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1 **Terrestrial shallow water hydrothermal outflow characterized from** 2 **out of space**

3

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5

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15

16 **Abstract**

17

18 We investigate the potential of satellite imagery to map and monitor the activity of shallow-
19 water hydrothermal systems, which are often found at volcanic islands. For this study, we used
20 publicly available data and proprietary WorldView-2 satellites images, with spectral bands that
21 can penetrate up to water depths of 30 m. Shallow water hydrothermal sites are visible on satellite

22 imagery, primarily with publicly available data, demonstrating the potential of satellite imagery to
23 study and monitor shallow water hydrothermal activity. We focus our work on volcanic islands,
24 showing intense near-shore, shallow-water hydrothermal activity, and distinct styles of
25 hydrothermal venting. Satellite imagery constrains regional outflow geometry and the temporal
26 variability or stability of these systems. Milos Island shows hydrothermal outflow associated with
27 reflective mineral precipitates and/or bacterial mats, which are stable over time (2010-2014).
28 These outflows locally define polygonal patterns likely associated with hydrothermal convection
29 in porous media. In Kueishantao Island individual hydrothermal plumes charged with particles are
30 visible at the sea surface, and display great variability in intensity and distribution of plume sources
31 (2002-2019). Worldwide we have identified ~15 shallow water hydrothermal sites with satellite
32 imagery, that are similar to either the Milos system (e.g., Vulcano and Panarea, Italy), or the
33 Kueishantao system (numerous sites in Pacific volcanic islands). This study demonstrates that
34 satellite imagery can be used to map and monitor different types of shallow-water hydrothermal
35 systems, at regional scale, and monitor their evolution. Satellite data provides not only regional
36 and temporal information on these systems, unavailable to date, but also the regional context for
37 follow-up *in situ* field data and observations (e.g., instrumental monitoring, sampling, observations
38 and mapping with divers or AUVs) to understand both the nature and dynamics of these systems,
39 and ultimately the associated fluxes.

40

41 **Keywords:** Shallow water; Seafloor mapping; Hydrothermal activity; Satellite imagery; Volcanic
42 island.

43 **1. Introduction**

44

45 Submarine hydrothermal activity is common at volcanically active areas (e.g., mid-ocean
46 ridges, seamounts, volcanic arcs), controlling heat and chemical exchanges through the seafloor.
47 Mapping is critical to locate hydrothermal outflow, characterize its geometry, and document
48 temporal variability. This mapping also provides context for instrumental measurements and
49 sampling (e.g., temperature of outflow, chemistry, etc.). Numerous deep-sea vents are identified
50 by local hydrothermal plumes detected in the water column (Baker et al., 1995; Baker and German,
51 2004; Baker et al., 2016), and subsequently surveyed acoustically and optically, and instrumented
52 for monitoring (Barreyre et al., 2012, 2014a, 2014b; Barreyre and Sohn, 2016; Wilcock et al.,
53 2016; Nooner and Chadwick, 2016; Baker et al., 2019). While numerous shallow-water (<200-300
54 m) hydrothermal systems have been identified (e.g., see Table 1 in Price and Giovannelli, 2017),
55 we lack systematic and extensive optical surveys of these, hence their detailed extent, structure,
56 and evolution are not documented. This information is also critical to understand the link to
57 underlying heat sources, and the thermal, mass and chemical transfer between the solid Earth and
58 the overlying ocean.

59 Satellites provide temporal series of high-resolution images throughout the Earth's surface
60 acquired with various sensors. Specific spectral bands can penetrate shallow-water areas, and are
61 used in coastal studies for benthos mapping (e.g. corals, seagrass), and estimation of near-shore
62 bathymetry, (Eugenio et al., 2015; Reshitnyk et al., 2014; Baumstark et al., 2016; Dattola et al.,
63 2018). To our knowledge, the only study of shallow water hydrothermal systems using satellite

64 data monitored and documented a +1°C surface temperature anomaly over the 10-m deep Punta
65 Mita site in Mexico (Torres-Vera et al, 2010), which is not visible in satellite imagery.

66 Satellite can document temporal variability of submarine hydrothermal activity, and
67 ultimately evaluate the associated fluxes associated with these sites; optical surveys coupled to
68 instrumental measurements, have been successfully applied to study deep-sea hydrothermal sites
69 (Barreyre et al., 2012). Here we evaluate the use of satellite imagery to observe and monitor
70 shallow-water hydrothermal activity, and at a low cost relative to repeated, extensive field surveys.
71 Remotely-detected anomalies in hydrothermal activity may be ultimately linked to deep-seated
72 processes (e.g., magmatic activity, seismicity), and contribute to hazard (e.g., phreatic explosions)
73 and risk assessment near populated areas. Finally, the study of terrestrial hydrothermal systems
74 using satellite data may provide insight into the potential indicators of hydrothermal activity at the
75 surface of extraterrestrial bodies (e.g., Collins et al., 2000; Vance et al., 2007; Osinski et al., 2013).

76 In this pilot study we demonstrate that we can investigate shallow-water hydrothermal
77 activity with satellite views, using both publicly available images, and WorldView-2 data provided
78 by the Digital Globe Foundation. Image analyses reveal two different types of hydrothermal
79 manifestations in satellite imagery (Figs. 1, 2). Firstly, satellite data directly image hydrothermal
80 outflow zones at the seafloor, at depths of up to 30 m (Fig. 2a), owing to the high reflectivity of
81 associated hydrothermal deposits, microbacterial mats, or both. We can thus map the
82 hydrothermally active zones, and monitor potential temporal variations in their geometry.
83 Secondly, we document turbidity at the sea surface due to hydrothermal plumes, which is the most

84 common manifestation seen in the satellite imagery reviewed (Fig. 2b, Chen et al., 2018), and that
85 documents the intensity of the hydrothermal activity and spatial distribution of plumes.

86 The Milos (Greece) shallow water hydrothermal system (Fig. 2a) shows seafloor patterns
87 visible from space and is our main target. Prior studies of this site (e.g., Aliani et al., 1998; Aliani
88 et al., 2004; Naden et al., 2005; Price et al., 2013) provide both ground-truthing and background
89 information to validate satellite imagery interpretations, mapping, and characterization of this
90 hydrothermal system. Available images from 2010, 2011 and 2014 also allow us to document
91 temporal stability or variability. We also explore similar sites elsewhere (e.g., Panarea and Vulcano
92 in Italy, Fig. 1, Table 1, and section 5.1.2).

93 We also evaluate the spatial monitoring of hydrothermal plumes reaching the sea surface
94 at Kueishantao (Taiwan, Fig. 2b, Chen et al., 2018). Here satellite imagery documents variations
95 in the intensity of the turbidity plumes, and their appearance and disappearance over time. Figure
96 1 and Table 1 locate and list all shallow-water hydrothermal systems with associated turbidity
97 plumes visible on satellite images.

98 Finally, we evaluate the untapped potential of satellite imagery to better understand
99 hydrothermal activity in shallow water environments, including its distribution, geometry, and
100 temporal variability.

101

102 **2. Datasets and methods**

103

104 This study uses satellite imagery provided through Google-Earth, Bing Microsoft, EOS
105 viewer, Wayback viewer by ESRI and Copernicus ESA (Table 1). These portals use images from
106 various satellites (Sentinel, SPOT, Pleiades, Quickbird, WorldView-2 and 3) with resolutions
107 ranging from 10 m to 1.24 m for multispectral images, that can be pansharpened with panchromatic
108 images (2.5 to 0.31 m resolution, Ieronimidi et al., 2006). Archived imagery also provides sets of
109 images acquired at different times at several sites. We report here the publicly available imagery
110 used for the different shallow water hydrothermal sites studies in Table 1, together with the
111 acquisition date. These images were selected by visual inspection, based on the absence of large
112 waves, cloud-free scenes, and visibility of the hydrothermal activity offshore.

113 We complemented our study with WorldView-2 (WV2) satellite images provided by the
114 Digital Globe Foundation (Table 2). The WV2 satellite collects both panchromatic and
115 multispectral images of scenes of ~ 6.4 km x 18.0 km, with high spatial resolution of 0.46 m for
116 imagery acquired at 450-800 nm, and 2 m for that acquired in 4 or 8 bands covering 396-1043 nm
117 wavelengths. WV2 acquires images at spectral bands that penetrate water: coastal band 1 (396-
118 458 nm), band 2 Blue (442-515 nm), and band 3 Green (506-586 nm), thus well-suited for littoral
119 mapping at a regional scale down to water depths of up to ~ 30 meters (e.g., Eugenio et al., 2015;
120 Koedsin et al., 2016; Collin et al., 2017).

121 The Digital Globe Foundation provided 13 WV2 images over our main study site, Milos
122 (Greece). After rigorous visual inspection, we selected 4 suitable images for this study (Table 2).
123 These clear-visibility scenes (wave- and cloud-free) reveal hydrothermal features with only
124 smooth processing (interactive stretching in region of interest). The Digital Globe Foundation also

125 provided 37 images from Panarea from which we selected 4 WV2 images (Italy, Table 2). WV2
126 satellite images were processed using ENVI standard procedures. We interactively stretched
127 histograms in region of interest (Figs. 4a, 5b-d, 6a, 8a). In some other cases we also used
128 multispectral analyses over the 8 available bands of the WV images, including principal
129 component analyses (Figs. 3, 4b, 8c, d), and forward minimum noise fraction transform (Figs. 6b,
130 c). Multispectral analyses gave highly contrasted black and white pictures, with smoothing
131 sunlight reflection on waves. The different optical restitutions facilitated the mapping and
132 interpretation (Fig. 4c).

133 We note that for data provided via a public source or through the Digital Globe Foundation,
134 visual inspection of a large set of views was essential to obtain the best images of the seafloor
135 hydrothermal systems. We also note that many images obtained during periods with no cloud cover
136 or significant waves lack visible hydrothermal patterns.

137

138 **3. Geological setting and prior work of studied submarine hydrothermal systems**

139

140 *3.1. Milos (Greece)*

141

142 Milos Island, in the Hellenic Volcanic Arc, resulted from a Late Pliocene to late Pleistocene
143 - Holocene volcanic pulse with submarine to subaerial eruptions emplaced on Mesozoic
144 metamorphic basement and Neogene sediments (Fytikas et al., 1986; Stewart and McPhie, 2006).
145 Intense offshore hydrothermal activity is correlated with tectonic activity (Papanikolaou et al.,

146 1993; Dando et al., 1995b, Aliani et al., 2004; Nomikou et al., 2013; Yücel et al., 2013).
147 Manifestations of this hydrothermal activity include gas emissions, high temperature fluids,
148 microbacterial mats and precipitates of hydrothermal minerals (Fitykas and Marinelli 1976;
149 Liakopoulos, 1987; Dando et al., 1995a; Valsami-Jones et al., 2005; Gilhooly et al., 2014). The
150 Milos submarine hydrothermalism is best studied at the Paleochori Bay, to the SE of the island,
151 through various methods, including echo sounding, divers, submarine robots (ROVs), and drones
152 (Dando et al., 1995a, Price et al., 2013; Gilhooly et al., 2014; Godelitsas et al., 2015; Teague et
153 al., 2018, Durán-Toro et al., 2019). Venting includes free-gas (CO₂, H₂, H₂S, CH₄) variably mixed
154 with seawater, and fluids that are saline and sulphidic, depleted in Mg²⁺ and SO₄²⁻, and enriched
155 in As and metals (Fitzsimons et al., 1997; Valsami-Jones et al., 2005; Wu et al. 2011, 2016; Price
156 et al., 2013; Gilhooly et al. 2014; Godelitsas et al., 2015). This hydrothermal activity results in
157 yellow-orange and whitish precipitates respectively made of As-sulfide and a mix of sulfur and
158 silica (Price et al., 2013; Yücel et al., 2013, Durán-Toro et al., 2019). The coupled hydrothermal,
159 geochemical, and biogenic processes here are also intimately linked to microbial communities
160 (e.g., Houghton et al., 2019). Locally, gas flow rates have been measured underwater (0.2 to 18.5
161 l.h⁻¹, Dando et al., 1995a) or at vent surfaces (<0.1 to 229 ml.m⁻².min⁻¹, Botz et al., 1996), but no
162 site-wide estimates is available to date. Temporal monitoring of the hydrothermal outflow
163 temperature has also been conducted, but at a limited number of sites and over ~ 3 months (Dando
164 et al., 1995a; Aliani et al., 2004; Yücel et al., 2013), showing tidally driven variations.

165 Despite all these studies, we lack a comprehensive and coherent view of the hydrothermal
166 activity at Paleochori Bay (and elsewhere along the Milos shoreline). Prior studies are often local

167 (e.g., Gilhooly et al., 2014; Price et al., 2013), and observations are not properly replaced in a
168 regional map showing the distribution, structure, and geometry of hydrothermal outflow. Figure 3
169 compiles available observations of hydrothermally active areas, and of point measurements of
170 temperature of fluids and/or sediments in Paleochori Bay available in the literature. Processed
171 WV2 satellite imagery in the background reveals the outflow in white and, to a first order, field
172 measurements correlate with hydrothermal outflow features that we describe in detail below.

173 Table 1 reports additional sites along the Milos coast, where the seafloor images reveal
174 similar patterns to those found at Paleochori (Spathi, Voudia, and Agia Kiraki Bays), in Panarea
175 (Italy, see also Table 2), Vulcano (Italy) and Ko-Takara-Jima (Japan, Table 1).

176

177 *3.2. Kueishantao (Taiwan)*

178

179 Shallow-water hydrothermal activity along the southern coast of the Kueishantao Island
180 displays prominent hydrothermal plumes reaching the sea surface and observable in satellite
181 imagery (Chen et al., 2018). Kueishantao, located between the Okinawa Trough and the
182 Philippines basin, hosts recent magmatic activity attributed to extension of the Okinawa Trough,
183 with the most recent eruption dated around 7 ka (Chen et al., 2001). Hydrothermal venting is well-
184 studied (e.g., Chen et al., 2005; Yang et al., 2012; Chen et al., 2016; Lin et al., 2019), and is
185 associated with highly acidic fluids (pH ~2.5-3) venting at temperatures of up to ~120°C and with
186 free gases, mainly CO₂ (Chen et al., 2005; Chen et al., 2016). These plumes are also particle-rich,
187 discharging whitish and yellow fluids, depending on the concentration of sulfur particles (Chen et

188 al., 2001; Han et al., 2014). Gas geochemistry indicate both magmatic degassing and interaction
189 of fluids with marine sediments at depth (Chen et al., 2016), and likely indicate a magmatic system
190 located beneath this island, as indicated by recent seismic studies (Lin et al., 2018). This area is
191 seismically active, owing to both the underlying subduction and intra-arc extension (e.g., Lin et
192 al., 2018), and a possible 2005 diking event associated with the Ilan earthquake (Lai et al., 2009).
193 Seismic activity and extreme meteorological events have induced transient changes of this system,
194 and in situ observations document a decline in the intensity of the hydrothermal activity, in addition
195 to variations in the chemistry and degassing of the system (Lebrato et al., 2019). Overall, both in
196 situ observations (Lebrato et al., 2019) and satellite imagery suggest a significant, recent decrease
197 of hydrothermal activity here.

198 Table 1 reports several additional sites where similar hydrothermal plumes and associated
199 turbid waters are visible from space. All the sites are located along the shore of volcanic areas,
200 mainly in the Pacific. Sites include the active Nishinoshima volcano (Japan), which shows
201 hydrothermal plumes associated with the recent lava flows.

202

203 **4. Results**

204

205 *4.1. Seafloor hydrothermal seepage mapping at Paleochori Bay*

206

207 Figure 4a shows a RGB composition from WV2 bands 1, 2, 3, showing white features at
208 Paleochori and at Agia Kyriaki Bays. Figure 4b corresponds to the band 3 from a PCA processing

209 on 8 bands, showing zones of varying grey tones throughout the two bays, which are visible to
210 water depths of ~ 20 m. These patterns correspond to either seagrass meadows, or to hydrothermal
211 features, as interpreted in Figure 4c, and described below.

212 First, light grey zones in Figure 4b dominate and constitute the background at the bays
213 from the sea shore towards the off-shore, where the seafloor is no longer visible in the satellite
214 imagery. These areas consist of sandy seafloor, and locally scattered seagrass *Cymodocea nodosa*
215 (Aliani et al., 1998). Darker grey areas, found farther from the shore, display curved limits and
216 consist of dense *Posidonia oceanica* seagrass meadows occluding the seafloor (Aliani et al., 1998).
217 Visibility of *seagrass* meadows has facilitated numerous satellite studies of *Posidonia* (e.g., Godet
218 et al., 2009; Costantino et al., 2010) or other species (e.g., Baumstark et al., 2016).

219 Second, the imagery also reveals complex patterns of white seafloor, defining lineations,
220 connected polygons, isolated spots, and diffuse patches (Figs. 3, 4). These patterns are observable
221 both in the processed WV2 images, and in the publicly available imagery (e.g., Google Earth,
222 Wayback ESRI, see Table 1 and Fig. 2a) as highly reflective, white areas visible through the water
223 column. We attributed this highly reflective association of hydrothermal activity with precipitates
224 of white hydrothermal minerals, development of microbacterial mats, or both as is well
225 documented in Paleochori Bay (e.g., Yücel et al., 2013; Price et al., 2013). The association of
226 microbacterial mats and hydrothermal precipitates yields highly reflective areas that are readily
227 recognizable optically. Such features are common in deep-sea hydrothermal systems, where
228 photomosaics have been used to map their geometry and temporal evolution of fluid outflow at
229 the seafloor, and of associated ecosystems (Barreyre et al., 2012; Marcon et al., 2014). Moreover

230 abundant temperature measurements of fluids and gas in the area (Aliani et al., 1998, 2004, Botz
231 et al., 1996, Dando et al., 1995a, Gilhooly et al., 2014, Durán-Toro et al., 2019), and aerial
232 photography at Paleochori (see Figure 1 in Durán-Toro et al., 2019) correlate well with the white
233 areas visible in the satellite imagery (Fig. 3). Hence, based both on satellite imagery and *in situ*
234 observations (Aliani et al., 1998, 2004, Botz et al., 1996, Dando et al., 1995a, Gilhooly et al., 2014,
235 Durán-Toro et al., 2019), the white seafloor features in Paleochori Bay, and at other bays along
236 the coast of Milos, at Panarea, and at Vulcano, are clear indicators of active hydrothermal outflow.

237 The mapping in Paleochori Bay shows that no hydrothermal activity is observed in the
238 immediate vicinity of seagrass meadows (Fig. 4). This confirms reports by Aliani et al. (1998), as
239 neither *Posidonia oceanica* nor *Cymodocea nodosa* develop in areas where the subseafloor (~10
240 cm) shows temperatures >2.5°C above that of ambient seawater.

241 Finally, we observe seafloor with a darker tone than that of the seagrass meadows described
242 above, and localized primarily within Agia Kiriaky Bay, West of Paleochori Bay (Fig. 4b). These
243 darker seafloor zones consist of lineations that in some cases form polygons, which have diameters
244 of 20 to 60 m (Fig. 4b SW region). We lack *in situ* observations that can be associated with these
245 features. Based on their geometry and on their apparent association with the white, hydrothermally
246 active areas, we speculate that these lineations may correspond to darker As-rich hydrothermal
247 sulfides (Dando et al., 2000; Price et al., 2013), or to inactive, fossil outflow zones with altered
248 and dark hydrothermal materials as described at deep-sea hydrothermal sites (Barreyre et al.,
249 2012).

250 The mapping of the different areas shown in Figure 4c both at Paleochori and Agia Kyriaki,
251 based on a WV2 image acquired in 2013, yields a total surface of ~60000 m² associated with white,
252 hydrothermally active seafloor, corresponding to ~2% of the map surface, while the seagrass
253 meadows cover ~19% of the seafloor in this area. Black areas, of possible hydrothermal origin,
254 account for <1% of the seafloor.

255

256 *4.2. Distribution of hydrothermal outflow at the scale of Milos Island*

257

258 The detailed satellite-based mapping of the Paleochori Bay seafloor, supported by
259 published *in-situ* observations, allow us to extrapolate our interpretation to other zones along the
260 Milos shore (Fig. 5b). Patterns similar to those found in Paleochori and Agia Kyriaki Bays (Fig.
261 4) are clearly identifiable in the Voudia Bay (NE of Milos Island, Fig. 5c) and in Spathi,
262 immediately East of Paleochori (Fig. 5d, Table 1). At these sites we identify structures similar to
263 those at Paleochori Bay (lineations, connected polygons and patches). Observations at Voudia Bay
264 are hindered by white water plumes derived from unconsolidated material emanating from
265 exploited quarries of industrial minerals (bentonite and barite). We also observed similar
266 bentonite-sourced white material about 1 km north of Spathi (Fig. 5b). These white sediments may
267 be misinterpreted as white hydrothermal features, and may also cover hydrothermal outflow
268 patterns in the area. The mapping of highly reflective, white seafloor both at Spathi and Voudia
269 Bays indicates that ~1.7% of the seafloor is associated with active hydrothermal outflow, a
270 proportion that is comparable to that found at Agia Kyriaki and Paleochori Bays (Fig. 4). Other

271 reported hydrothermal sites in Milos Bay close to Adamas or close to the airport (Fig. 5a, Dando
272 et al., 1995a; Valsami-Jones et al., 2005) are not visible in satellite imagery and *in situ* instead of
273 satellite mapping would be required instead.

274

275 *4.3. Tracking the evolution of hydrothermal activity in Milos*

276

277 In addition to providing constraints on distribution and geometry of hydrothermal activity
278 (Figs. 4, 5), satellite images acquired at different times document the stability and evolution of the
279 hydrothermal outflow. From our set of satellite images over Paleochori Bay we select two WV2
280 multispectral images (August 18th 2011 and August 30th 2014), in addition to a panchromatic
281 WV2 (November 16th 2010), all imaging the seafloor (Fig. 6) and thus constraining the evolution
282 of hydrothermal outflow geometry over 4 years.

283 The comparison of images acquired at different times (Fig. 6) indicates that the geometry
284 of the hydrothermal system is stable over a few years, and that the visible changes are minor and
285 local, and do not modify the overall structure. For example, the larger hydrothermal patch at the
286 center of Fig. 6 displays significant reflectivity variations within but shows stable boundaries over
287 this period of time. While we do not have imagery to evaluate variations at shorter temporal scales
288 (e.g., seasonal changes, storms, over a few weeks to a few days), Yücel et al. (2013) observed the
289 rapid development of microbacterial mats following a period of significant wind-driven wave
290 action, with seafloor patterns re-established in less than 3 days. This reported observation, together
291 with the imagery available (Fig. 6, Tables 1 and 2), suggests a multi-year stability of the system

292 and an overall geometry unaffected by short-term meteorological events (e.g., winter storms,
293 strong winds and associated waves).

294

295 *4.4. Temporal variability from hydrothermal plume observations*

296

297 The Kueishantao hydrothermal field (Fig. 7) shows a complex temporal evolution, with
298 variations in the number, location, and intensity of hydrothermal plumes imaged at the sea surface.
299 In addition to temporal variations in hydrothermal activity, these satellite images also reveal the
300 strong influence of currents sweeping the area on plume dispersion. These plumes are associated
301 with near-shore vents mapped at water depths of up to ~30 m (e.g., Chen et al., 2005; Yang et al.,
302 2012). The vents discharge high-temperature fluids rich with CO₂ (e.g., Lin et al, 2019). These
303 observations of the sea surface do not constrain the hydrothermal activity at the seafloor, as is the
304 case for the Milos systems, and therefore inferences on variations and distribution of hydrothermal
305 activity are qualitative and indirect.

306 Despite these limitations, satellite views document a decrease in the site's hydrothermal
307 activity from the early 2000's to 2016 (Fig. 7), which is consistent with reported in-situ
308 observations (e.g., Chen et al., 2018; Lebrato et al., 2019). Owing to the currents, it is difficult to
309 determine if observed variations at short time-scales (a few weeks to months) correspond to actual
310 variations in overall hydrothermal fluxes, or, alternatively, to water column processes (currents,
311 waves), which control plume dispersion. This system shows transient behavior as a result of
312 seismicity and major weather events (Lebrato et al., 2019).

313 Satellite images also suggest that hydrothermal outflow geometry at Kueishantao varies
314 significantly over time, consistent with overall flux variations. Plume sources appear and disappear
315 over time, and the temporal persistence of individual plumes is highly variable (Fig. 7). Lacking
316 imagery that is regularly spaced in time, we cannot accurately constrain the life-span of individual
317 vents. However, some vent sources are observed in a single image, suggesting that they are
318 activated and deactivated over periods of time that vary between a few months and a year. These
319 observations suggest that the Kueishantao system is more dynamic and variable than that of Milos,
320 where persistent seafloor patterns indicate a stable outflow geometry over several years.

321

322 **5. Discussion**

323

324 *5.1. Shallow water hydrothermal outflow: modes, temporal variability, and fluxes*

325

326 *5.1.1. Polygonal hydrothermal circulation*

327

328 The well-defined, polygonal patterns of highly reflective hydrothermal deposits or
329 bacterial mats identified at different bays along the southern and eastern coast of Milos (Figs. 4-6)
330 are similar to seafloor features at the Baia di Levante on the Vulcano hydrothermal site (Fig. 8e).
331 These white polygons vary in size from 1 m to up to ~25 m, and appear to develop in bays with a
332 sandy bottom. While we lack *in situ* long-term instrumental data (e.g., temperature) to accurately
333 monitor temporal variability, the satellite images suggest that the organization of hydrothermal

334 deposits and microbacterial mats is associated with a stable sub-seafloor fluid flow geometry over
335 periods of a few years. These hydrothermal polygonal structures are reminiscent of patterns that
336 develop from free convection in porous media heated from below (e.g., Shattuck et al., 1997;
337 Hennenberg et al., 1997; Tasaka et al., 2005; Nield and Bejan, 2006), described in the literature as
338 the Horton-Rogers-Lapwood Problem (Horton and Rogers, 1945; Lapwood, 1948), a porous-
339 medium analog of the Rayleigh-Bénard problem.

340 *In situ* studies in Milos also indicate that areas with white microbacterial mats are
341 associated with higher fluid outflow temperatures than surrounding zones (Wenzhofer et al., 2000,
342 Houghton et al., 2019). While we do not have a precise location of these measurements relative to
343 the structures imaged with satellite, these results would suggest that seafloor patterns indicate
344 hydrothermal upflow (i.e., higher temperature) at white seafloor areas (i.e., edges of polygons).
345 The predicted sense of fluid motion in a hexagonal cell is driven by property variations of
346 convecting fluids. Detailed studies of both the geometry and the temperature associated with these
347 patterns (spatially and in depth), are required to constrain the associated hydrodynamic and thermal
348 conditions (e.g., Nield and Bejan, 2006), and ultimately evaluate thermal and chemical fluxes
349 when coupled with temperature and geochemical data. Satellite images also indicate that this
350 polygonal organization of hydrothermal circulation is restricted in space, laterally transitioning to
351 other modes of hydrothermal outflow (e.g., patches of diffuse flow, see below), that may indicate
352 different hydrothermal circulation regimes.

353

354 *5.1.2. Diffuse flow*

355

356 In addition to polygonal patterns, we observe patches of white seafloor with irregular
357 edges, often displaying variations in their surface (density of their color from white to grey,
358 continuity). These patches, which we attribute to hydrothermal deposits and/or microbacterial mats
359 as in the case of polygonal structures, are found at Paleochori and Spathi Bays (Figs. 5, 6) and
360 Panarea (Fig. 8a), and maintain their overall geometry and extent over several years (Paleochori,
361 Fig. 6 and Panarea, Figs. 8b,c,d). Visually similar patches are observed in deep-sea hydrothermal
362 systems showing diffuse flow (Barreyre et al., 2012; Campbell et al., 2013), with intensity
363 variations attributed to changes in the local hydrothermal flux (e.g., Barreyre et al., 2012). This
364 observation thus suggests that in Paleochori and Voudia Bays both hydrothermal circulation
365 organized in polygonal circulation and pervasive diffuse outflow at white seafloor patches co-exist
366 and persist over several years.

367

368 *5.1.3. Hydrothermal plumes*

369

370 The polygonal and the diffuse hydrothermal circulation systems discussed above are likely
371 associated with low flow rates with clear fluids relative to sites with focused venting, such as the
372 Kueishantao particle-laden plumes (Fig. 7). Plumes imply elevated fluid outflow velocities at a
373 point source, generating a jet and an associated turbulent plume that spreads in the water column
374 (e.g., Speer and Rona, 1989). If water depth is sufficiently shallow or buoyancy flux sufficiently
375 high, plumes can be observed at the sea surface (Fig. 7). While the satellite data acquired at

376 Kueishantao reveal plumes of different sizes, their geometry cannot be used to estimate fluxes as
377 we lack *in situ* measurements on water depth, outflow temperature, or fluid exit velocity.

378 While plumes are observed at other shallow water hydrothermal systems at volcanic islands
379 (Table 1), their nature differ from the Kueishantao plumes (Figures 7c-h). For example, the
380 hydrothermal system in Nagahama Bay, Japan (Table 1) shows several discharge zones along the
381 shoreline (Kiyokawa et al., 2012), with plumes derived from broad zones of outflow rather than a
382 clear point source. The temporal study of this system (Kiyokawa et al., 2012) suggests a
383 hydrothermal discharge coupled with the meteoric groundwater fluctuations along the coast. These
384 systems thus show a coupling of hydrothermal activity with subaerial and subsurface processes
385 (e.g., pluviometry) near shore, and differ with those at Kueishantao (Chen et al., 2005; Chen et al.,
386 2018) and other deep sea vents (e.g., Barreyre et al., 2012; Mittelstaedt et al., 2012), where the
387 focused flow and vents are controlled solely by deep-seated hydrothermal processes.

388

389 *5.1.4. Temporal variability*

390

391 Satellite imagery reveals that shallow water hydrothermal systems display both stability
392 (e.g., Paleochori at Milos) and variability (e.g., Kueishantao, Chen et al., 2018) at time-scales of
393 months to years. The patterns and distribution of hydrothermal deposits and microbacterial mats
394 in areas with repeated imagery available (Milos, Panarea, Figs. 6, 8b-d), suggest that these systems,
395 dominated by distributed flow and low flux rates relative to focused venting, are stable in the long-
396 term (years to decades). In contrast, sites with focused and vigorous venting, such as Kueishantao

397 (Fig. 7, Chen et al., 2018), are highly dynamic systems, with possible unstable heat sources and/or
398 fluid paths that lead to activation and deactivation of vents, in addition to variations in overall flux.
399 Hence, in shallow-water systems with diffuse flow, variations in their distribution and geometry
400 can be monitored from space.

401 Our satellite database cannot document very short-term variability (less than a few months)
402 at shallow water hydrothermal systems (i.e., Milos, Kueishantao). Temperature records of
403 hydrothermal outflow often show a tidal modulation, as shown for Milos (e.g., Aliani et al., 2006;
404 Yücel et al., 2013), Kueishantao (Chen et al., 2005) or Panarea (e.g., Schipeck et al., 2011), and at
405 deep-sea vents (e.g., Barreyre et al., 2014a, b). In addition to periodic variability, these systems
406 may also show events over time as a response to deep-seated processes (e.g., seismicity, magmatic
407 events, etc.) that may modify seafloor permeability, heat sources location, or fluid paths.
408 Stochastic events are common in deep-sea vents (e.g., Sohn 2007; Barreyre et al., 2014a), and
409 documented at Panarea, with a gas outburst in 2002 associated with a change in the hydrothermal
410 circulation at depth (e.g., Esposito et al., 2006; Tassi et al., 2014) that generated plumes visible on
411 the sea surface (e.g., see Fig. 1 in Capaccioni et al., 2005). While this event was not captured in
412 the satellite imagery that we have reviewed (Table 1), it would be visible in satellite imagery and
413 therefore could be monitored from space in real time. Similarly, Milos has experienced similar
414 events, attributed to seawater influx in the hydrothermal circulation system leading to sudden
415 modifications of fluid temperature and chemistry of the hydrothermal fluids, possibly linked to
416 microseismic activity (Aliani et al., 2004, Yücel et al., 2013). These events triggered temporal
417 disappearance of microbacterial mats at the seafloor, with a subsequent recovery (Yücel et al.,

418 2013) (Fig. 6). As such events can be imaged from space, satellite imagery with high revisit
419 frequency has the potential to identify and monitor variations in hydrothermal circulation and
420 associated fluxes at different time-scales (from year to few days).

421

422 5.1.5. Fluxes

423

424 While numerous *in situ* studies have been conducted at some of our studied sites (e.g.,
425 Yücel et al., 2013; Valsami-Jones et al, 2005; Caracussi et al, 2005; Price et al., 2013; Tassi et al.,
426 2014; Chen et al., 2016; see also Fig. 3), neither the fluid or chemical fluxes are constrained. Flux
427 estimates require the systematic optical mapping of zones of fluid emissions and other
428 hydrothermal features, to precisely locate instrumental measurements and samples, and to
429 subsequently extrapolate these local observations to estimate fluxes (chemical, heat, and mass).
430 For example, at the hydrothermal systems described in Milos (Agia Kyriaky, Paleochori, Spathi
431 and Voudia Bays, Figs. 4, 5, Table 1), hydrothermally active areas corresponding to white patches
432 and polygonal patterns represent between 1.7% and ~2% of the total mapped surface (~3.4 km²).
433 Calculation of fluxes would require integration of *in situ* temperature and fluid chemistry data from
434 the mapped hydrothermal structures, an approach successfully applied at deep-sea hydrothermal
435 systems (e.g., Barreyre et al., 2012; Escartin et al., 2015). Furthermore, *in situ* measurements and
436 observations would also document hydrothermal activity that may not be associated with visible
437 hydrothermal structures, and thus not considered in flux estimates based on optical mapping alone.
438 Hence, satellite imagery has the potential to provide the geological context, the distribution and

439 geometry of diffuse shallow water hydrothermal outflow (Figs. 3,5), in order to plan field work,
440 and to ultimately allow flux estimation that is not feasible with *in situ* measurements alone.

441

442 5.2. Mappability of terrestrial submarine hydrothermal systems from space

443

444 5.2.1. Limitations

445

446 While this study demonstrates the possibility of mapping different types of shallow water
447 hydrothermal systems using satellite imagery, several limitations are imposed by the imaging
448 conditions, and by the nature of the hydrothermal systems. Numerous factors can preclude the
449 observation of the seafloor, including water turbidity (e.g., sediment plumes), sun illumination
450 angle, sea surface state, currents, winds, clouds, etc. Indeed, numerous satellite images in Milos or
451 Panarea are unusable, resulting in inhomogeneous time series from one site to another, or at
452 different time windows.

453 Hydrothermal plume sources can be identified in satellite imagery in certain sites (e.g.,
454 Kueishantao), but currents control their appearance, dispersion, and shape at the sea surface of
455 hydrothermal plumes. Furthermore, the interaction between the hydrothermal system and
456 groundwater circulation nearshore can also modify the hydrothermal plumes (e.g., Nagahama Bay,
457 Kiyokawa et al., 2012). Hence, in these systems, the shape and size of plumes cannot be directly
458 interpreted as an indicator of intensity of hydrothermal activity or as a proxy for associated fluxes,
459 and additional parameters (e.g, meteorological data, pluviometry, hydrographic, sea state, and

460 current data, etc.) are required to identify and evaluate the role of processes other than
461 hydrothermal activity.

462 The nature of the submarine hydrothermal system controls its visibility from space. After
463 careful review of satellite imagery, we have identified 15 hydrothermal systems (Table 1) from the
464 >40 sites at water depths of up to 20-30 m identified in the literature (see compilation by Price and
465 Giovannelli, 2017, and references therein). Sites not identified here may not exhibit visible
466 hydrothermal features, such as hydrothermal precipitates, microbacterial mats, or hydrothermally-
467 induced turbidity. For example free gas escapes through both sand and rocky seafloor (e.g.,
468 Champagne Springs, Caribbean) display no distinct texture nor color (e.g., Fig. 2 in Kleint et al.,
469 2017), precluding their identification.

470

471 *5.2.2. Regional mapping of shallow water hydrothermal systems*

472

473 Satellite imagery provides a regional view of hydrothermal systems that is not captured
474 with traditional *in situ* field survey methods. For example, hydrothermal activity has been reported
475 at all the Milos sites shown in this paper but *in situ* observations cannot constrain properly the
476 geometry and distribution of hydrothermal features over very large areas (e.g., Spathi and Voudia
477 Bays, Fig. 5). We propose several approaches to further improve hydrothermal outflow
478 characterization (i.e., nature and extent of the activity). First, a more complete library of satellite
479 data available by different providers (with highest resolution, and adequate spectral measure from
480 one satellite or aggregated images from different satellite taken at same time, Nikolakopoulos, et

481 al., 2007, 2008) would increase the number of images at shallow water hydrothermal sites with
482 more homogeneous data, adequate imaging conditions, and large time covering. Second, *in situ*
483 field work (e.g., scuba-divers, robotic vehicles) at different spatial scales would provide a complete
484 view of the hydrothermal system, and data co-registered with imagery to conduct well-constrained
485 quantitative studies at regional scales (e.g. real extent of the outflow system and characterization
486 of fluxes). Finally, the hydrothermal structures mapped from 0 to up to 30 meter depths may extend
487 to deeper areas (e.g., up to 500 m in Milos, Dando et al., 1995), and studies with remotely operated
488 vehicles or autonomous vehicles are required for the full characterization of these systems from
489 the shore to the deep sea.

490

491 **6. Conclusions**

492

493 Satellite imagery is suitable to study shallow-water active hydrothermal systems, and in
494 particular for (i) imaging hydrothermal outflow at the seafloor to depths of up to 30 m owing to
495 reflective seafloor (hydrothermal deposits, microbacterial mats), and (ii) detecting turbidity at the
496 sea surface associated with hydrothermal plumes. We have identified 15 shallow water
497 hydrothermal systems worldwide in satellite imagery, and focus our study on Milos (Greece) and
498 Kueishantao (Taiwan), two well studied and characterized sites, and with available satellite
499 imagery spanning several years.

500 At Milos, satellite imagery reveals areas of well-organized, polygonal hydrothermal
501 patterns with cells up to 25 m in width, and that are stable over several. The seafloor with reflective

502 zones (active high-temperature outflow) covers ~2% of the studied surface at Milos. At
503 Kueishantao the imaged hydrothermal plumes records a fluctuating activity over several years,
504 with individual plumes varying in intensity, appearing and disappearing. Satellite data thus provide
505 information on the extent and distribution of hydrothermal activity and its temporal evolution.
506 These data are also critical to extrapolate *in situ* field observations and measurements (e.g.,
507 mapping with underwater vehicles, physical and chemical measurements), to estimate fluxes
508 (mass, heat, chemical) associated with this fluid hydrothermal circulation, and focus new *in situ*
509 field work, sampling, and instrumental monitoring.

510

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512

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520

521

522

523 **Figure captions**

524

525 Fig. 1. Active submarine hydrothermal sites visible on satellite images, either as seafloor structures
526 linked to hydrothermal outflow (green dots) or hydrothermal plumes visible at the sea surface
527 (red). See Table 1 for additional details on these sites. A synthesis of identified sites in the literature
528 is available in review papers (e.g., Tarasov et al., 2005; Price and Giovanelli, 2017), and references
529 therein.

530

531 Fig. 2: Satellite images showing hydrothermal activity identified as seafloor structures (Milos,
532 Greece, UTM35-WGS84 coordinate system were used), a) or sea-surface turbidity from
533 hydrothermal plumes (Kueishantao, Taiwan, b). Imagery is from Digital Globe, and obtained from
534 (a) Google Earth viewer (2015/03/15), (b) Bing Microsoft images viewer (undated).

535

536 Fig. 3. Compilation of observations on the occurrence of hydrothermal activity and temperature
537 measurements at Paleochori Bay. Temperatures were measured at different depths subseafloor and
538 within the sediment. Red dots correspond to measurements reported by Aliani et al. (2004), and
539 include a site monitored for 70 days (red dot with thick outline). The orange circle corresponds to
540 the site studied by Botz et al. (1996), and the pink circles to vent sites and temperatures reported
541 by Dando et al. (1995a). Green dots correspond to temperature measurements nearshore by
542 Gilhooly et al. (2014) (SE: Spiegelei). The blue square shows the aerial imagery from Durán-Toro
543 et al. (2019), and the blue line within the transect studied by these authors. RP: Rocky Point. Violet

544 and orange transparent areas correspond to seepage areas of highly saline and sulphidic brines
545 (Fitzimons et al., 1997; Aliani et al., 1998). Background corresponds to multispectral WV2 image
546 from 8 July 2013 (enhanced band 2, from Principal Component Analysis processing on 8 bands).
547 Isobaths from Aliani et al. (1998). UTM35-WGS84 coordinate system were used.

548

549 Fig. 4. Mapping of the geometry and distribution of identified seafloor areas, including zones of
550 interpreted hydrothermal outflow identifiable in satellite imagery at Milos, from Agia Kyriaki
551 beach to Paleochori Bay. Multispectral satellite data (a) is processed to obtain images that enhance
552 features visible at the seafloor (b), that are then used for detailed mapping (c). Seafloor is imaged
553 adequately to depths of ~20 m. As in Figure 3, the 20-m isobaths in 4b are from Aliani et al. (1998).
554 See text for discussion of the different seafloor features and zones interpreted in c). Multispectral
555 WV2 image from 8 July 2013: (a) RGB composition bands 1, 2, 3 (b) enhanced band 3, from PCA
556 processing on 8 bands. UTM35-WGS84 coordinate system were used.

557

558 Fig. 5. Milos Island (a) and overview of seafloor hydrothermal features identified from satellite
559 imagery along the SE coast (b) and detailed view of Spathi and Voudia Bays (c,d). White and
560 reflective seafloor showing textures similar to those presented in figure 4, and defining polygonal
561 patterns, lineations, and patches, are found at different sites of Milos. We also indicate white
562 sediment from a landslide (black arrow). Multispectral WV2 image acquired 8 July 2013 with
563 RGB composition on bands 1, 2, 3 respectively. On figures (c) and (d) the white, reflective seafloor
564 represents ~1.7% of the mapped seafloor surface. UTM35-WGS84 coordinate system were used.

565

566 Fig. 6. Set of images from Paleochori Bay (Figs. 4b) showing the overall temporal stability of the
567 hydrothermal outflow geometry between 2010 and 2014. Red ellipses indicate the same areas to
568 facilitate comparisons among images. Images were acquired in (a) 16 November 2010
569 panchromatic, (b) 18 August 2011 multispectral, (c) 30 August 2014 multispectral. The image
570 were acquired under different conditions: image (a) has different resolution and was acquired at
571 different spectral wavelength, image (b) was acquired under windier and wavier conditions than
572 those of the other two images. The panchromatic images were stretched. For multispectral images
573 stretching was done on images obtained by forward minimum noise fraction transform on 8
574 available bands: resulting band 3 and band 4 for (b) and (c) respectively.

575

576 Fig. 7. Kueishantao Island north-east Taiwan showing the temporal variations in hydrothermal
577 plumes evolution visible at the sea surface and spanning 17 years. White arrows indicate active
578 sites, red arrows new sites, grey transparent arrows inactive sites relative to prior image. The
579 yellow arrow localized breaking waves on a rock peak. Google-Earth viewer images from Digital
580 Globe satellite (a, b, c, e) and CNES/Airbus image source (satellite not indicated), (g), ESRI
581 Wayback Imagery from WV2 satellite (d), and Sentinel-2 imagery (Copernicus viewer, h).

582

583 Fig. 8. Distribution and temporal evolution of hydrothermal structures near Bottaro Island (Italy),
584 hosting the Panarea hydrothermal site (a-d), and of Vulcano (Italy) (e). At Bottaro Island (a-d),
585 hydrothermal activity is associated with light grey to white areas corresponding to white

586 biofilms, sulfur precipitates, brine concentration and the absence of *Posidonia* plants. Red dots
587 indicate main exhalative centers with bubbles obtained by multibeam echo sounding surveys
588 performed between December 2002 and December 2003 (published maps from Anzidei et al.,
589 2005; Esposito et al., 2006). White sand sourcing from the island is trapped in depressions. The
590 rest of the seafloor, partly covered by *Posidonia* mats, consists of loosely to consolidated
591 Holocene sands, gravels and conglomerates derived from lava erosion (Esposito et al., 2006). (a)
592 WV2 multispectral image 25 July 2014. (b,c,d) monochromatic WV2 images from three dates of
593 view, the small square shows stability of a white patch : (b) 9 October 2010, stretched
594 panchromatic image; (c) 3 August 2013, stretched band 4 from PCA analyses on 8 bands; (d) 25
595 July 2014, band 3 from PCA analyses on 8 bands. (e) Baia di Levante at Vulcano Island where
596 two vents has been studied (Capasso et al., 1997, Amend et al., 1998, Skoog et al., 2007). This
597 area shows a polygonal pattern (few meters to 10 meters in diameter) that likely corresponds to
598 structures that are similar to those from Milos. Google-Earth images, July-2017. UTM33-
599 WGS84 coordinate system were used.

600

601 **Tables**

602

603 **Table 1**

604 Shallow water hydrothermal systems visible from Space, and corresponding publicly available
605 imagery. A synthesis of identified sites in the literature is available in review papers (e.g., Tarasov
606 et al., 2005; Price and Giovanelli, 2017), and references therein.

607

608 (1) Imagery names identify access through Google Earth (GE) or Wayback ESRI's viewer

609 (WB). Numbers indicate the year, month and date of scene acquisition (YYYYMMDD).

610 World View satellites are the main source of imagery for both GE and WB viewers,

611 although imagery without the satellite source is also provided (e.g. CNES/Airbus source

612 that may correspond to SPOT images).

613 (2) In the case of the Kueishantao, Methana, and Nea and Palea-Kameni hydrothermal fields,

614 we provide a qualitative indication of the degree of hydrothermal activity, classified as

615 high, medium, low, and no activity (HA, MA, LA, NA), respectively, and based on the

616 number and intensity of recognizable turbid hydrothermal plumes at the sea surface.

617 (3) In Methana hydrothermal activity near-shore is also visible on a near-shore artificial

618 lagoon. Plumes observed in the satellite imagery may correspond to seepage from this

619 lagoon, in addition to or instead of local seepage at the seafloor nearby.

620

621 **Table 2**

622

623 World-View remote sensing data (LV2A, WV2 images) for Milos (Greece) and Panarea Islands

624 (Italy), provided by the Digital Globe Foundation.

625

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