

1 **Interpretations of Reservoir Induced Seismicity may not always be valid: The case of**
2 **seismicity during the impoundment of the Kremasta dam (Greece, 1965-1966).**

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4 **¹Stiros, S.C. and ²Pytharouli, S.**

5 ¹Department of Civil Engineering, University of Patras, GR 26500 Patras, Greece

6 ²Department of Civil and Environmental Engineering, University of Strathclyde, 75 Montrose
7 Street, G1 1XJ Glasgow, UK

8

9 **Abstract**

10 The ‘Kremasta seismic sequence’ in western Greece is one of the most commonly cited
11 examples of Reservoir Induced Seismicity (RIS). Here, we show that this ‘sequence’ is a result
12 of normal tectonic activity and that only some small, unrelated microseismic events are reservoir
13 induced. Shortly after the beginning of the impoundment of the Kremasta Dam in 1965, the then
14 newly established seismic monitoring network in Greece recorded two $M_s \geq 6.0$ events and
15 numerous small shocks spread over a 120 km wide region. These were interpreted as a single
16 seismic sequence (namely the Kremasta seismic sequence), and assumed to be reservoir induced.
17 We revisit the epicenter locations of these events and interpret them in the framework of the
18 regional tectonic context and the local hydrogeology. Placing these events into the local context
19 shows that they represent an amalgamation of separate, ordinary (tectonic) seismic sequences.
20 Further, the regional rocks are highly fragmented by small faults and the spatial distribution of
21 seismic events is not consistent with a model of stress transfer from reservoir loading. In
22 addition, it is not likely that events at such long (> 20 - 30 km) distances from the reservoir could
23 be induced by an initial reservoir load head of 30 m. Whilst the larger magnitude events are

24 tectonic, after impoundment local residents reported an unusual frequency of small microseismic
25 events felt only within 10 km of the dam. We provide evidence that these are a result of the
26 collapse of numerous shallow karstic cavities adjacent and beneath the reservoir due to increased
27 water load (locally 100-150 m depth). This study has significant implications for interpretation of
28 seismic triggering mechanisms in other regions: earthquake occurrence within the proximity of
29 reservoirs during and after impoundment time cannot be assumed to be RIS unless supported by
30 seismological, geological and hydrogeological evidence.

31

32 **Introduction**

33 In 1966 a $M_s 6.2$ earthquake sequence hit a mountainous and poorly populated area NE of the
34 Kremasta dam in central-western Greece (Fig. 1a). The main shock, known as the Kremasta
35 earthquake, occurred in February 5, 1966. This event occurred about six months after the onset
36 of the reservoir impoundment of the 160.3 m high Kremasta dam, the tallest earthfill dam in
37 Europe at the time, owned by PPC (Public Power Corporation in Greece). Because the Kremasta
38 earthquake was preceded and followed by certain smaller seismic events, some of which were
39 felt only in the vicinity of the dam, especially at the residence settlement of the dam personnel
40 (Kremasta campus, about 1 km from the dam), it produced rumors for dam-associated seismicity
41 and motivated a detailed seismological study by Comninakis et al. (1968).

42 This study proved a benchmark in Greek seismology, because the Kremasta earthquake was the
43 first strong earthquake to be recorded by a new seismological network consisting of five, three
44 component, short-period stations, operational in Greece since mid-1965. This new network
45 permitted the recording, for the first time in a broad area, of numerous small shocks preceding
46 and following the shock of February 5th. Comninakis et al. (1968) associated all earthquakes

47 recorded in western Greece mainland between September 1965 and November 1966 to a single
48 seismic sequence (the “Kremasta seismic sequence”), and related it to the impoundment of the
49 nearby Kremasta dam reservoir on the basis of two arguments: the Kremasta seismic sequence,
50 appearing to contain foreshocks, a main shock and a delayed major aftershock (29.10.1966
51 M_s5.8/6.0 Katouna earthquake, Fig. 1c), seemed very long, different from the ordinary seismic
52 sequences recorded previously. In addition, it occurred shortly after the onset of the Kremasta
53 dam reservoir impoundment, at a close distance from the dam.

54 Comninakis et al. (1968) clearly stated that the water load from the dam was *not enough to*
55 *produce an earthquake*, but it was at a level to *trigger* an earthquake; this was because the
56 tectonic strain in the area was assumed to be at a critical level prior to the dam impoundment
57 (“delicate tectonic equilibrium”, Comninakis et al. (1968), p.61), and they argued that “*it was*
58 *just a coincidence that the filling of the lake occurred when the stored energy was ready to be*
59 *released*” (Comninakis et al. (1968), p. 67). Hence, this study considers the Kremasta seismic
60 sequence as a case of Reservoir Triggered Seismicity (RTS).

61 Since then, two main hypotheses have been formulated regarding the Kremasta 1966 M_s6.2
62 earthquake. According to the first, this earthquake is usually viewed as a possible case of
63 Reservoir Induced Seismicity (RIS) (Ambraseys and Sharma, 1968; Gupta et al., 1972; Fitch and
64 Muirhead, 1974; Stein et al., 1982; Meade, 1991). A main argument favoring this association is
65 the absence of reports for earthquakes with magnitude above M_s5.3 in the critical area
66 (Delibassis and Karydis, 1977). An alternative hypothesis is that the Kremasta earthquake may
67 represent ordinary (background) seismicity in a tectonically active region (Fig. 1a; Stein et al.,
68 1982; Ambraseys and Jackson, 1990).

69 Forty to fifty years ago, Seismology in Greece was in its infancy, but since then, much progress
70 was made both in the field of instrumental seismology (Papazachos and Papazachou, 1997) and
71 of palaeoseismology, and such data permit re-evaluation of the relationship between the
72 impoundment of the Kremasta reservoir and seismicity in the area. Clearly, no data that can
73 permit a study similar to that proposed by Dahm et al., (2015) for the discrimination between
74 induced, triggered and natural seismicity based on maxima of occurrence probabilities, exist.
75 However, in this article we re-examine in details the “Kremasta seismic sequence” based on new
76 seismological and tectonic evidence, and in combination with geotechnical evidence, and we
77 conclude that:

78 (1) What was described as the “Kremasta seismic sequence”, is in fact an amalgamation of
79 different seismic sequences, that reflect different causative processes in a tectonically active
80 region and in different tectonic provinces (extensional/compressional; Fig. 1)). In addition, the
81 earthquakes cover an area too large, with strong earthquakes at tens of kilometers from the
82 reservoir, i.e. conditions not favoring reservoir-induced or reservoir-triggered seismicity. The
83 more striking point is that the hypothesis of the ‘Kremasta sequence’ being a case of RIS implies
84 that 40 days after the very start of its impoundment, and while the reservoir level was at the level
85 of 30 m, the Kremasta Dam triggered a seismic sequence, the first event of which was located
86 more than fifty kilometers away (Fig. 2a).

87 (2) Numerous micro-earthquakes at the immediate area of the Kremasta dam, ignored by most
88 investigators, mostly because they were not recorded by the poor seismic network of the period,
89 are likely to reflect RIS. We assign these micro-earthquakes to collapse of karstic cavities
90 because of the imposed reservoir water load. This is a perspective supported by experience in
91 mining and tunneling (e.g. McGarr et al., 2002; Kontogianni and Stiros, 2005; Dahm et al., 2015

92 and references therein), and by the history of leakage of the dam and of the works to control and
93 limit it through extensive grouting. Despite these extensive grouting works, leakage still remains
94 a problem as reflected by the fact that the reservoir level has been kept 9.3 m below its design
95 level (elevation of 273.7 m instead of 282.0 m), reducing its storage capacity by around 15%
96 (Pytharouli & Stiros, 2009). This leakage is in turn the proposed cause of karstic cavity collapse.

97

98 **Previous views for the Kremasta seismic sequence**

99 Comninakis et al. (1968) presented the first study on the “Kremasta seismic sequence”.

100 According to their work, the first “foreshock” of magnitude $M_L 3.7$ occurred on September 11th,
101 1965, approximately one month since the beginning of the impoundment of the Kremasta dam
102 reservoir and ~ 55 km away from it (Fig. 1b). At that time the reservoir level was at the height of
103 174 m (corresponding to a depth of 30 m behind the dam, Fig. 2a). Between 16 and 19 January
104 1966, with the water in the reservoir having reached the elevation of about 250 m (106 m depth
105 behind the dam, Fig. 2), seven shocks were reported, that caused much nuisance to the dam
106 personnel residing at Kremasta PPC settlement (Fig. 3a), approximately 1 km away from the
107 dam. A few weeks later, on February 5th, 1966, the main shock, $M_s 6.2$ occurred at a distance of
108 approximately 28 km NE of the Kremasta dam (Fig. 1b). Several strong aftershocks with
109 magnitude between 2.3 and 5.6 were recorded in the wider region until 27.11.1966 and were
110 regarded as “aftershocks”, including a $M 5.8/6.0$ earthquake (Katouna earthquake) which
111 occurred on 29.10.1966, SW of the main shock (Fig. 1c) and was regarded as a delayed
112 aftershock.

113 Among numerous small shocks, Comninakis et al. (1968) selected and studied 160 events with
114 $M_L \geq 3.4$, more precisely defined and covering a broad area. However, the quality of their

115 epicenters is low, because these shocks were recorded by only a few distant seismological
116 stations; the closest station among them was VLS in Cephalonia Island, ~100 km SW of the dam.
117 In fact, some of the epicenters were defined using recordings only from VLS (Comninakis et al.,
118 1968, p. 42). The distribution of events regarded as “foreshocks” and “aftershocks” in
119 Comninakis et al. (1968) is shown in Fig. 1b using refined location information provided by the
120 Institute of Geodynamics, National Observatory of Athens (NOA). The solution of the fault
121 mechanism of the main shock by Comninakis et al. (1968) showed that it was a shallow event
122 (hypocentral depth of the order of 20 km), and it was also suggested that many of the foreshocks
123 and aftershocks were also shallow.

124 Comninakis et al. (1968) argued that the Kremasta seismic sequence had some particularities: (1)
125 an extraordinarily long length, about 15 months (September 1965 to November 1966), (2) the
126 fluctuations of the frequency of shocks did not comply with the typical time distribution of
127 events in a seismic sequence, (3) the b-value in the logarithmic Gutenberg-Richter equation for
128 the distribution of foreshocks was of the order of 1.41 ± 0.02 . This value is higher than the b-
129 value of 0.64 for previous earthquakes in the region (in Comninakis et al. 1968, p. 59) and $b \sim$
130 0.95 estimated much later (Papazachos and Papazachou, 1997). For this reason, a causative
131 relationship with the reservoir loading of the type of triggering was assumed.

132 Independently of the study of Comninakis et al. (1968), Therianos (1974) reported small shocks
133 felt only in the vicinity of the Kremasta dam for years, increasing in frequency until 1969-1970,
134 and then decaying till 1972 (Fig. 2b). No instrumental recordings are available for these micro-
135 earthquakes, which were empirically recorded by the Kremasta PPC personnel, and who
136 estimated intensities IV and V of the modified Mercalli scale.

137 The main events of the seismic sequence were also analyzed using teleseismic data. These
138 analyses indicated that the main shock (Kremasta earthquake) and the assumed delayed
139 aftershock (Katouna earthquake) had different focal mechanisms than those initially computed,
140 and that the aftershocks seemed to be much deeper than the mainshock (Fitch and Muirhead,
141 1974; Stein et al., 1982). Still, this last result could be an artefact, due to the large uncertainties
142 in the hypocenter locations (Stein et al., 1982; see also Fig. 1d). Because of the limitations of the
143 available seismological recordings, Anderson and Jackson (1987) estimated a focal mechanism
144 compatible to that presented previously by Fitch and Muirhead (1974) and Stein et al. (1982) but
145 assuming an epicenter derived from macroseismic data. A shallow shock (5 km depth) was
146 derived from waveform modelling, in contrast to 15 km – 20 km proposed in previous studies.

147

148 **Re-evaluation of the Kremasta seismic sequence**

149 Based on new evidence, in this section we revisit the proposed causative relationship between
150 strong earthquakes and the Kremasta dam reservoir impoundment, based on the examination of
151 the background seismicity and tectonics of the area, of the pattern of the seismicity in 1965-1966
152 in Western Greece and on the distribution of epicenters in relation to areas of important water
153 loading.

154

155 *Tectonic background: A low seismicity region?*

156 Greece has an excellent, about 2,500 years long historical seismicity record (Papazachos and
157 Papazachou, 1997; Guidoboni et al., 1994), but the distribution of pre-instrumental earthquakes
158 is highly selective, confined to the vicinity of important inhabitation, cultural, commercial,
159 transportation and military centers (Ambraseys, 1971). The broader Kremasta area is very

160 unfavorable for preservation of historical records of earthquakes: it is located in a mountainous,
161 poorly populated and rarely visited area without any significant cultural centers (mostly
162 monasteries).

163 In addition, local lithology is dominated by easily eroding flysch deposits (Bornovas and
164 Rondogianni-Tsiampaou, 1983), not preserving signs of seismic faulting. Under these conditions,
165 it is expected that possible strong earthquakes which may have hit the wider Kremasta area have
166 remained unnoticed (missed events), or in the best of the cases, they have been recorded as
167 moderate earthquakes of neighboring areas (biased events).

168 This poor knowledge of long-term seismicity was a problem of wider scale in Greece, and the
169 existing data were giving evidence of a broad region of seismicity containing aseismic zones
170 (Fig. 1a). However, after the 1956 magnitude 7.6 Amorgos earthquake, which hit the center of
171 the previously assumed aseismic central Aegean, and especially after the 1995 M6.6 Kozani-
172 Grevena earthquake which hit another, previously, assumed aseismic zone in NW Greece (Fig.
173 1a; Stiros 1995; 1998), this hypothesis was practically abandoned. This was also the case with
174 the wider Kremasta area, which was believed to be free of strong earthquakes (Fig. 1a; Delibasis
175 and Karydis, 1977). Recent evidence indicates that several $M > 6.0$ earthquakes per century
176 occur at distances of 20-40 km from the Kremasta dam (Fig. 1 in Kiratzi et al., 2008). This result
177 is consistent with paleoseismological evidence of important tectonic activity in the area of the
178 Katouna earthquake (Pérouse et al., 2017).

179

180 ***Pattern of 1965-1966 seismicity in the wider Kremasta region***

181 Comninakis et al. (1968) *a priori* assigned all earthquakes recorded between September 1965
182 and November 1966 in the wider Kremasta region to a single seismic sequence. This single

183 seismic sequence appeared too long, consisting of several distinct clusters of earthquakes. It was
184 characterized by an overall pattern much different from that known till then for tectonic seismic
185 sequences in the region, involving some foreshocks, a main shock and a sequence of decaying
186 aftershocks. This favored a hypothesis for non-tectonic origin for this seismic sequence.

187 Recent evidence, however, indicates that tectonic seismic sequences deviating from the above
188 pattern are in fact not that unusual: A 1975 seismic sequence near Kremasta included three main
189 events (magnitude 5.4, 5.0, and 5.9, with the first and third events accompanied by foreshocks
190 and aftershocks) and covered a period of more than five months (Delibasis and Karydis, 1977;
191 Kiratzi et al., 2008). The 1996 Konitsa seismic sequence, near the Greek-Albanian borders,
192 consisted also of three moderate events (26.07.1996 M_w 5.2; 06.08.1996 M_w 5.6; 14.11.1996
193 M_w 5.0) and lasted for four months (Theodoulides et al., 1996). Ambraseys and Finkel (1995) and
194 Papazachos and Papazachou (1997) provided evidence of several seismic sequences which lasted
195 between five and six months (01.1544 in Anatolia, 05.02.1641 in Azerbaijan, 07.08.1668 in the
196 North Anatolian Fault; 03.05.1868 Samos Island, 08.11.1905 Athos Peninsula) to up to one year
197 (05.08.1766 Sea of Marmara; 29.07.1752 Thrace) or even up to three years (22.06.1759,
198 Thessaloniki). Whether or not such long seismic sequences reflect an amalgamation of several
199 seismic sequences, it is not easy to say.

200 Experience from recent well-recorded events in NE Aegean may be enlightening. During a
201 period of about one year, three distinct seismic sequences occurred north of Lesvos (Mytilini)
202 island (February-April 2017 M_w 5.3 Ayvacik seismic sequence), south of Lesvos (June to
203 November M_w 6.2 Lesvos earthquake) and east of Lesvos (December, M_w 5.3 Foca earthquake, T.
204 Taymaz et al., in preparation). The feeling, however, of the population of Lesvos for example,
205 was a long seismic sequence with recurrent clusters of seismicity. Hence, the length and

206 fluctuations in the aftershock rates of the “Kremasta seismic sequence”, even if it is regarded as a
207 single seismic sequence, cannot on its own be an argument for RIS or RTS.

208

209 *Distance of the epicenters of major shocks from the reservoir*

210 In Fig. 1c we plotted the approximate 50 m and 100 m contours of the reservoir water depth, i.e.
211 the areas of important water loading ($\sim 0.5\text{-}1.0\text{MPa}$), which was proposed to have induced or
212 triggered seismicity during or after the Kremasta dam reservoir impoundment. The correlation of
213 the water loading with the epicenters of four main shocks which occurred in 1965-1966 in
214 Western Greece is not easy, because these epicenters have large uncertainties (Fig. 1d).

215 However, two main scenarios for the epicenters of the $M_s 6.2$ Kremasta earthquake and of the
216 $M_s 5.8/6.0$ Katouna earthquake are shown in Fig. 1c. A distance of at least 18 and 26 kilometers
217 separates the epicenter of the Kremasta earthquake and the contours of 50 km and 100 km water
218 depth, respectively. The distance between the Katouna earthquake and the Kremasta reservoir is
219 much larger. Within the framework of the local hydrogeology, such distances are too large to
220 favor a causative relationship between the water loading and large earthquakes. Simpson and
221 Negmatullaev (1981) studied in detail the seismicity rates before and after the impoundment of
222 the Nurek dam reservoir. They suggest that increased rates of seismicity were observed within
223 10-15 km from the reservoir and only after the water level exceeded 100 m. In the case of the so-
224 called first “foreshock” (11.09.1965 $M_L 3.7$) of the “Kremasta seismic sequence” the distance
225 between its epicenter and the dam is 56 km (Fig. 1b, epicenter indicated by a black arrow) with
226 the reservoir level being only 30 m (Fig. 2a). If this event is indeed a foreshock of the Kremasta
227 earthquake, it means that the fracture process started soon (about 40 days) after the start of the
228 impoundment, when the causative hydrostatic load was too small (30 m) and at a large distance

229 from it. This water load, corresponding to approximately 0.3MPa, cannot induce an earthquake
230 at that distance.

231 It must be noticed that even at higher water loading levels, any transfer of stresses cannot be
232 facilitated through water conduits at large distances. This is because the wider region is
233 dominated by flysch deposits, characterized by a frequent and chaotic lateral and vertical
234 alternation of impermeable argillaceous rocks (mostly siltstone) and of carbonate rocks that
235 extend to distances between a few meters and a few hundred meters only (Bornovas and
236 Rondogianni-Tsiampaou, 1983). Hence, any transfer of stresses through karst formations, such
237 as those found in the immediate vicinity of the reservoir and discussed in detail further in the
238 text, at distances longer than 0.5-1 km was not possible.

239

240 *Induced/triggered seismicity and different tectonic environments*

241 The 29.10.1966 M_s5.8/6.0 Katouna earthquake (Fig. 1c and 1d) was regarded by Comninakis et
242 al. (1968) as a “delayed aftershock” of the 05.02.1966 Kremasta earthquake. A first difficulty
243 with this interpretation, presented without any specific justification, is that the distance between
244 the two epicenters is > 70 km. A second difficulty is that the two shocks have different focal
245 mechanisms (Stein et al., 1982) and belong to different tectonic provinces: an extensional to east
246 and compressional province to the west, separated by a narrow transition zone correlating with
247 the Pindus Thrust (Fig. 1a-c; Konstantinou et al., 2017). For this reason, the Katouna earthquake
248 has been regarded as an independent earthquake (Anderson and Jackson, 1987; Ambraseys and
249 Jackson, 1990; Baker et al., 1997), that reflected the reactivation of one of the NNW-striking
250 thrusts which control the tectonics of western Greece (Bornovas and Rondogianni-Tsiampaou,
251 1983).

252 The hypothesis that both the Kremasta and the Katouna earthquakes represent cases of triggered
253 or induced seismicity implies that water loading had a critical impact simultaneously in both an
254 extensional and a compressional tectonic province and the potential to produce $M \sim 6.0$
255 earthquakes with a separation of ~ 70 km. An additional difficulty is that the crust in the wider
256 area is highly fractured, without very large faults that have the potential to transfer stress/strain at
257 large distances (Peterie et al., 2018).

258 The possibility that the 29.10.1966 Katouna earthquake was triggered by the 05.05.1966
259 Kremasta earthquake is difficult to evaluate in view of the data uncertainties. Galanopoulos and
260 Economides (1973) argued that the Katouna earthquake was produced by differential loading of
261 underlying evaporites (see Fig. 2 in Pavlou et al., 2016) by the Kremasta earthquake. This
262 argument is also difficult to accept because the east limit of the Triassic evaporites correlates
263 with the Pindus Thrust, the thickness of the evaporites in the Katouna area is limited and any
264 seismic mobilization of evaporites would be expected to occur within a few days to a few weeks
265 from the main shock (Stiros et al., 1994; Nissen et al., 2014; Saltogianni et al., 2016), not eight
266 months later.

267

268 **Karstic void collapse as source of induced microseismicity at Kremasta**

269 Previous studies focused on the possible relationship between large, distant, $M \sim 6.0$ earthquakes
270 and the Kremasta dam reservoir impoundment as a case of RTS. The occurrence of small shocks
271 within 5-10 km from the dam, with a pattern, magnitude range and physical origin very different
272 to the postulated RTS, was ignored. In this study, we provide evidence of micro-earthquakes in
273 the vicinity of the Kremasta dam and suggest that they are the result of collapse of karstic voids
274 due to water loading and therefore a case of RIS.

275

276 ***Microseismicity in the vicinity of the Kremasta dam***

277 There are two sources of information for micro-seismicity in the vicinity of the Kremasta dam:
278 First, Comninakis et al. (1968) report that their detailed study was motivated by seven shocks of
279 short period which were felt in the Kremasta Residential site next to the dam (Fig. 3a), between
280 16 and 19 January 1966, some weeks before the M6.2 Kremasta earthquake. These events were
281 between IV and V on the Mercalli scale and were also associated to “*earth sounds giving the*
282 *impression of abrupt striking at depth*”.

283 Second, Therianos (1974) reported a different set of micro-earthquakes, felt only in the vicinity
284 of the Kremasta dam. These shocks were short, frequently associated with noise and their pattern
285 was felt as an oscillation, or as a pulse. No instrumental records for these micro-earthquakes
286 exist, but they were empirically recorded very carefully by the community living close to the
287 dam. This record covers shocks which culminated in 1967 to 1970 and gradually attenuated by
288 1972 (Fig. 2b). No clear explanation for such events was, however, given.

289

290 ***Karstic voids and leakage at the Kremasta dam***

291 The gradual rising of the reservoir level during the first filling was associated with leakage at
292 several locations at the dam abutments and downstream (arrows in Fig. 3a). Leakage seemed to
293 be proportional to the reservoir level (water load) and reached the amount of 400 - 500 litres/sec
294 in each abutment in spring 1966 for a water depth of 124 m behind the dam (reservoir water
295 elevation of 268 m). Pressurized flow in the diversion tunnel was also observed (ECI, 1974).
296 This situation was critical, and instead of a typical first filling of the dam, several cycles of rising

297 and lowering of the reservoir level were attempted in order to investigate and fix leakage related
298 to hydrostatic loading (reservoir level).

299 A geotechnical study by ECI (1974) revealed that leakage in the dam abutments was associated
300 with karstic voids in three different layers of conglomerates (Upper Conglomerate, U.C., Middle
301 Conglomerate, M.C., Lower Conglomerate, L.C. shown in Fig. 3), alternating with siltstone.

302 Such alternations represent the geological background in the flysch deposits in the region, two to
303 three kilometers thick and with a chaotic pattern (Bornovas and Rondogianni-Tsiampaou, 1983).

304 The detailed geotechnical study indicated that karstic effects were underestimated in the dam
305 design. An extensive program of grouting through numerous boreholes drilled in 10 adits at the
306 downstream side of the dam, was then decided. Adits were typically 2.20 m wide, 2.60 m high
307 and usually more than 200 m long, and their additional role was to drain leaking water and direct
308 it downstream, avoiding piping at the dam's foundations. Voids that were crossed by adits were
309 formally surveyed (Fig. 4a). For voids crossed by drillholes, a cross-section was predicted (Fig.
310 4b). An extensive discussion of the leakage and of the grouting programme to limit them is
311 discussed by Kalkani (1997).

312 The geotechnical study revealed large scale cavities in the three layers of conglomerates found in
313 the dam abutments, especially along faults cutting the area of the abutments, mainly fault FE. A
314 void with maximum vertical range of 16 m was found in a 150 m deep, \varnothing 101 mm drillhole,
315 along one of the faults marked in Fig. 3a (ECI, 1974). Selected cross-sections of these cavities
316 observed along adits or inferred from boreholes are shown in Fig. 4. However, the dimensions
317 and frequency of voids in the wider reservoir area are not known, because the geotechnical study
318 was limited to areas critical to the dam. Leakage was significantly reduced after grouting, but the

319 leakage rates were dependent on the hydrostatic level and kept increasing with time, at least for
320 the lower conglomerate (Kalkani, 1997).

321

322 *Fracture of karstic voids and induced microseismicity*

323 Loading of the reservoir with water of depth exceeding 100 m led to increase of geostatic
324 stresses by about 1 MPa. Such stress change is expected to have led to failure of shallow karstic
325 voids. Because voids seem to be mostly arranged along faults (ECI, 1974), each failure is
326 expected to have led to re-arrangement of stresses, and to new failure, in analogy to collapses in
327 mining and tunneling (Kontogianni and Stiros, 2005; Stiros and Kontogianni, 2009). Because
328 karst is found at shallow depths, fracture conditions are analogous to shallow tunneling (depth <
329 300 m, ambient stresses <10 MPa), and in these conditions viscoelastic properties of the
330 rockmasses play the principal role in the failure mode (Stiros and Kontogianni, 2009; Sulem et
331 al., 1987). This favors relatively slow series of void roof collapses and generation of clusters of
332 shallow micro-earthquakes (“bumps”, Kontogianni and Stiros, 2005; Stiros and Kontogianni,
333 2009, Mc Garr et al., 2002; Dahm et al., 2015), in agreement with the results of Fig. 2b. These
334 clusters of micro-earthquakes could contribute to a growing ‘weak’ damage zone resulting in
335 stress rotation and slip of existing faults even if they are unfavorably oriented (Faulkner et al.,
336 2006). Microseismicity produced at shallow levels (< 200-300 m) can only be felt locally, and
337 this is consistent with the observations in Therianos (1974).

338 It is relevant to note other cases of seismicity caused by karstic collapses following reservoir
339 loading, e.g. at the Three Gorges Dam in China (Yao et al., 2017), as well as the collapse of
340 other types of underground cavities (Dahm et al., 2011; Jousset and Rohmer., 2012; Rudzinski et
341 al., 2016).

342 A critical question is the magnitude of earthquakes that can be generated by collapse of
343 underground cavities. Evidence comes from mining, with M5.0-5.5 typically representing the
344 upper level of magnitude of induced earthquakes (Wong and McGarr, 1990; Pechmann et al.,
345 1995; Walter et al., 1997; Pechmann et al., 2008; Dahm et al., 2015). In the case of Kremasta, the
346 cross-sections of the voids susceptible to collapse are of the order of a few meters, and hence,
347 they may account for shallow events with magnitude $M < 3 - 4$.

348 Another point is whether filling of karstic voids by water prevents failure or further induced
349 failure (cf. Kontogianni and Stiros, 2005). This is clearly a possibility, but judging from the
350 investigated area, karstic voids are numerous and distributed along numerous faults (Figs 3, 4).
351 Furthermore, karstic voids are confined to conglomerates intercalated with layers of
352 impermeable siltstones. In these conditions, numerous flow paths are expected, and despite the
353 extensive grouting through curtains of boreholes (Fig. 4b) leakage was only reduced, not
354 avoided. Furthermore, after the partial or full filling of the reservoir, it would be possible to
355 assume that water has filled karstic voids, especially because they are arranged along faults.
356 Water filling of voids is likely to have led to a new stress budget not favoring gradual, long-
357 lasting void collapses and micro-seismicity, as that summarized in Fig. 2b. The geology of the
358 area, however, does not favor this scenario. The reason is that lithological conditions in flysch
359 terrains are laterally and vertically very variable and chaotic, and terms such as “Upper” or
360 “Lower Conglomerate” in fact indicate formations of non-uniform lithology in which different
361 carbonate rocks might dominate, and at the same time, alternate with argillaceous formations
362 (mostly siltstones). For this reason, karstic voids near the dam were not laterally continuous, and
363 flooding of a certain void was not necessarily followed by flooding of nearby voids, usually
364 protected by a shield of impermeable rocks (siltstone). This “shield” was not endangered by

365 cracks induced by collapses of voids because the plastic zone around them (i.e. a zone of cracks
366 and of permanent deformation formed around a deforming underground void) has typically a
367 width of few meters, as is known from tunnels and mines (Kontogianni and Stiros, 2005). For
368 this reason, even arranged along a fault plane, not all karstic voids, collapsed or not, were
369 flooded, and this favors their gradual collapse and microseismicity lasting for years (Fig 2b).

370

371 **Discussion**

372 We suggest that the “Kremasta seismic sequence” and especially its major seismic events, are
373 unlikely to reflect RIS or RTS effects, for the following reasons:

374 (1) the Kremasta M6.2 and the Katouna M6.0/5.8 are likely to represent tectonic (ordinary,
375 background) earthquakes in a tectonically active area marked by rather frequent earthquakes.

376 This was only a working hypothesis several decades ago (Stein et al., 1982; Ambraseys and
377 Jackson, 1990).

378 (2) what was recognized as the “Kremasta seismic sequence” is likely to reflect an
379 amalgamation of different earthquake sequences in different tectonic environments and in an
380 area too broad to reflect a single seismic sequence (Fig. 1b).

381 (3) the spatio-temporal distribution of the earthquakes in 1965/1996 in western Greece in relation
382 to the location and filling of the Kremasta reservoir cannot justify any causative relationship
383 between hydrostatic loading and seismicity. This is the case both for the strong $M_s6.2$ Kremasta
384 and Katouna M6.0/5.8 earthquakes, and for smaller events such as the first “foreshock” of
385 11.09.1966 (Fig. 1b). This is because the causative effect (water loading) was at large (>20 km)
386 distances from the epicenters of these earthquakes. At least concerning the “foreshocks” of
387 “Kremasta seismic sequence”, water loading was too small (30 m) to have initiated a sequence of

388 induced or triggered seismicity only 40 days after the start of the dam impoundment and at a
389 distance of 56 km (Fig. 2a). Because of the local character of karstic systems, any transfer of
390 stresses through water (karst) conduits at distances longer than 0.5-1 km was deemed not
391 possible during the design process of the Kremasta dam. This hydrogeological model prediction
392 proved correct and no large-scale leakage has been observed in the reservoir, except for the
393 leakage observed next to the dam.

394 (4) Effects of induced or triggered seismicity can be transferred at relatively large distances
395 under certain conditions, especially if there exist faults to permit transfer of stresses (Peterie et
396 al., 2018 and references therein). Such conditions are not met in western Greece, because the
397 crust in this area is highly fragmented and fault lengths are small, favoring a local
398 accommodation and release of stresses.

399 On the contrary, ignored evidence of micro-earthquakes can be assigned to induced
400 microseismicity related to fracturing and collapse of shallow karstic voids beneath and around
401 the dam and the reservoir (McGarr et al., 2002; Dahm et al., 2011; Jousset and Rohmer, 2012;
402 Rudzinski et al., 2016 and references therein). A water column of >100 m induces stresses of
403 around 1 MPa which are important relative to the ambient stresses at shallow levels (<300 m, in
404 which karst is limited) and do not exceed 10 MPa, as is known from tunneling and mining
405 (Panet, 1969; Stiros and Kontogianni, 2009). Failure of such voids, especially as a chain effect
406 through induced/transferred stresses, in analogy to tunnels and mines (Kontogianni and Stiros,
407 2005; Stiros and Kontogianni, 2009) can explain the swarms of micro-earthquakes felt locally in
408 the area of the dam for years (Fig. 2b). Grouting in combination with collapse of karstic voids
409 has not prevented leakage which remains a threat for the dam and has prevented the reservoir

410 from reaching its design level (130 m instead of 138 m), limiting its storage potential to 85%
411 (Pytharouli, 2007; Pytharouli and Stiros, 2009).

412 The scenario that karstic void collapse could instead be due to normal tectonic activity in the
413 region is not likely: similar to mining and tunneling, collapse of tunnels in rock happens only in
414 extreme cases and at high magnitude events ($M > 6.5$), even when tunnels are close to or cutting
415 through faults (Jaramillo, 2017). The magnitudes of recorded seismicity in the region during that
416 period do not support this hypothesis.

417

418 **Conclusions**

419 We suggest that within the framework of the regional tectonic context and the local
420 hydrogeology, the $M \sim 6$ earthquakes which occurred in western Greece in 1966 are likely to
421 represent cases of ordinary (tectonic, background) seismicity as proposed previously in the
422 international literature (e.g. Stein et al., 1982; Ambraseys and Jackson, 1990). More specifically,
423 we note that the occurrence of big earthquakes ($M > 5.8$) at large distances ($> 20 - 30$ km) from
424 the areas of high hydraulic loading, in different tectonic regimes and in highly fragmented crust,
425 cannot be characterized as RIS. This conclusion challenges the previously held assumption that
426 these events were RIS/RTS activity and highlights the fact that earthquake occurrence within the
427 proximity of reservoirs or close to impoundment time cannot always be assumed to be reservoir
428 induced or reservoir triggered activity. On the other hand, we provide new evidence for induced
429 seismicity, associated with collapse of karstic voids (implosions). This seismicity has a pattern,
430 magnitude range and physical origin very different to the postulated RTS before, and explains
431 ignored, non-instrumentally recorded, micro-earthquakes at the Kremasta dam. This seismicity is

432 broadly related to leakage, which, despite an extensive program of grouting through adits and
433 boreholes, it still represents a threat for the structural integrity of the dam.

434

435 **Data and Resources**

436 The epicenters used in Figure 1 can be obtained from the Institute of Geodynamics, National
437 Observatory of Athens (NOA) at <http://www.gein.noa.gr/en/seismicity/maps> (last accessed
438 November 2017) and the International Seismological Center Thatcham, United Kingdom, (ISC)
439 at <http://www.isc.ac.uk/iscbulletin/search/bulletin/> (International Seismological Centre, On-line
440 Bulletin, <http://www.isc.ac.uk>, Internatl. Seismol. Cent., 2014, last accessed November 2017) .
441 All other data used in this paper came from published sources listed in the references.

442

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447

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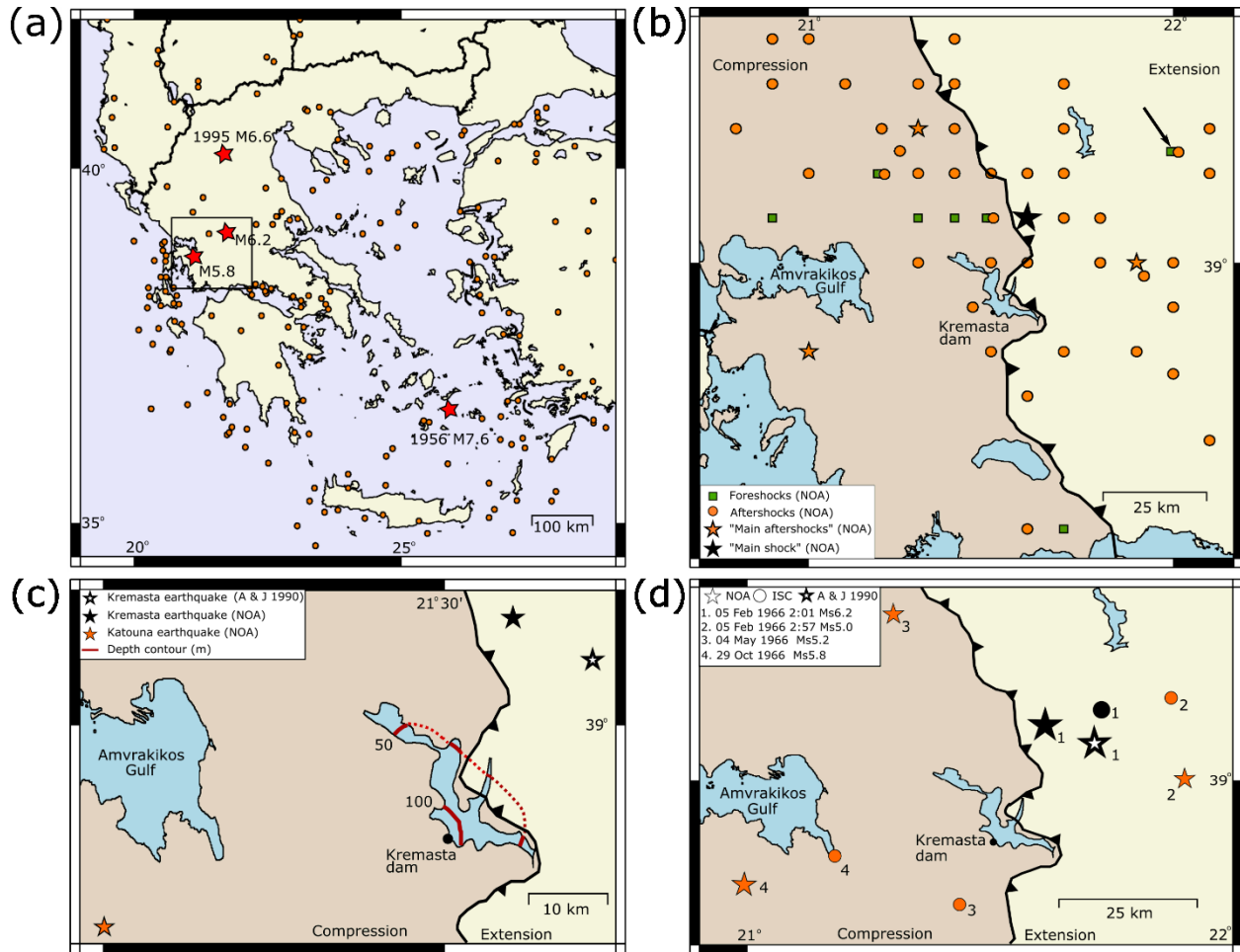
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577 Stathis Stiros
578 Geodesy and Geodetic Applications Laboratory,
579 Department of Civil Engineering, University of Patras
580 GR 26500 Patras
581 Greece
582

583 Stella Pytharouli
584 Department of Civil and Environmental Engineering, University of Strathclyde
585 James Weir Building, Level 5
586 75 Montrose Street
587 G1 1XJ Glasgow
588 United Kingdom
589
590
591
592

593 **Figure Captions**

594



595

596 **Figure 1.** Seismicity in the wider area of the Kremasta dam in 1965-1966.

597 (a) Location map and background seismicity in Greece, 1900 - 2009, $M > 5.8$ (based on
 598 earthquake catalogue data from NOA). Seismicity gives the impression of certain earthquake-
 599 free zones because of scarcity of data and of longer recurrence intervals of earthquakes. Stars
 600 mark the 1966 $M6.2$ Kremasta earthquake, the 1966 $M5.8$ Katouna earthquake, the 1956 $M7.6$
 601 Amorgos earthquake and the 1995 $M6.6$ Kozani-Grevena earthquake, all in the middle of
 602 apparently aseismic zones. The magnitudes of the earthquakes differ between the solutions
 603 provided by different sources. Rectangle marks the area shown in Fig. 1b.

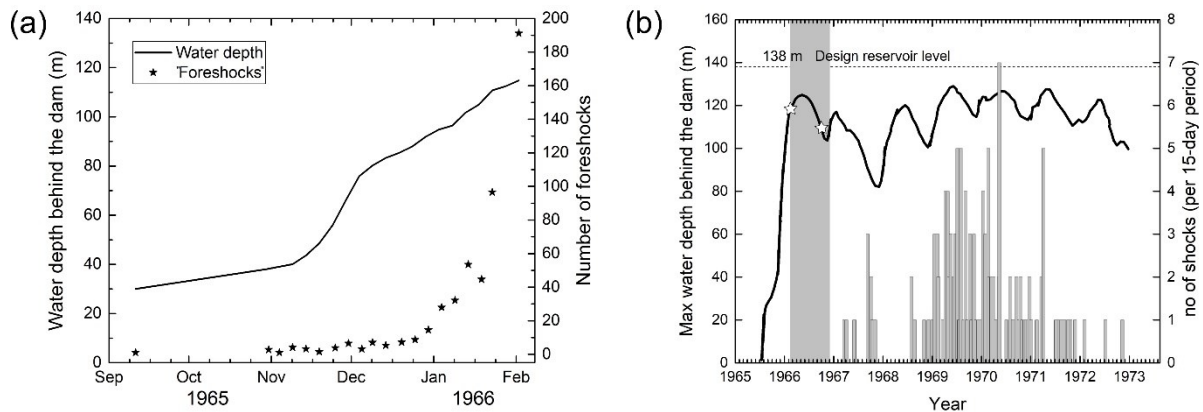
604 (b) Distribution of what was regarded as “foreshocks” and “aftershocks” of the “Kremasta $M_s6.2$
605 seismic sequence” according to Comninakis et al. (1968). Epicenters from the NOA database.
606 The area covered by the earthquakes is too broad to reflect a single seismic sequence. In
607 particular, the 11.09.1965 $M_L3.7$ earthquake, NE of the reservoir, regarded as the first foreshock
608 of the seismic sequence (marked by arrow) is too distant (56 km) from the dam to represent and
609 occurred when loading was rather insignificant (30 m reservoir level) (Fig. 2a).

610 (c) The Kremasta reservoir in relation to the epicentre of the 1966 $M_s6.2$ earthquake (black and
611 white star, after Ambraseys and Jackson, 1990 (A & J 1990), derived from macroseismic data).
612 The solid black and solid orange stars indicate NOA estimates of the epicenter of the $M_s6.2$
613 Kremasta earthquake as well as the epicenter of its assumed main “aftershock”. The 50 m and
614 100 m contours of the reservoir depth are at a distance of > 20 km from the epicenter of the main
615 shock.

616 (d) Epicenters of the main earthquakes in western Greece in 1965-1966 by NOA and ISC. The
617 macroseismic epicenter of the Kremasta earthquake by Ambraseys and Jackson (1990) – A & J
618 1990, based on macroseismic data, is also shown.

619 In (b-d) the Pindus Thrust represents a simplified boundary between an extensional terrain to the
620 east and a strike slip/compressional terrain to the west (Bornovas and Rondogianni-Tsiampaou,
621 1983; Konstantinou et al., 2017).

622



624

625 **Figure 2.** Water level fluctuations in the Kremasta reservoir and seismicity in the broader area

626 (a) The number of foreshocks (stars) seems to correlate with the maximum reservoir depth before

627 the main shock (modified after Comninakis et al., 1968). However, this apparent correlation does

628 not reflect a causative relationship, as analyzed in the text. (b) Relationship between the reservoir

629 level fluctuations and empirically recorded local aftershocks next to the dam, between 1967 –

630 1973 and reservoir level fluctuations (partly based on Therianos, 1974). A shaded zone indicates

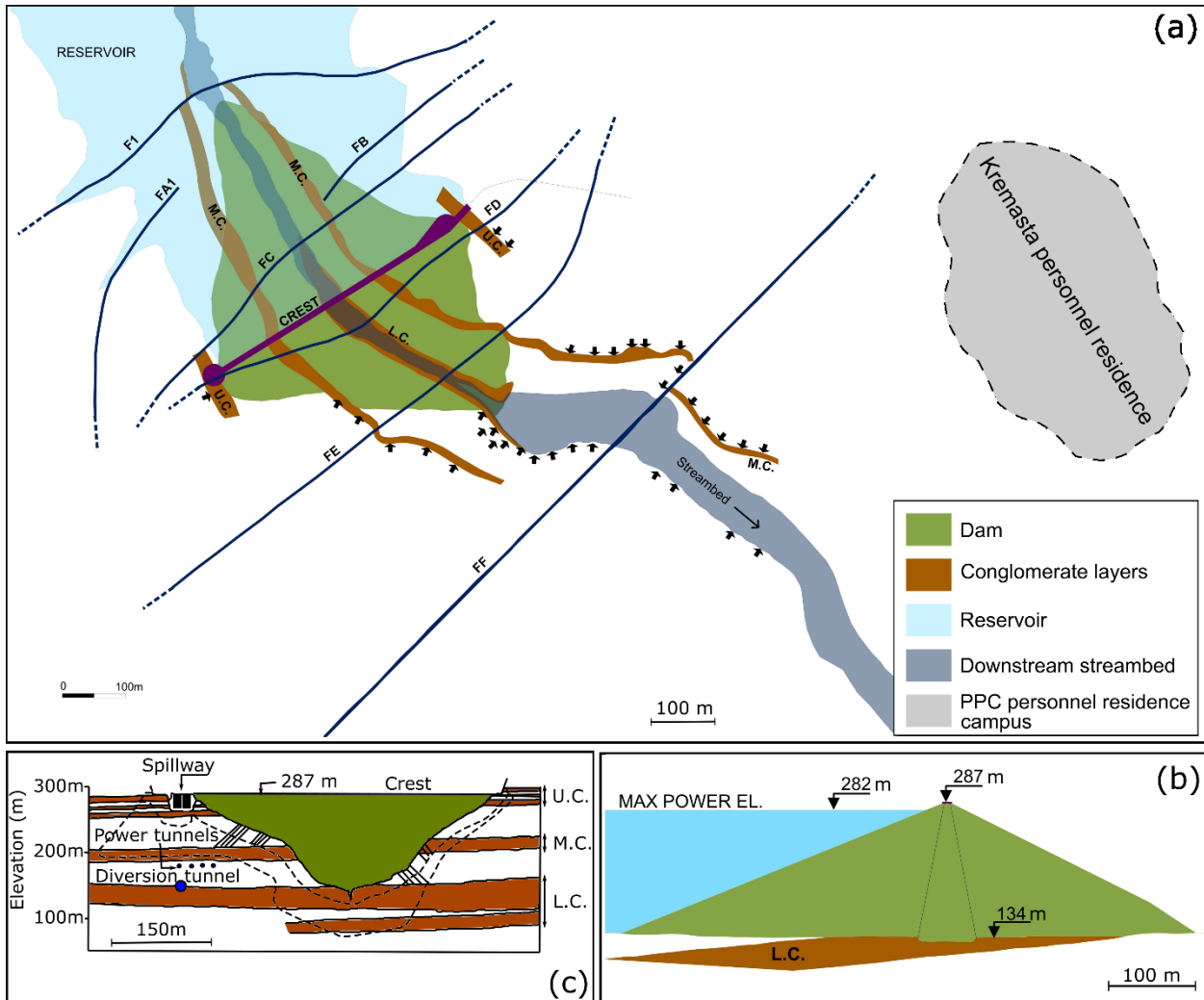
631 the interval of aftershocks of the Kremasta main event, according to Comninakis et al. (1968).

632 Two stars indicate the timing of the assumed main shock (Kremasta earthquake, 05.02.1996) and

633 of the assumed main delayed aftershock (Katouna earthquake, 29.10.1966). The maximum

634 design water depth of the reservoir, 138m, was never attempted, for fear of excessive leakage.

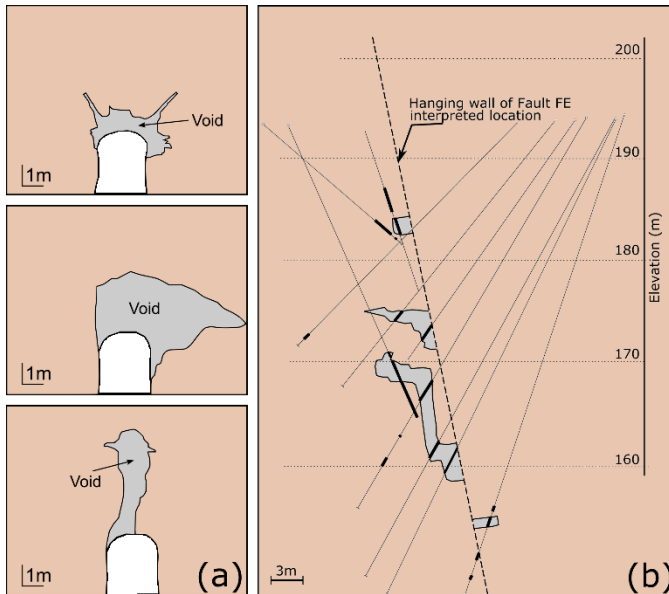
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636
 637 **Figure 3.** Distribution of conglomerates with karstic voids in the foundations and abutments of
 638 the Kremasta dam. The scale is the same on both axes unless otherwise indicated. (a) Plan view,
 639 (b), cross-section and (c) longitudinal cross-section of the Kremasta dam, showing three layers of
 640 highly karstified conglomerates (U.C.- upper conglomerates, M.C. – medium conglomerates,
 641 L.C. – lower conglomerates) and a series of almost vertical faults (marked F1 – FF). This fault
 642 pattern is representative of the wider reservoir area. Hydraulic conductivity tests have shown that
 643 the faults act as barriers to flow at areas dominated by siltstone but can become conduits at areas
 644 with conglomerates. Leakage was observed at several locations downstream at the toe of the
 645 dam, indicated by black arrows (based on ECI, 1974; Pytharouli, 2007). In (c) the dashed lines

646 indicate the approximate limit of the grout lines constructed as part of the foundation treatment
647 under the dam mainly in the Middle and Lower Conglomerates (ECI, 1974).

648



649
650

651 **Figure 4.** (a) Observed and (b) borehole modelled cavities in the abutments and foundations of
652 the Kremasta dam. (a) Representative cavities found along an adit (in white), excavated along
653 Fault FE and the lower conglomerate (L.C.; for location see Fig. 3) to control leakage through
654 extensive grouting. Light shading above the tunnel section indicates the main shape of the void.
655 Void in the form of fissures (‘open channel’) extends all along the fault and was partly filled
656 with soft sediments. (b) A representative vertical cross-section showing a curtain of boreholes
657 ($\text{Ø}101$ mm) and their segments crossing voids (thick lines), used to model karstic voids along a
658 fault (dashed line). Modified after ECI (1974). The overall pattern is representative of the wider
659 area. Voids were found in different levels within the three conglomerate layers, mostly where
660 crossed by faults.