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HAL Authorization

1 **New heat flow data on the South Balearic margin: evidence of regional fluid circulation**
2 **system**

3

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19

20 **Abstract**

21 Crustal heat loss processes in contexts other than mid-ocean ridge flanks are still poorly
22 understood and described in the literature. In this work, we present 56 new surface heat flow
23 measurements recorded along the South Balearic margin and across the Hannibal High area,
24 in the Western Mediterranean Sea, away from spreading centres. The South Balearic margin
25 is generally considered as a right-lateral strike-slip area expressed on the seabed topography
26 by the steep Emile Baudot Escarpment (EBE) while the Hannibal area as a volcanic presumed
27 oceanic crust zone. Recent heat flow studies pointed out the presence of strong local thermal
28 anomalies, imprinted in a regional deep basin heat flow increasing from the eastern to the
29 western Algerian basins (70-90 mW/m² to 100-130 mW/m). The new data confirm local

30 anomalies around the EBE seamounts and allow to delimit some low and high heat zones. We
31 show that (1) a correlation exists between the heat flow intensity and the sedimentary cover
32 thickness, and (2) the most pronounced anomaly is a low heat flow zone (30 km wide)
33 observed in the mid-slope South Formentera basin, close to the basaltic basement of the Los
34 Martines volcano. The correlation of heat flow with sedimentary thickness, the lateral extent
35 of the heat flow anomalies, the flux peak magnitudes, and the co-existence of both low and
36 high anomalies suggest the presence of an active fluid circulation system. Based on the
37 arrangement of the anomalies in relation to the basaltic basement seamounts, we consider a
38 syphon-type circulation system in the Formentera basin. Reduced heat flow suggests a
39 recharge zone close to the Los Martines seamount, while local high heat flow located close to
40 a smaller seamount could be a potential zone of fluid discharge. Although different buoyancy
41 driven circulations could occur in the South Balearic margin, we believe that a syphon-type
42 hydrothermal circulation along permeable basaltic mounds and sedimented basement
43 conduits, similar to the off-axis oceanic crust, is best developed on the young marginal basin
44 of the South Balearic strike-slip margin.

45

46 **1 Introduction**

47 The thermal field plays a predominant role in the evolution of sedimentary basins and passive
48 margins. The thermo-mechanical structure of the lithosphere controls oceanic crust opening
49 mechanisms and post-rift thermal relaxation (e.g. Cloething *et al.* 2013; Aslanian *et al.* 2019).
50 The understanding of some regional processes related to the thermal regime, such as high
51 mantle heat flow (HF) (Lucazeau *et al.* 2004; Goutorbe *et al.* 2007) or the high position of the
52 transitional crust domain at least until the break-up (Aslanian *et al.* 2009; Bache *et al.* 2010)
53 goes through the characterisation of heat flow anomalies driven by surface activities. It is now
54 well established that hydrothermal fluid circulation is responsible for 15-25% of global heat
55 loss (Stein and Stein, 1994; Hasterok *et al.* 2013). Fluid circulation is strongly representative
56 of ridge-flank ocean environments (Fisher *et al.* 2003; Villinger *et al.* 2002), characterised by
57 a thin sedimentary overburden above a permeable basement. In sedimentary basins, which are
58 usually floored by continental and/or transitional crust, fluid circulation is inhibited by a
59 thicker sedimentary column (Spinelli *et al.* 2004; Winslow and Fisher, 2015), sometimes
60 partially intercalated by evaporites deposits. However, evidence of local anomalies has been
61 observed above continental crust, in volcanically active (Lucazeau *et al.* 2009) or thin
62 sedimentation areas (Lucazeau *et al.* 2010). In this study, we interpret new heat flow

63 measurements acquired in the Algerian Basin and southern Balearic margin, in the
64 Mediterranean Sea, away from off-axis oceanic ridge. The South Balearic margin is generally
65 considered as a divergent or right-lateral strike-slip area expressed on the seabed topography
66 by the steep Emile Baudot Escarpment (EBE) (e.g. van Hinsbergen et al., 2014) (ajouter une
67 ref). The formation of the Algerian basin still harbours several doubts in the scientific
68 community: its geodynamic evolution is poorly constrained and the role of the South Balearic
69 margin in accommodating its opening is still debated (e.g. van Hinsbergen et al., 2014;
70 Leroux *et al.* 2019). Poort *et al.* 2020 have recently pointed out a regional heat flow
71 asymmetry within the Algerian Basin: the heat flow is increasing westward, from 70-90
72 mW/m² in the East Algerian Basin (**EAB**) to 100-130 mW/m² in the West Algerian Basin
73 (**WAB**). This asymmetry can be assimilated to the diachronous opening between the western
74 (younger) and the eastern (older) basin (e.g. Mauffret *et al.* 1992, 2004; Haidar *et al.* 2022).
75 Several authors (Foucher *et al.* 1992; Della Vedova and Pellis, 1983; Poort *et al.* 2020)
76 described a large surface heat flow variability in the Algerian Basin and related margins.
77 Discriminating these local anomalies from regional trends is a major challenge for assessing
78 the parameters influencing the surface heat flow. Additionally, the East and West Algerian
79 basins are separated by the Hannibal High, a sub-circular group of high amplitude positive
80 magnetic anomalies, basement highs, and volcanic bodies that is still poorly documented
81 (Mauffret *et al.* 2004; Aidi *et al.* 2018). The thermicity of this area is poorly defined, although
82 it may bring new elements to constrain its nature.

83 The new data analysed in this paper were acquired during the WestMedFlux-2 survey,
84 carried out in 2018 on the R/V L'Atalante. These data allow us to identify in more detail the
85 local heat flow anomalies present in the South-Balearic margin, with a focus on the area close
86 to the EBE, and on the northern part of the Hannibal High, in the deep basin. We evidence the
87 presence of different local heat flow anomalies on seismic transects, we describe their relation
88 to the margin structuration and volcanism, and we propose interpretations for the processes
89 that are at the source of these anomalies.

90

91 **2 Geological setting**

92 The Algerian Basin is a back-arc basin located in the south-western Mediterranean Sea,
93 between the Balearic Islands (Spain) and Algeria (e.g. Gueguen *et al.* 1998). It is commonly
94 divided in the Eastern basin, the Hannibal High area, and the Western basin (Mauffret *et al.*

95 2004; Leroux *et al.* 2019). Its northern part is bordered by the South Balearic margin, which
96 in its central part is characterized by a NE-SW steep scarp, the EBE, and in its north-eastern
97 part by the South Menorca Block (**SMB**) extending to the south of Menorca.

98 The opening of the Algerian basin is still controversial regarding the kinematic evolution
99 and the nature of the margins (see Leroux *et al.* 2019 for a summary). In the Early Miocene,
100 the stretching of the European plate is assumed to have caused the drifting, spreading, and
101 finally the collision of parts of a continental block, the Internal Zones, called AlKaPeCa (for
102 Alboran, Kabylies, Peloritan, and Calabria; Bouillin *et al.* 1986), with the African continent.
103 At the present day, those internal blocks are scattered around the Western Mediterranean
104 basin, part of them having been accreted along the Algerian margin, such as the Kabylean
105 blocks. While the presence of a thin oceanic crust in the East Algerian seems to be confirmed
106 by aligned magnetic anomalies testifying the oceanic accretion (Mihoubi *et al.* 2014; Haidar
107 *et al.* 2022), in the Western Algerian Basin, the different geodynamics interpretation led to
108 uncertainties on crustal nature in deep and transitional domains. Last geodynamic
109 reconstruction confirmed an older east Algerian basin opening (between 15.2 and 12.7 Ma,
110 Haidar *et al.* 2022) compared to the west Algerian and Alboran basins (D'Acromont *et al.*
111 2020), also confirmed by heat flow asymmetry detected in Poort *et al.* (2020). According to
112 several authors (e.g. Spakman and Wortel, 2004; Mauffret *et al.* 2004; Medaouri *et al.* 2014),
113 the northern Algerian and the South Balearic margins became transforms since the middle
114 Miocene, when the onset of the slab tearing led to slab detachment migrating westward,
115 leading the formation of the Gibraltar Arcs. Coeval with the westward migration of the
116 Alboran Domain, the EBE and the Formentera Basin would therefore be developed in a
117 general right-lateral trans-tensional movement (e.g. Acosta *et al.* 2001; Camerlenghi *et al.*
118 2009; Etheve *et al.* 2016). The middle Miocene to Holocene alkaline volcanism widely
119 observed in the South Balearic margin could be associated with the extensional tectonics
120 (Maillard *et al.* 1992; Marti *et al.* 1992; Roca *et al.*, 1999) combined with the decompression
121 driven by the Algerian basin opening (Acosta *et al.* 2004) or by the strike-slip movement of
122 the Ibiza-Mallorca running parallel to the EBE (Maillard *et al.* 2022). Most of the volcanic
123 structures are located upslope the EBE. The volcanic activity in the Balearic Promontory,
124 including its southern margin, show two cycles: an early to middle Miocene (Maillard *et al.*
125 1992; Marti *et al.* 1992) and a Miocene to Holocene (Acosta *et al.* 2004). A K/Ar date (1.46 +
126 0.18 Ma) from a basalt sample recovered on the flank of the Emile Baudot sector supports the
127 interpretation of the volcanic structures as Early Pleistocene in age (Acosta *et al.* 2001; 2004).

128 South of the EBE, the Ocean-Continent Transition crust is interpreted from gravity modelling
129 to be 25 km wide and 12 km thick (Driussi *et al.* 2015).

130 The stratigraphic column in Algerian Basin and South Balearic margin is characterized
131 by a variable pre-Messinian unit thickness between the eastern and the western Algerian
132 basins (Mauffret *et al.* 2004). In the deep basin, the evaporites deposited during the Messinian
133 Salinity Crisis (MSC; ~5.96- 5.32 Ma, Krijgsman *et al.* 1999) left a thick salt blanket in all
134 present-day sub-deep basins in the Western Mediterranean. The salt, also called Mobile Unit
135 (MU), is underlain by the Upper Unit (UU), still belonging to the MSC, formed by evaporites
136 and clastic sediments (Lofi *et al.* 2018). The Hannibal High in the deep basin is characterised
137 by the absence/scarce salt (Fig. 1), located between the eastern and the western Algerian
138 basins and characterized by structural highs and suggested volcanism (Aidi *et al.* 2018;
139 Mauffret *et al.* 2004; Bellucci *et al.* 2021a). The Plio-Quaternary in the deep basin is locally
140 deformed by salt tectonics, especially in the western Algerian deep basin, where salt tectonics
141 is much more intense than in the EAB (Bellucci *et al.* 2021a; Blondel *et al.* 2022; Soto *et al.*
142 2022).

143

144 **3. Heat flow acquisition**

145 **3.1 Previous Heat Flow surface dataset**

146 Heat flow (HF) data acquisition in the Algerian Basin and South Balearic margin has a
147 long history that started in the early 1960's, when the first marine type heat flow instruments
148 were under development (e.g. Lister, 1963). The data coverage has however long time stayed
149 very poor, and most data acquisitions have been focused only on the extreme western part
150 (Polyak *et al.* 1996; Marzan, 2000) or in the south Sardinia (Della Vedova *et al.* 1995). Heat
151 flow differences between the Western (69 mW/m²) and the Eastern (124 mW/m²) Alboran
152 Basin are depicted (Polyak *et al.* 1996) while in the Sardinia-Tunisia channel the values are
153 generally higher than 100 mW/m² (Della Vedova *et al.* 1995). Moreover, two heat flow
154 measurements have been obtained in the DSDP-372A (103 mW/m²; Erickson and Von
155 Herzen, 1978) and ODP-975C (88 mW/m²; Pribnow *et al.* 2000) boreholes, both measured
156 near the Minorca Island.

157 Recently, between 2015 and 2018, surface heat flow were acquired in the Western
158 Mediterranean Sea during three surveys (Fig. 1A): The MEDSALT and WestMedFlux-1

159 surveys took place in 2015 and 2016 and allowed the acquisition of 143 new heat flow
160 measurements (Poort *et al.* 2020). The WestMedFlux-2 survey took place in 2018 and has
161 allowed the acquisition of 56 new heat flow measurements (Fig. 1B), discussed in this paper.
162 The heat flow acquisition was carried out using two different methods: i) the MCHF (Micro-
163 Computerized Heat Flow) instrument and ii) sediment corer. The two types of acquisition
164 give mutually consistent results (Lucazeau *et al.* 2010).

165 **3.2 MCHF instrument (POGO type measurement)**

166 The **MCHF** instrument was designed by Von Herzen R.P. (Von Herzen, 1987;
167 Bonneville *et al.* 1993) at Woods Hole Oceanographic Institution and upgraded significantly
168 since 2001 at IPGP. It allows to measure the temperature and the thermal conductivity *in-situ*
169 and, with a battery life of 72 hours, to acquire several measurements before to taking back the
170 instrument on deck (pogo type measuring). This instrument is composed of a 5-meters lance
171 and 7 thermistors arranged in an elliptical shape and with regular intervals around the lance.
172 Each sensor has a resistance and a heating wire for measuring temperature (resolution of
173 0.002 K) and thermal conductivity. An inclinometer situated on the lest allows to measure the
174 angle of the instrument in relation to the vertical in order to correct the true thermistors depth.
175 The electronics in the container of top is controlled from the surface *via* a bidirectional
176 acoustic connection at 2400 bit/s. The data are transmitted in real time to the surface but also
177 stored in the instrument's memory. Between two measurements, the instrument is towed
178 behind the vessel at 100 meters above the sea-bottom. The instrument is inserted in the
179 sediment under its own weight (1.5 tons). Penetration causes heating of thermistors, and a
180 minimum of 5 minutes of recording is needed in order to be able to extrapolate the value of
181 the equilibrium temperature. After this step, to determinate the thermal conductivity, a
182 constant heating is activated in the sediments (about 1W) and the instrument extrapolates the
183 measurement from the temperature increasing (Von Herzen and Maxwell, 1959). Then, the
184 heating is stopped, the instrument pulled out of the sediments and towed to the next station.

185 The amount of heat flow measurements per POGO station varied between 5 and 18 sites
186 and the total measurements are 46. Table 1 gives an exhaustive list of the heat flow stations
187 with tilt and penetration information and thermal parameters results (thermal conductivity,
188 thermal gradient and heat flow) calculated at each site. The successful heat flow measurement
189 amounts to 45 (98%), while in one site (HF03-06) both a large tilt and a small penetration did
190 not allow a reliable estimation. Generally, tilt was small with 72% measurements having a tilt
191 less than 10°.

192 **3.3 Sediment coring heat flow**

193 The sediment coring includes the acquisition of the temperature gradient with the
194 autonomous temperature loggers (THP on the core) equipment. In order to measure
195 temperatures and thermal gradients in the sediments, the coring piston tool can be equipped
196 with these high precision temperature loggers at different intervals. A logger (S2IP NKE©)
197 added at the top of the cores is equally autonomous and measures water depth and tilt angle of
198 the corer. On deck, the measurements are then downloaded using an induction pencil (Data
199 pencil NKE©). To allow heat friction dissipation, the cores must stay at least 5-6 minutes in
200 sediments without tensions. When the core is on-board, the thermal conductivity is measured
201 using a needle-probe technique developed by Von Herzen and Maxwell, (1959). The needle,
202 which includes a heating wire and a thermistor or a thermo-couple, is inserted transversally
203 into the core and heated at a constant power. The temperature increase of the probe with the
204 logarithm of time is proportional to the inverse of thermal conductivity. Usually, three values
205 for 1-meter core section are measured.

206 With a 10-m long Kullenberg corer equipped with the THP sensors, we performed 10
207 insertions in the sediments. One measurement failed, but 9 stations returned useful thermal
208 measurements over intervals of 5.6 to 10 m (see Table 1), showing a corer tilt of not more
209 than 4.1°. On-board, in the laboratory, a total of 315 thermal conductivity measurements were
210 performed in the sediment cores.

211

212 **4. Heat flow results**

213 **4.1 Thermal gradient and thermal conductivity**

214 The average thermal gradient, measured with the POGO instrument and sediment coring,
215 is 69.5 ± 2.6 mK/m (min-max of 0-144 mK/m among 45 measuring stations). The mean heat
216 flow including both techniques is 70.7 ± 8.25 mW/m² (Table 1).

217 The average of the thermal conductivity is 1.03 ± 0.07 W/m/K, with minimum and
218 maximum site values of 0.88 and 1.46 W/m/K. The thermal conductivities measured on the
219 sediment cores in the laboratory are very similar to the in-situ data (average of 1.01 ± 0.11
220 W/m/K).

221 **4.2 Sea-bottom temperature**

222 The measurements during WestMedFlux-2 were acquired at water depths ranging from
223 1302m (HF 05-12) to 2848m (KF-02), but all up to sub-bottom depths of 4-5 m and more.
224 The accuracy of the measured heat flow can be biased by the variability of bottom water
225 temperature, especially when the data are acquired at small penetration (e.g. Lachenbruch and
226 Marshall, 1968). In water depth exceeding 2000m, it is normally assumed that deep-ocean
227 temperatures are sufficiently constant and that they do not affect surface heat flow
228 measurements (Davis *et al.*, 2003). The temperature-depth profiles recorded in the sediments
229 are all linear (see Supplementary Materials), suggesting that the effect of variations in sea-
230 bottom temperatures can be neglected.

231 **4.3. Sedimentation correction**

232 Sedimentation effects are induced by the sedimentary history of the basin and, above all,
233 by the sedimentation rate: a high sedimentation rate will tend to decrease the surface heat
234 flow, and uneven sediment thickness distribution will cause lateral variations in the surface
235 heat flow (Langseth *et al.* 1966). The duration and the magnitude of this “cooling” will
236 depend on the sedimentation and the duration of the event. This can be estimated from the
237 thickness and age of sedimentary sequences. When sedimentation ceases, the system
238 rebalances itself with a time which depends on the thermal response of the entire lithosphere
239 (Hutchison, 1985). Conversely, an erosion episode will amplify the value of the heat flow. In
240 order to include variable sedimentation rates, compaction and thermal interaction with
241 basement for high sedimentation rates, numerical solutions and algorithms have been
242 proposed by Hutchison (1985) and Lucazeau and Le Douaran (1985). Although the two
243 algorithms use different strategies and hypothesis, both give very similar results (within 0.5%
244 of heat flow anomaly). We calculated the sedimentation correction for heat flow acquired
245 during the MedSalt and WestMedFlux 1-2 oceanographic campaigns according to the method
246 presented by Hutchison (1985) (Fig. 2). Older HF could not be corrected as they were not
247 acquired above available seismic profiles. The sediment blanketing effect is strongest in the
248 deeper parts of the basins with correction up to 32% (Fig. 2). On and near the slope, deposits
249 often generate a surface heat flow decrease of <8%.

250

251 **4.4 Heat flow profiles**

252 All WestMedFlux-2 measurements were acquired above seismic profiles interpreted in
253 the frame of this work. We discuss three regional heat flow profiles: i) a 100-km long profile

254 in the eastern SMB margin, ii) a 145-km long profile crossing the northern sector of the
255 Hannibal High between the west and east Algerian deep basins and iii) a 30-km long profile
256 in the South Balearic margin with very closely spaced heat flow measurements. **The heat flow**
257 **profiles are**

258 **4.3.1 Profile 1: East Minorca slope**

259 HF profile 1 is located in the South-East of Menorca Island (Fig. 3), in the lower slope of
260 the SMB, aligned along the SH73-23A seismic profile (Fig. 1).

261 The profile crosses another NW-SE heat flow profile from an earlier acquisition (Fig. 1;
262 fig. 5.5b in Poort *et al.* 2020). In the upper continental part (km 30-45), the heat flow average
263 is $72.1 \pm 14 \text{ mW/m}^2$. Towards the deep basin, in the lower slope (km 45-75), the average of
264 measurements is around 94.3 mW/m^2 , with a maximum peak at 126.3 mW/m^2 (HF 02-05) at
265 the upslope salt pinch-out limit. Higher values are measured at the lower limit of the lower
266 slope (km 80), where some listric faults given by the basinward movement of salt are
267 interpreted. A relatively low value (56 mW/m^2 ; HF 01-06) was measured on a seafloor and
268 basement escarpment (around km 48 in the profile). In the deep basin, the average measured
269 value is around $78.4 \pm 5 \text{ mW/m}^2$, coherent with the average values of the EAB (82.1 mW/m^2 ;
270 Della Vedova and Pellis, 1984; Poort *et al.* 2020) (Fig. 3). The salt, unlike the deep domain of
271 the Gulf of Lion (Bellucci *et al.* 2021a), shows less piercing deformation: the structures can
272 deform the Pliocene deposits, but they do not impact the seafloor. The highest HF values
273 along the profile are found at the upslope pinch-out of salt, which also corresponds to the limit
274 between continental and transitional crust following Driussi *et al.* (2015) interpretation. In the
275 SE margin of the SMB, the values seem to be highest in the lower slope area, close to the
276 deep basin, at the upslope edge of the margin. The low and high heat flow anomalies are
277 mainly located at the edge of a basement deepening (Fig. 5b in Poort *et al.* 2020 and fig. 3 -
278 km 45 and 80). Some variations may come from refraction of heat conduction given by
279 thermal conductivity lateral variations, but not enough information is available to well
280 estimate it on the current profile.

281 **4.3.2 Profile 2: Hannibal High northern sector**

282 The heat flow profile 2 is located in the deep Algerian Basin, between the EAB and
283 WAB. It is transecting the northern part of the Hannibal High (Figs 1B, 4), from ENE to
284 WSW (Fig. 4).

285 13 HF measurements were acquired during WestMedFlux-2 (2 KF and 11 HF, Table 1)
286 along the seismic profile SH73-37B (Fig. 4). The measurements in the western part of the
287 EAB (km 200-230) show a heat flow average of 72 mW/m^2 with a peak of about 87.4 mW/m^2
288 (HF03-07) showing a measurement error quite high for this latter. The average found is
289 coherent with Poort *et al.* (2020) measurements in the nearby profile. Moving south-
290 westward, towards the WAB, the average slightly increase (average about 89 mW/m^2), with a
291 peak around 110 mW/m^2 (HF04-09). Above the volcanic-type structure (Aidi *et al.* 2018;
292 Mauffret *et al.* 2004) in the central sector (km 140-150) (Fig. 4), no heat flow anomalies are
293 detected, although the measurements are laterally about 5 km away from the deformed
294 seafloor. The salt is curiously thinner than in the eastern and western nearby Algerian basins,
295 also according to other authors (Mauffret *et al.* 2004; Bellucci *et al.* 2021a; Aidi *et al.* 2018).

296 **4.3.3 Profile 3: South Balearic margin**

297 Profile 3 (Fig. 5) is located in the southern margin of the Balearic Promontory, but
298 contrary to profile 1 it is not perpendicular to the margin but aligned with the EBE direction.
299 It crosses a regional heat flow profile acquired during WMF1 survey (Poort *et al.* 2020),
300 located perpendicular to the margin. HF are acquired on the south-western part of the
301 Escarpment, in the margin connecting the slope of the Ibiza and Formentera Islands
302 continental domain to the deep Algerian basin, separated by the Formentera basin. The South
303 Formentera Basin is located between the south Ibiza margin and EBE, which upslope limit in
304 our area of study is marked by a volcanic seamount (Los Martines; Canals *et al.* 1983; Rovere
305 and Wurtz, 2005; Acosta *et al.* 2004) (Fig. 5).

306 The entire Formentera Basin shows low heat flow values, from maximum of 63.9 to a
307 minimum of 0.8 mW/m^2 . This latter value is characterized by a thermal gradient close to zero
308 mK/m and a thermal conductivity around 1 W/m/K . The main average along the profile is
309 25.8 mW/m^2 , considerably lower than the continental crust average in the South Balearic
310 margin (around 66 mW/m^2) (Poort *et al.* 2020) (Fig. 5). The measurements were acquired at 3
311 km maximum distance of MEDS-07D seismic profile because during the acquisition the sub-
312 bottom profile warned on the hard penetrating sediments just above it. The values exhibit their
313 minimums at the Los Martines Seamount while they appear to increase in the sedimentary
314 depocenter towards the SW (Fig. 5).

315

316 **5 Discussion**

317 The three new regional HF profiles acquired during the WestMedFlux-2 survey on the
318 South-Balearic margin and the northern sector of the Hannibal High confirm the main heat
319 flow trends of the Algerian basin described by Poort *et al.* (2020). The Western Algerian deep
320 basin is considerably warmer (average of 105 mW/m² including the new data) compared to
321 the East (average of 82 mW/m²). Poort *et al.* (2020) already showed the co-existence of both
322 low and high heat flow anomalies on the distal continental margin near the ocean-continent
323 transition zone (OCT). The new data presented here on margin perpendicular and parallel
324 profiles confirm the strong heat flow variability and further outline the extent of the
325 anomalies. A non-uniform heat flow trend is also depicted in the deep Algerian Basin, around
326 the Hannibal High. Poort *et al.* (2020) discarded a deep heat source such as edge driven
327 convection or crustal magmatic intrusions which could explain such variations. The effect of
328 salt refraction could lead to local anomalies, as is the case in the Gulf of Lion (Bellucci,
329 2021). In our area of study, however, the HF anomalies are located where salt is absent or
330 very thin and only slightly deformed (Figs 3, 4, 5) (also according to Blondel *et al.* 2022). On
331 the other hand, we observed a clear coincidence between the heat flow variation, the
332 sedimentary thickness and the basement depth. The variations are more pronounced with a
333 thin sedimentary thickness and a shallower basement.

334 **5.1 Sedimentary thickness control on heat flow variations**

335 The analysed profiles in the Algerian deep basin and South Balearic margin (Figs. 3, 4, 5)
336 recorded differences in sedimentary thickness above basement. In the deep basin, sedimentary
337 thickness is on average greater than 1 km (Figs. 2b, 4). Where sedimentary infill is thick and
338 rather uniform, the observed heat flow variation is of long-wavelength scale, as for instance in
339 the northern sector of Hannibal High (Profile 2, fig. 4). On the other hand, where the
340 sedimentary cover is thin and the basement is high, the heat flow variation increases (Fig. 6b),
341 as shown in the plot of heat flow as a function of sedimentary thickness (Fig. 6c). The widest
342 range of heat flow variation recorded (from 0 to about 90 mW/m²) in the new data
343 measurements appears when sedimentary thicknesses above the basement are less than 1 km
344 (Fig. 6c). These are mainly localised in margin boundaries, especially in areas of continental
345 and transitional crust. In contrast, in the deep basin, the variation is smaller (from 61 to 113
346 mW/m², Profile 2, fig. 4). Also, the wavelength is larger, as observed in the profile in the deep
347 Algerian basin (Profile 2, fig. 4).

348 The relationship between heat flow variability and sedimentary thickness is well known
349 for the oceanic plate (Davis *et al.* 1992). To reveal the real lithospheric cooling rate of an

350 oceanic plate, Sclater *et al.* (1976, 1980) and subsequently Hasterok *et al.* (2011) filtered
351 global heat flow sites using sediment thickness and basement morphology criteria. A better
352 match between measurements surface and expected background heat flow from oceanic
353 cooling model (e.g. GDH1 Stein and Stein, 1992) is found by only including measurements
354 acquired above a minimum sediment cover (400 m) and minimum distance from the nearest
355 seamount (60 km) (Hasterok *et al.* 2011). In this context, the high heat flow variability is
356 caused by the regional fluid circulation, with recharge and discharge zones separated by only
357 tens of kilometers.

358 The observed correlation between sedimentary thickness and the variations in measured
359 surface heat flow is a first indication of the presence of fluid circulation on the South Balearic
360 margin.

361 **5.2 Role of the Messinian salt and fluids release observations**

362 In the deep basin, the sedimentary column is characterized by the presence of a thick salt
363 layer (e.g. Mauffret *et al.* 2004). Salt (halite) is characterised by high thermal conductivity, up
364 to three times higher than the surrounding sediments (REF). It therefore influences the
365 expected thermal field, acting as a heat pump along diapirs often reaching the surface (e.g.
366 Jensen, 1983). The three heat flow profiles interpreted in this study are located in areas where
367 there is little or no salt deformation. Even along the Hannibal High, in the deep basin, the salt
368 is unusually little deformed (Mauffret *et al.* 2004; Bellucci *et al.* 2021a). The short
369 wavelength anomalies do not seem to be influenced by salt refraction phenomena. Although
370 the Messinian salt in the Mediterranean is not completely impermeable and is subject to faults
371 and fractures that favor the fluid migration (e.g. Warren, 2010; Dale *et al.* 2021, Bertoni and
372 Cartwright, 2015), its permeability is significantly lower than the sediments surrounding it
373 (Warren, 2006). The sedimentary thickness and the salt layer above the basement may inhibit
374 the cooling of post-salt sediments by restricting fluid circulation to the underlying pre-salt
375 layers (Warren, 2006). In the margin boundaries, salt gliding towards the deep basin leaves
376 behind scars, called welds, and a series of listric faults typical of thin-skinned tectonics (Fig.
377 7) (e.g. Vendeville and Jackson, 1992). The formation of welds associated with the listric
378 faults activity may favour the release of overpressure hot fluid in the sub-salt (Dale *et al.*
379 2021). These structural pathways could allow the escape of fluids that were confined below
380 the impermeable salt layer (Fig. 7), thereby explaining some of the positive anomalies
381 observed at the salt pinch-out areas in the area of study (Figs. 3, 7). Along the South Menorca
382 margin, heat flow values up to 126 mW/m² have been measured. Also, in some areas we

383 clearly identify fluid migration close to where our high heat flow values are measured (Fig.
384 7). Locally transparent facies and small faults suggest fluids release coming from the
385 basement or the Miocene sequences through the Plio-Quaternary sequence (Fig. 7).

386 **5.2 A fluid circulation system in the South Balearic margin?**

387 In the three analysed profiles we have outlined different local high heat flow anomalies
388 both upslope and downslope of the margin. In the Formentera basin, the high heat flow
389 anomaly is clearly limited to only a few kilometres in extent (Fig. 8). Close to this heat flow
390 high, we contoured a large zone of low heat flow, approximately 30 km-long, where heat flow
391 consequently decreases from a background value of 60 mW/m² to only 0.8 mW/m² (Fig. 8).
392 The lateral extent of these pronounced heat flow anomalies, the flux peak magnitudes and the
393 co-existence of both low and high anomalies is typical of a heat redistribution system driven
394 by a regional fluid circulation (e.g. Fisher and Von Herzen, 2005; Winslow and Fisher, 2015;
395 Lauer *et al.* 2018). The area of lower heat flow has been observed upslope to the EBE in the
396 Formentera Basin, adjacent the outcrop of the Los Martines volcanoes (Fig. 8). This basement
397 high structure genetically belongs to the volcanism of the EBE, which is more exposed in the
398 Emile Baudot seamount area, located within a 513 km² Pleistocene volcanic field (Acosta *et al.*
399 *et al.* 2004) and composed of 118 pinnacles (Acosta *et al.* 2001). The very low surface values
400 could suggest a recharge zone located around the Los Martines seamount (Fig. 8). Two HF
401 measurements with values of 147 and 163 mW/m² (Poort *et al.* 2020) were observed in an
402 area where the volcanic basement is covered by a reduced sedimentary thickness, in the NE
403 most sector of Los Martines volcanic area (Fig. 8). This small area, very close to the low
404 anomalies, could be interpreted as a discharge potentially linked to the recharge zone
405 previously described. The second high heat flow zone and thus prone to be a fluid discharge
406 area is located about 40 km downslope (Figs. 7, 8). A significant uplift of the basement is
407 recorded in the lower slope, at the boundary with the deep basin (Fig. 7b) (Camerlenghi *et al.*
408 2009; Blondel *et al.* 2022). Here, the sedimentary thickness is reduced and the basaltic faulted
409 basement locally outcrops. The heat flow values are anomaly higher all along the SE part of
410 the ridge.

411 Permeability is the main property controlling the fluid circulation (e.g. Spinelli *et al.*
412 2004; Winslow and Fisher, 2015). Migration of fluids in marine sedimentary column is
413 normally very limited due to the poor permeability of these sediments and not permeable and
414 unfaulted basement. In our area of study, several pinnacles are scattered throughout all the
415 South Balearic margin, mainly located upslope the EBE. Acosta *et al.* (2001) interpret these

416 structural highs as volcanic, also in agreement with Desforbes, (1973) and Palomo *et al.*
417 (1976). Also, the Hannibal High between the EAB and WAB is characterized by Miocene
418 volcanic high structures and volcano-clastic sediments, showing not-outcropping basement
419 highs and decreasing in the sedimentary thickness (Mauffret *et al.* 2004; Aidi *et al.* 2018;
420 Haidar *et al.* 2022). On the South Balearic margin, the thin and often faulted sedimentary
421 column coupled with basaltic, faulted basement could allow a similar circulation to that
422 interpreted in the oceanic ridge.

423 **5.3 What is the driving mechanism of the regional fluid circulation?**

424 On land, regional fluid circulation systems are mainly topographically driven by the
425 hydraulic head of the water level elevation differences that directs a meteoric fluid in the
426 mountains towards the valleys and shores (e.g. Gleeson & Manning, 2008). The higher the
427 topographic gradient, the deeper the fluids descend and the larger lateral distances they can
428 bridge and redistribute subsurface heat (Poort and Polyansky, 1998). In regions of strong
429 magmatic activity fluid circulation can also be induced by local heat sources creating high
430 enthalpy geothermally driven systems (Yellowstone, Hurwitz *et al.* 2012; Campi Flegrei,
431 Troise *et al.* 2019).

432 In the marine environment, away from coastal areas, there is a complete absence of
433 topographic head and sub-seafloor fluid circulations must be driven by deviatoric pressures
434 from other mechanisms, such as tectonic, compaction or buoyancy forces (e.g. Winslow and
435 Fisher, 2015). Sediment compaction continuously pushes pore fluids towards the surface, and
436 generally does not induce strong advective heat transport. In the presence of permeable
437 conduits (e.g. faults, pinch-outs, welding), these pore fluids can induce positive heat flow
438 anomalies (Poort and Polyansky, 1998). This is probably the case in the downslope domain of
439 the South Balearic margin (Fig. 9), where some heat flow anomalies can be related to lateral
440 and vertical fluids release (Fig. 7). More effective heat transfer can be caused by buoyancy
441 driven fluid circulations (Yang *et al.* 2006). On margin slopes, two types of buoyancy driven
442 circulations have been described in literature: (1) an upslope thermal convection driven by the
443 non-horizontal isotherms in the subsurface of a steep slope (Kohout, 1967; Wilson, 2005), and
444 (2) a downslope brine reflux convection resulting from dissolution of evaporite deposits at
445 continental platforms (e.g. Manning and Emsbo, 2018). These systems have been mostly
446 evoked in carbonate platform to explain dolomite occurrence (Hughes *et al.* 2007; Staudigel
447 *et al.* 2021), but the upslope thermal convection has also been described at deep sea
448 seamounts (Harris *et al.* 2000). The South Balearic margin has a favourable setting for both

449 type of buoyancy circulations because of the steep and high Emile Baudot slope and the
450 Messinian evaporitic deposits on the marginal Formentera Basin (Fig. 9). While an
451 upslope/downslope circulation cannot be excluded in our study area, the disposition of the
452 observed thermal anomalies in the Formentera Basin privileges a margin parallel fluid
453 circulation.

454 On the oceanic ridge flanks, a buoyancy driven fluid circulation occurs where a confined
455 aquifer in the upper basaltic basement is overlain by impermeable sediments perched by
456 seamounts (syphon-type hydrothermal circulation) (Fisher and Wheat, 2010; Wheat and
457 Fisher, 2008; Le Gal *et al.* 2018). Sea water enters at large seamounts, heats up during a
458 lateral transport of several tens of km and discharges into the sea at smaller seamounts (e.g.
459 Lauer *et al.* 2018). These systems are driven by the integrated contrast of fluid density from
460 the difference of temperature in the recharge and discharge zones. Despite the relatively small
461 pressure differences and fluid temperature involved, these hydrothermal circulations are able
462 to redistribute by advection large amount of heat. They are responsible for the large heat loss
463 in the young ocean (Sclater, 1980; Hasterok, 2013) as they reduce the heat flow in the
464 overlying sediments and only locally induce elevated heat flow in and around the discharge
465 zone or pit holes (Villinger *et al.* 2017).

466 In the South Balearic margin, we are far from an off-axis oceanic ridge context, but
467 different observations suggest that a syphon-type hydrothermal circulation could be the main
468 responsible mechanism to explain the heat flow anomalies in the Formentera Basin of this
469 continental margin. In an area of 30 km, our measurement disclosed a large zone of reduced
470 heat flow (0-20 mW/m² over more than 10 km) and a local spot with high heat flow of more
471 than 150 mW/m² (Fig. 8). This anomalous heat flow zone is located on the rim of the
472 marginal basin where different volcanic seamounts are outcropping and where the basement
473 (strongly intruded by magmatic material) is overlain by 100-150 m of sediments. Our reduced
474 heat flow anomaly is located nearby the exposure of the large Los Martines seamount, which
475 could be a recharge zone of this hydrothermal circulation system (Fig. 8). This particular
476 disposition of heat flow anomalies and seamounts support a syphon-type circulation.
477 Evidence of hydrothermal circulation on continental margins are still poor, but Lucazeau *et al.*
478 (2010) has also evoked a seamount related fluid circulation in the Gulf of Aden. It is more and
479 more clear that syphon-type hydrothermal circulation is not limited to young oceanic crust,
480 but also occurs in older crust as long as a covered permeable basalt exhibits the needed

481 recharge and discharge conduits to the surface (Fisher and von Herzen, 2005; Lucazeau *et al.*
482 2019).

483

484 **6 Conclusion**

485 We have interpreted 54 new heat flow measurements along three regional seismic
486 profiles in the northern part of the Algerian Basin including two margins perpendicular and
487 one parallel deep basin transects. The heat flow measurements are closely spaced, acquired
488 above seismic profiles and of excellent quality as nearly all display linear temperature
489 gradients. Small-wavelength surface HF anomalies, thin sedimentary cover, nearly
490 outcropping volcanic basement and seismic facies signatures in the South Balearic margin
491 suggest the presence of fluids circulation and percolation systems that can reach a lateral
492 extent of several tens of kilometres. Similar to well-known fluid circulation systems in certain
493 off axis oceanic domains, low and high heat flow anomalies (between 0 and 160 mW/m²) are
494 located adjacent to outcropping basaltic structures or near volcanic faulted basement highs.
495 The disposition of the anomalies coupled with indications and location of basaltic basement
496 seamounts support a syphon-type circulation in the Formentera Basin. Reduced heat flow
497 suggests a recharge zone close to the Los Martines seamount while local high heat flow
498 located close to a smaller seamount could be the potential zone of fluid discharge. In the deep
499 basin, the circulation is inhibited by greater sedimentary thickness and Messinian salt layer.
500 On the slope, where salt pinches-out, a leakage of fluids is observed coupled by heat flow
501 increase. The northern strike-slip margin of the young Algerian Basin is an area of heat
502 redistribution clearly showing indication of fluid systems. This study pointed out how the
503 sedimentary thickness, volcanic basement and outcropping seamounts are first order
504 parameters controlling the fluid circulation even far from an off-axis oceanic ridge context.

505

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507 **Figure Captions:**

508 **Figure 1.**

509 A) Regional setting, crustal segmentation and available heat flow measurements in the
510 Western Mediterranean Sea. Wide-angle segmentation is taken from Leroux *et al.* (2019).

511 Gravity modelling segmentation on the South Balearic margin is from Driussi *et al.* (2015).
512 Free-air anomaly map is from Sandwell and Smith, (1997). Black squares and white circles
513 represent the heat flow measurements acquired during WestMedFlux-1 (2016) and
514 WestMedFlux-2 (2018), respectively. Triangles represent previous measurements. GoL: Gulf
515 of Lion margin; LPB: Liguro-Provençal basin; WS: Western Sardinian margin; EAB: East
516 Algerian basin; HA: Hannibal High Area; SMB: South Minorca block; WAB: West Algerian
517 basin; EA: East Alboran margin; SB: South Balearic margin; BP: Balearic Promontory; VB:
518 Valencia basin; MB: Menorca basin. B) Zoom of the area of study on bathymetric map
519 (Emodnet) showing the new WestMedFlux-2 and older heat flow data. Structural elements are
520 from Driussi *et al.* (2015) and Blondel *et al.* (2022). Il manque des acronymes dans la légende
521 (elles sont dans le texte mais autant les ajouter là aussi) : FB (Formentera Basin ; OCT :
522 Ocean-Continent Transition, EBE (Emile Baudot Escarpment)

523

524 **Figure 2.** A) Surface heat flow measurements available in the area of study. Basement high
525 structures are from Acosta *et al.* (2001); Driussi *et al.* (2015) and this study. B) Sedimentary
526 thickness above the basement is taken from seismic interpretation available in Bellucci
527 *et al.* (2021b) and Blondel *et al.* (2022). The heat flow sedimentary correction in percentage is
528 shown. The correction is calculated on MedSalt, WestMedFlux-1 and WestMedFlux-2 heat
529 flow measurements.

530

531 **Figure 3.** Heat flow variations along Profile 1 crossing the South Menorca Block. Heat flow
532 values are indicated above the profiles with black dots (measured values) and red triangles
533 (after sedimentation correction). Thin lines above seafloor indicate the heat flow measurement
534 location. Mean crustal heat flow are taken from Poort *et al.* (2020). Crustal segmentation is
535 taken from Driussi *et al.* (2015). PQ refers to Plio-Quaternary sediments, UU (green unit) to
536 the Messinian Upper Unit. Messinian salt is represented in pink.

537

538 **Figure 4.** Heat flow variation along Profile 2 crossing the northern Hannibal Area from the
539 Western (WAB) to the Eastern (EAB) deep Algerian basin. Heat flow values are indicated
540 above the profiles with black dots (measured values) and red triangles (after sedimentation
541 correction). Thin lines above seafloor indicate the heat flow measurement location. Mean

542 crustal heat flow are taken from Poort *et al.* (2020). Crustal segmentation is from Leroux *et al.*
543 (2019). PQ refers to Plio-Quaternary sediments, UU (green unit) to the Messinian Upper Unit.
544 Messinian salt is represented in pink. Inset: zoom of Plio-Quaternary unit showing amplitude
545 variations and discontinuous reflectors suggesting possible fluid release.

546

547

548 **Figure 5.** Heat flow variation along Profile 3 crossing from SW to NE the southern sector of
549 the Formentera basin. Heat flow values are indicated above the profiles with black dots
550 (measured values) and red triangles (after sedimentation correction). Thin lines above seafloor
551 indicate the heat flow measurement location. Mean crustal heat flow are taken from Poort *et*
552 *al.* (2020). Seamounts naming are taken from Rovere and Wurtz, (2005). MSC refers to
553 Messinian deposits.

554

555 **Figure 6.** Sketch representing the heat flow distribution compared to the sedimentary
556 thickness above basement (yellow colour) in the area of study. A) Location summary of the
557 analysed heat flow profiles. B) Representation of sedimentary thickness, heat flow variations
558 and crustal segmentation for each profile. Yellow represents the sedimentary column above
559 acoustic basement. Light brown represents the continental crust, dark brown the transitional
560 crust and the light blue the oceanic crust as interpreted in the literature (e.g. Leroux *et al.*
561 2019; Driussi *et al.* 2015). Dashed horizontal black lines and number represent the mean heat
562 flow value for each crustal segment. C) Plot representing the surface heat flow values against
563 the sedimentation thickness for each profile. The dashed ellipse zooms on the heat variations
564 in areas of thin sedimentary thickness, so more likely to be affected by fluid circulation (see
565 text for discussion).

566

567 **Figure 7.** Seismic profiles located in the lower slope of the South Balearic margin. A)
568 Amplitude variations and discontinuous reflectors suggest the presence of fluid release in the
569 Pliocene-Quaternary units. Evidence of fluid are located in areas characterized by salt welds
570 and fracture/faults created by shear stress zones faults. B) Polygonal faults in the Messinian
571 Upper Unit created by water release from gypsum- anhydrite (Dal Cin *et al.* 2016) or by
572 overpressure hydro-fracturing (Dale *et al.* 2021) form preferential pathways for fluid release.

573 C) Very high heat flow are observed nearby sub-outcropping basement high in the lower
574 slope domain.

575 **Figure 8.** Multi-beam bathymetry in the South Balearic margin acquired during
576 WestMedFlux surveys superposed on bathymetry acquired during SBALDEEP survey
577 (Camerlenghi *et al.* 2009). All heat flow measurements available in the area are represented.
578 Note the very low values upslope the Los Martines seamount and, about 20 km downslope,
579 the high heat flow measurements in the lower slope.

580 **Figure 9.** Sketch representing the interpretation of fluid circulation systems in the South
581 Balearic margin. A) Perpendicular profile from the upslope Formentera basin to the
582 downslope deep Algerian basin. B) Parallel profile in the southern Formentera basin and Los
583 Martinez seamount. Approximately location of the profiles in figure 8.

584 **Table 1.** Results of the 54 new heat flow measurements acquired during the WestMedFlux-2
585 campaign. HF refers to measurements acquired with the multi-penetration MCHF device
586 while KF with sediment cores equipped with temperature loggers. “Lon” is the longitude
587 (east) and “Lat” the latitude (north); “Depth W” is the water depth from multibeam (meter);
588 “PenD” is the penetration of the lowest sensor (meter); “Tilt” is the tilt of the MCFH
589 device/sediment core (degree); “Wat.T” is the sea-bottom water temperature (°C); “SigWat”
590 is the standard error on water temperature (°C); “nT” is the number of thermistors; “Grad” is
591 the average thermal gradient (mK/m); “SigG” is the standard error on thermal gradient
592 (mK/m); “nK” is amount of thermal conductivity measurements; “K” is the harmonic mean of
593 the thermal conductivity (W/m/K); “SigK” is the standard error on thermal conductivity
594 (W/m/K); “HF” is the calculated heat flow (mW/m²); “SigHF” is the standard error on heat
595 flow (mW/m²); “HFc” is the heat flow corrected for the sedimentation effect (mW/m²).

596

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