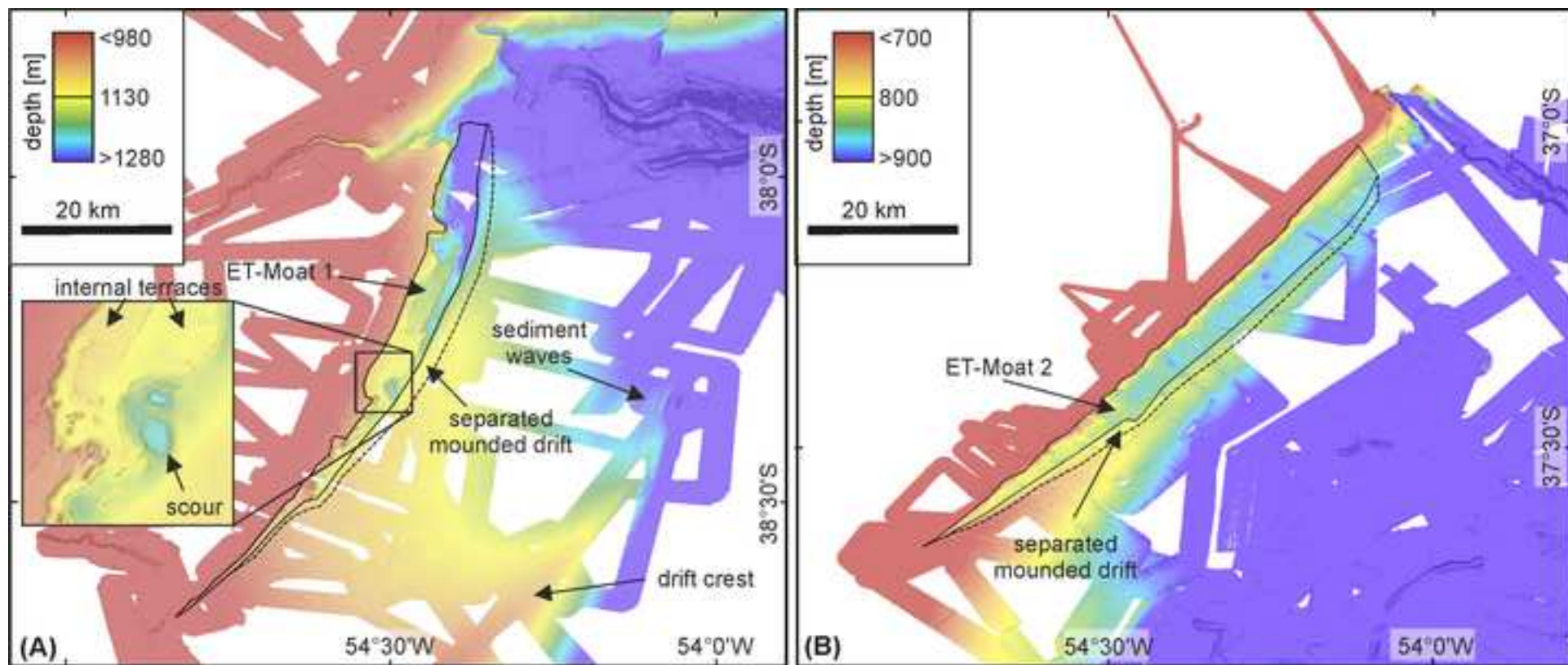


Figure 10

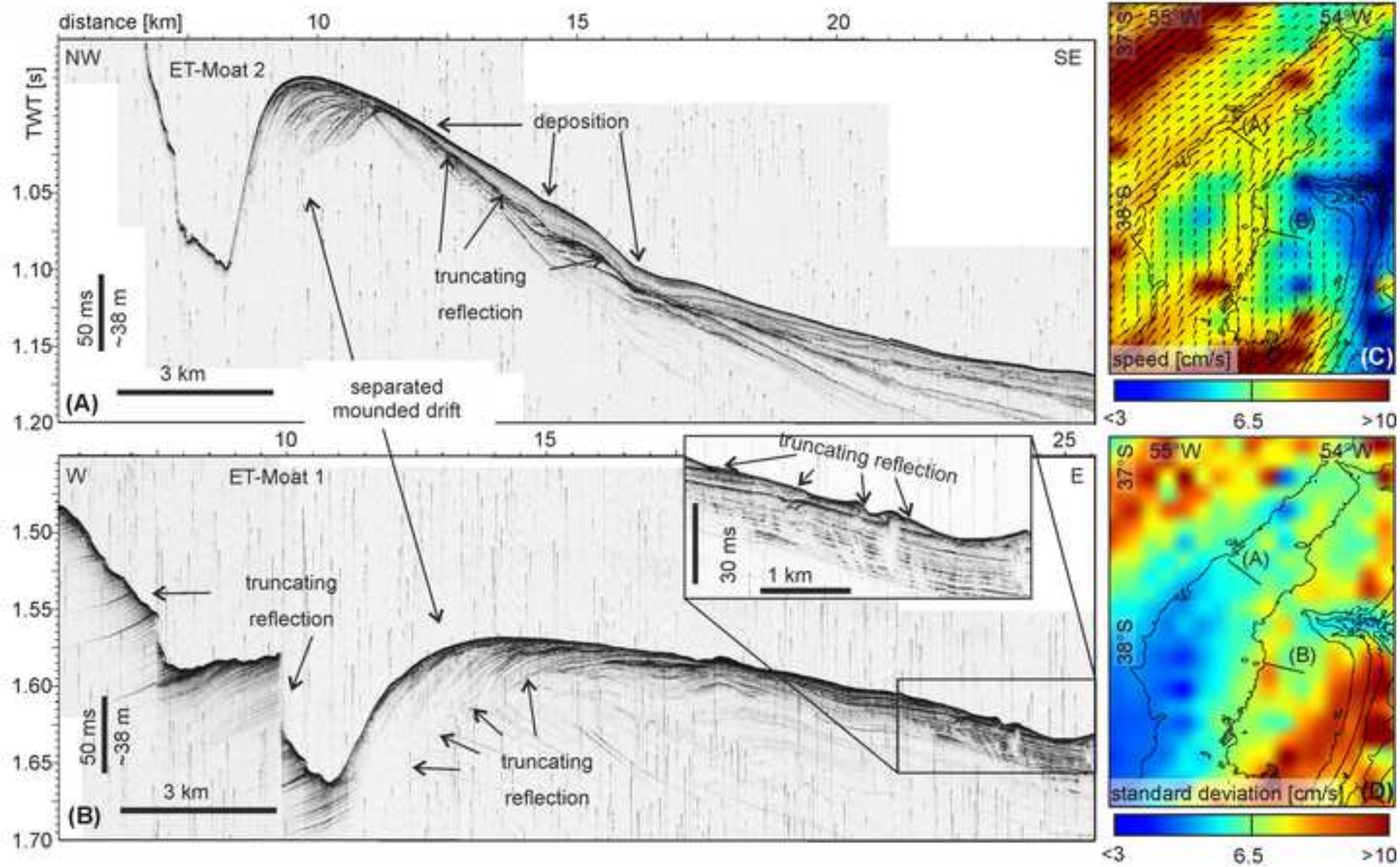
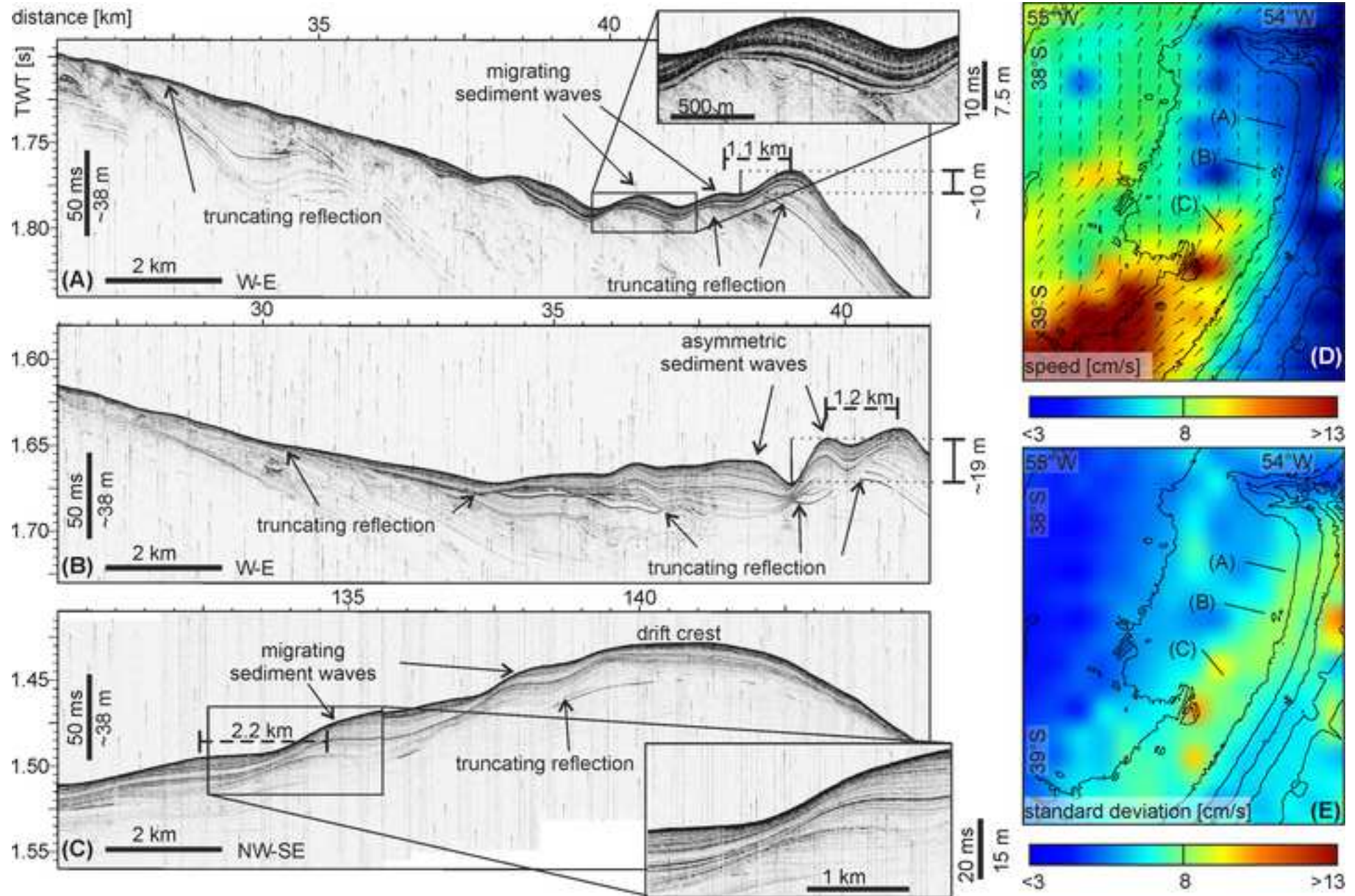


Figure 11



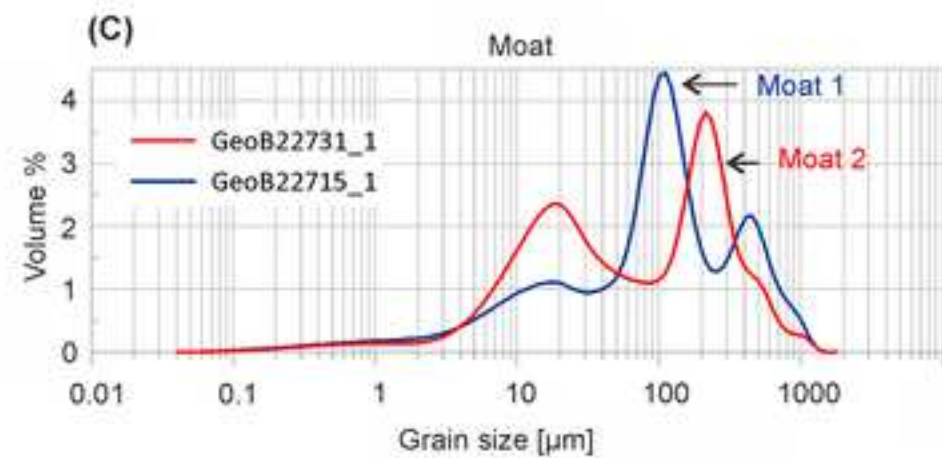
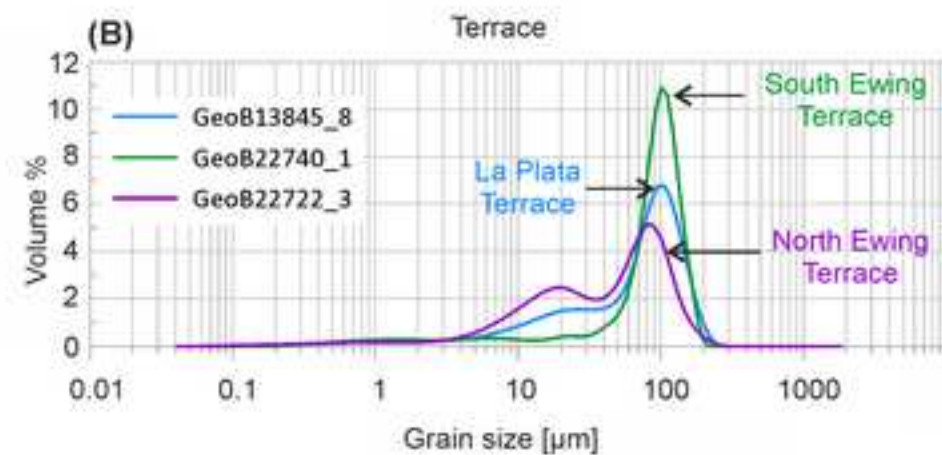
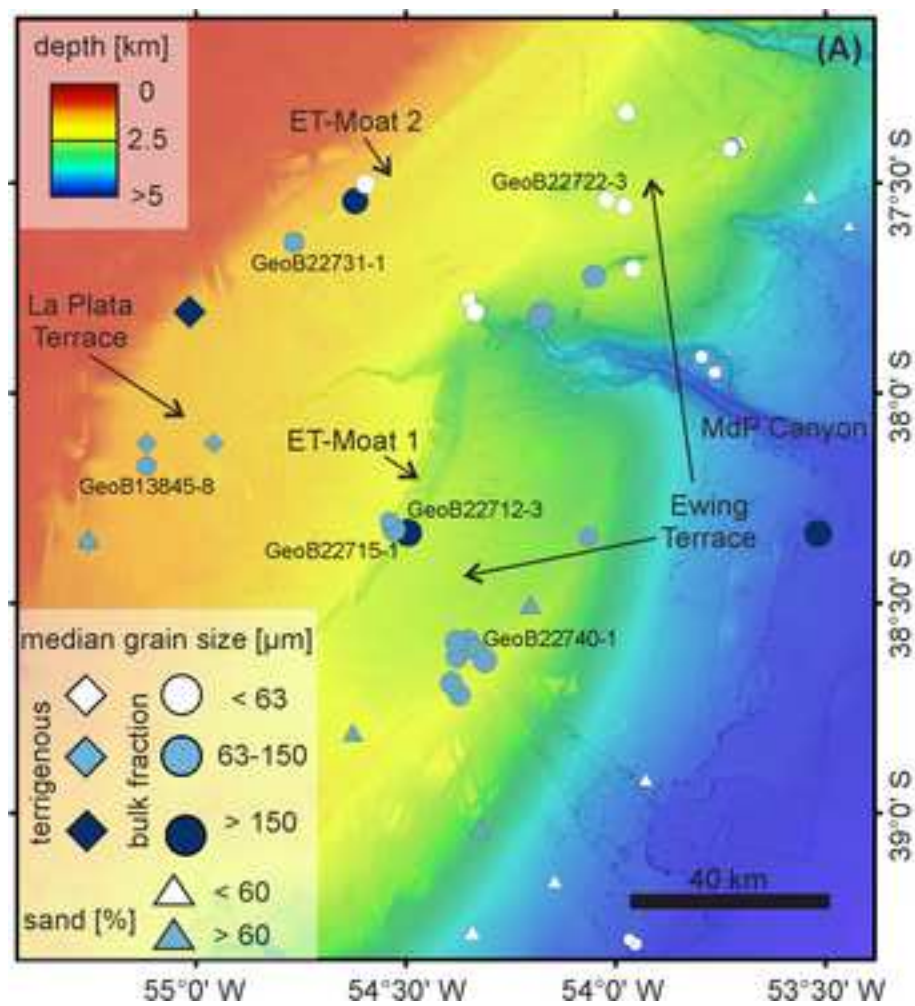


Figure 13

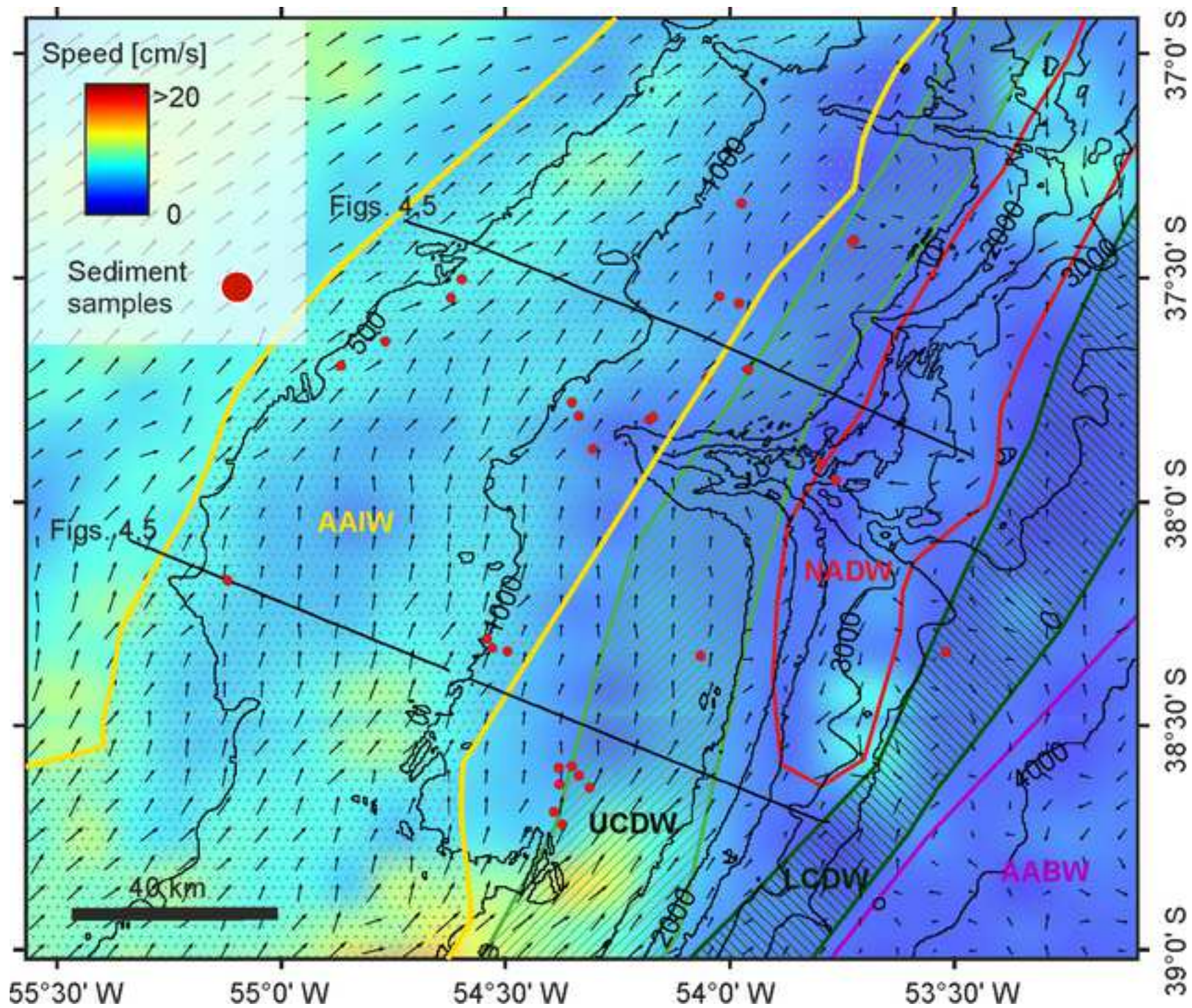
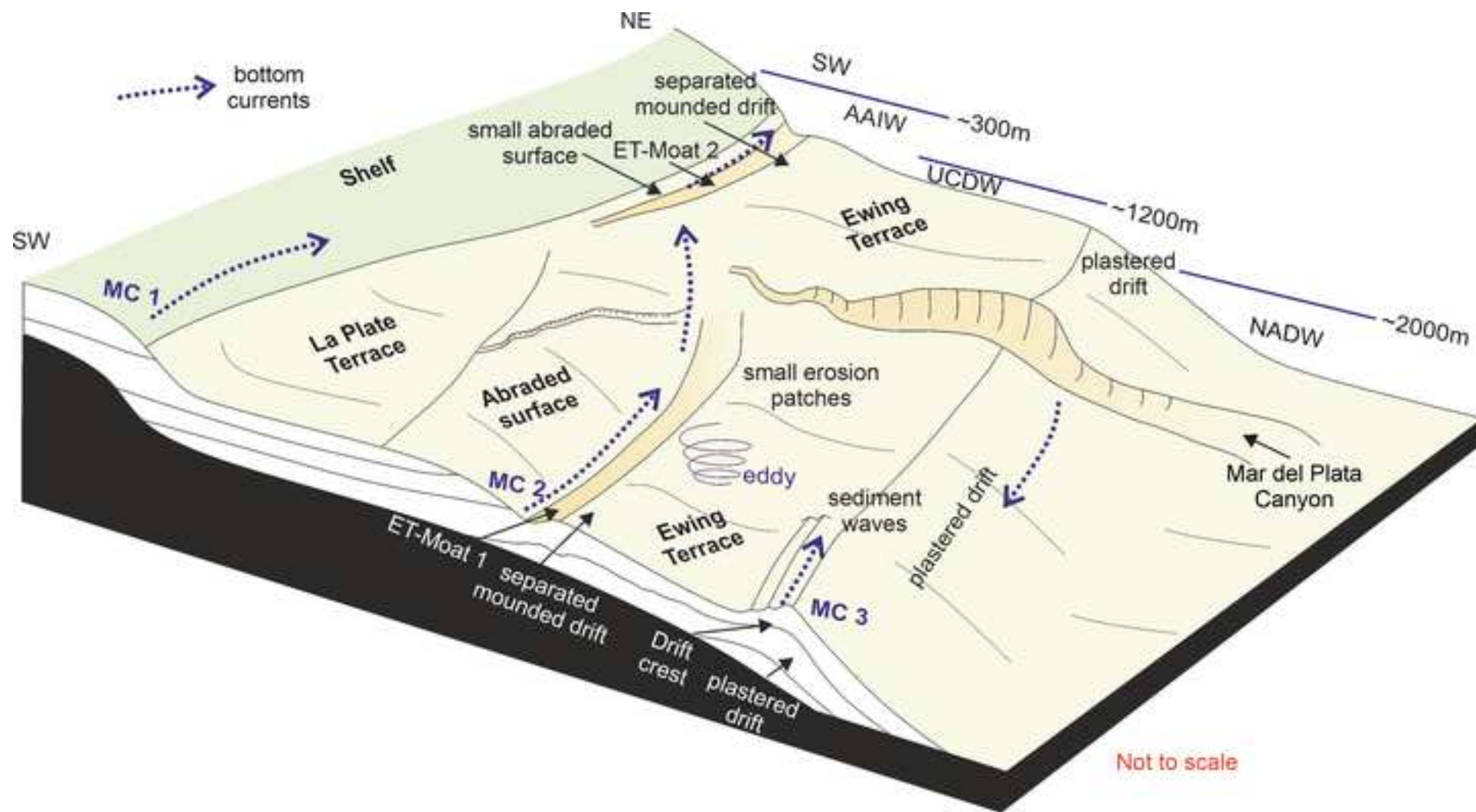


Figure 14



Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: