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

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Abstract

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

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

Introduction

In 1966 a M_s6.2 earthquake sequence hit a mountainous and poorly populated area NE of the Kremasta dam in central-western Greece (Fig. 1a). The main shock, known as the Kremasta earthquake, occurred in February 5, 1966. This event occurred about six months after the onset of the reservoir impoundment of the 160.3 m high Kremasta dam, the tallest earthfill dam in Europe at the time, owned by PPC (Public Power Corporation in Greece). Because the Kremasta earthquake was preceded and followed by certain smaller seismic events, some of which were felt only in the vicinity of the dam, especially at the residence settlement of the dam personnel (Kremasta campus, about 1 km from the dam), it produced rumors for dam-associated seismicity and motivated a detailed seismological study by Comninakis et al. (1968).

This study proved a benchmark in Greek seismology, because the Kremasta earthquake was the first strong earthquake to be recorded by a new seismological network consisting of five, three component, short-period stations, operational in Greece since mid-1965. This new network permitted the recording, for the first time in a broad area, of numerous small shocks preceding and following the shock of February 5th. Comninakis et al. (1968) associated all earthquakes recorded in western Greece mainland between September 1965 and November 1966 to a single seismic sequence (the "Kremasta seismic sequence"), and related it to the impoundment of the nearby Kremasta dam reservoir on the basis of two arguments: the Kremasta seismic sequence, appearing to contain foreshocks, a main shock and a delayed major aftershock (29.10.1966 M5.8/6.0 Katouna earthquake, Fig. 1c), seemed very long, different from the ordinary seismic sequences recorded previously. In addition, it occurred shortly after the onset of the Kremasta dam reservoir impoundment, at a close distance from the dam.

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

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

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

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

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

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

Previous views for the Kremasta seismic sequence

Comninakis et al. (1968) presented the first study on the "Kremasta seismic sequence". According to their work, the first "foreshock" of magnitude M_L3.7 occurred on September 11th, 1965, approximately one month since the beginning of the impoundment of the Kremasta dam reservoir and ~ 55 km away from it (Fig. 1b). At that time the reservoir level was at the height of 174 m (corresponding to a depth of 30 m behind the dam, Fig. 2a). Between 16 and 19 January 1966, with the water in the reservoir having reached the elevation of about 250 m (106 m depth behind the dam, Fig. 2), seven shocks were reported, that caused much nuisance to the dam personnel residing at Kremasta PPC settlement (Fig. 3a), approximately 1 km away from the dam. A few weeks later, on February 5th, 1966, the main shock, M_s6.2 occurred at a distance of approximately 28 km NE of the Kremasta dam (Fig. 1b). Several strong aftershocks with magnitude between 2.3 and 5.6 were recorded in the wider region until 27.11.1966 and were regarded as "aftershocks", including a M5.8/6.0 earthquake (Katouna earthquake) which occurred on 29.10.1966, SW of the main shock (Fig. 1c) and was regarded as a delayed aftershock.

Among numerous small shocks, Comninakis et al. (1968) selected and studied 160 events with $M_L \geq 3.4$, more precisely defined and covering a broad area. However, the quality of their epicenters is low, because these shocks were recorded by only a few distant seismological stations; the closest station among them was VLS in Cephalonia Island, ~100 km SW of the dam. In fact, some of the epicenters were defined using recordings only from VLS (Comninakis et al., 1968, p. 42). The distribution of events regarded as “foreshocks” and “aftershocks” in Comninakis et al. (1968) is shown in Fig. 1b using refined location information provided by the Institute of Geodynamics, National Observatory of Athens (NOA). The solution of the fault mechanism of the main shock by Comninakis et al. (1968) showed that it was a shallow event (hypocentral depth of the order of 20 km), and it was also suggested that many of the foreshocks and aftershocks were also shallow.

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

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

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

Re-evaluation of the Kremasta seismic sequence

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

Tectonic background: A low seismicity region?

Greece has an excellent, about 2,500 years long historical seismicity record (Papazachos and Papazachou, 1997; Guidoboni et al., 1994), but the distribution of pre-instrumental earthquakes is highly selective, confined to the vicinity of important inhabitation, cultural, commercial, transportation and military centers (Ambraseys, 1971). The broader Kremasta area is very unfavorable for preservation of historical records of earthquakes: it is located in a mountainous, poorly populated and rarely visited area without any significant cultural centers (mostly monasteries).

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

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

Pattern of 1965-1966 seismicity in the wider Kremasta region

Comninakis et al. (1968) *a priori* assigned all earthquakes recorded between September 1965 and November 1966 in the wider Kremasta region to a single seismic sequence. This single seismic sequence appeared too long, consisting of several distinct clusters of earthquakes. It was characterized by an overall pattern much different from that known till then for tectonic seismic sequences in the region, involving some foreshocks, a main shock and a sequence of decaying aftershocks. This favored a hypothesis for non-tectonic origin for this seismic sequence.

Recent evidence, however, indicates that tectonic seismic sequences deviating from the above pattern are in fact not that unusual: A 1975 seismic sequence near Kremasta included three main events (magnitude 5.4, 5.0, and 5.9, with the first and third events accompanied by foreshocks and aftershocks) and covered a period of more than five months (Delibasis and Karydis, 1977; Kiratzi et al., 2008). The 1996 Konitsa seismic sequence, near the Greek-Albanian borders, consisted also of three moderate events (26.07.1996 M_w5.2; 06.08.1996 M_w5.6; 14.11.1996 M_w5.0) and lasted for four months (Theodoulides et al., 1996). Ambraseys and Finkel (1995) and Papazachos and Papazachou (1997) provided evidence of several seismic sequences which lasted between five and six months (01.1544 in Anatolia, 05.02.1641 in Azerbaijan, 07.08.1668 in the North Anatolian Fault; 03.05.1868 Samos Island, 08.11.1905 Athos Peninsula) to up to one year (05.08.1766 Sea of Marmara; 29.07.1752 Thrace) or even up to three years (22.06.1759, Thessaloniki). Whether or not such long seismic sequences reflect an amalgamation of several seismic sequences, it is not easy to say.

Experience from recent well-recorded events in NE Aegean may be enlightening. During a period of about one year, three distinct seismic sequences occurred north of Lesvos (Mytilini) island (February-April 2017 M_w5.3 Ayvacik seismic sequence), south of Lesvos (June to November M_w6.2 Lesvos earthquake) and east of Lesvos (December, M_w5.3 Foca earthquake, T. Taymaz et al., in preparation). The feeling, however, of the population of Lesvos for example, was a long seismic sequence with recurrent clusters of seismicity. Hence, the length and fluctuations in the aftershock rates of the “Kremasta seismic sequence”, even if it is regarded as a single seismic sequence, cannot on its own be an argument for RIS or RTS.

Distance of the epicenters of major shocks from the reservoir

In Fig. 1c we plotted the approximate 50 m and 100 m contours of the reservoir water depth, i.e. the areas of important water loading (~0.5-1.0MPa), which was proposed to have induced or triggered seismicity during or after the Kremasta dam reservoir impoundment. The correlation of the water loading with the epicenters of four main shocks which occurred in 1965-1966 in Western Greece is not easy, because these epicenters have large uncertainties (Fig. 1d). However, two main scenarios for the epicenters of the M_s6.2 Kremasta earthquake and of the M_s5.8/6.0 Katouna earthquake are shown in Fig. 1c. A distance of at least 18 and 26 kilometers separates the epicenter of the Kremasta earthquake and the contours of 50 km and 100 km water depth, respectively. The distance between the Katouna earthquake and the Kremasta reservoir is much larger. Within the framework of the local hydrogeology, such distances are too large to favor a causative relationship between the water loading and large earthquakes. Simpson and Negmatullaev (1981) studied in detail the seismicity rates before and after the impoundment of the Nurek dam reservoir. They suggest that increased rates of seismicity were observed within 10-15 km from the reservoir and only after the water level exceeded 100 m. In the case of the so-called first “foreshock” (11.09.1965 M_L3.7) of the “Kremasta seismic sequence” the distance between its epicenter and the dam is 56 km (Fig. 1b, epicenter indicated by a black arrow) with the reservoir level being only 30 m (Fig. 2a). If this event is indeed a foreshock of the Kremasta earthquake, it means that the fracture process started soon (about 40 days) after the start of the impoundment, when the causative hydrostatic load was too small (30 m) and at a large distance from it. This water load, corresponding to approximately 0.3MPa, cannot induce an earthquake at that distance.

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

Induced/triggered seismicity and different tectonic environments

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

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

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

Karstic void collapse as source of induced microseismicity at Kremasta

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

Microseismicity in the vicinity of the Kremasta dam

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

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

Karstic voids and leakage at the Kremasta dam

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

A geotechnical study by ECI (1974) revealed that leakage in the dam abutments was associated with karstic voids in three different layers of conglomerates (Upper Conglomerate, U.C., Middle Conglomerate, M.C., Lower Conglomerate, L.C. shown in Fig. 3), alternating with siltstone. Such alternations represent the geological background in the flysch deposits in the region, two to three kilometers thick and with a chaotic pattern (Bornovas and Rondogianni-Tsiampaou, 1983). The detailed geotechnical study indicated that karstic effects were underestimated in the dam design. An extensive program of grouting through numerous boreholes drilled in 10 adits at the downstream side of the dam, was then decided. Adits were typically 2.20 m wide, 2.60 m high and usually more than 200 m long, and their additional role was to drain leaking water and direct it downstream, avoiding piping at the dam's foundations. Voids that were crossed by adits were formally surveyed (Fig. 4a). For voids crossed by drillholes, a cross-section was predicted (Fig. 4b). An extensive discussion of the leakage and of the grouting programme to limit them is discussed by Kalkani (1997).

The geotechnical study revealed large scale cavities in the three layers of conglomerates found in the dam abutments, especially along faults cutting the area of the abutments, mainly fault FE. A void with maximum vertical range of 16 m was found in a 150 m deep, Ø101 mm drillhole, along one of the faults marked in Fig. 3a (ECI, 1974). Selected cross-sections of these cavities observed along adits or inferred from boreholes are shown in Fig. 4. However, the dimensions and frequency of voids in the wider reservoir area are not known, because the geotechnical study was limited to areas critical to the dam. Leakage was significantly reduced after grouting, but the leakage rates were dependent on the hydrostatic level and kept increasing with time, at least for the lower conglomerate (Kalkani, 1997).

Fracture of karstic voids and induced microseismicity

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

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

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

Another point is whether filling of karstic voids by water prevents failure or further induced failure (cf. Kontogianni and Stiros, 2005). This is clearly a possibility, but judging from the investigated area, karstic voids are numerous and distributed along numerous faults (Figs 3, 4). Furthermore, karstic voids are confined to conglomerates intercalated with layers of impermeable siltstones. In these conditions, numerous flow paths are expected, and despite the extensive grouting through curtains of boreholes (Fig. 4b) leakage was only reduced, not avoided. Furthermore, after the partial or full filling of the reservoir, it would be possible to assume that water has filled karstic voids, especially because they are arranged along faults. Water filling of voids is likely to have led to a new stress budget not favoring gradual, long-lasting void collapses and micro-seismicity, as that summarized in Fig. 2b. The geology of the area, however, does not favor this scenario. The reason is that lithological conditions in flysch terrains are laterally and vertically very variable and chaotic, and terms such as “Upper” or “Lower Conglomerate” in fact indicate formations of non-uniform lithology in which different carbonate rocks might dominate, and at the same time, alternate with argillaceous formations (mostly siltstones). For this reason, karstic voids near the dam were not laterally continuous, and flooding of a certain void was not necessarily followed by flooding of nearby voids, usually protected by a shield of impermeable rocks (siltstone). This “shield” was not endangered by cracks induced by collapses of voids because the plastic zone around them (i.e. a zone of cracks and of permanent deformation formed around a deforming underground void) has typically a width of few meters, as is known from tunnels and mines (Kontogianni and Stiros, 2005). For this reason, even arranged along a fault plane, not all karstic voids, collapsed or not, were flooded, and this favors their gradual collapse and microseismicity lasting for years (Fig 2b).

Discussion

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

(1) the Kremasta M6.2 and the Katouna M6.0/5.8 are likely to represent tectonic (ordinary, background) earthquakes in a tectonically active area marked by rather frequent earthquakes. This was only a working hypothesis several decades ago (Stein et al., 1982; Ambraseys and Jackson, 1990).

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

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

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

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

On the contrary, ignored evidence of micro-earthquakes can be assigned to induced microseismicity related to fracturing and collapse of shallow karstic voids beneath and around the dam and the reservoir (McGarr et al., 2002; Dahm et al., 2011; Jousset and Rohmer, 2012; Rudzinski et al., 2016 and references therein). A water column of >100 m induces stresses of around 1 MPa which are important relative to the ambient stresses at shallow levels (<300 m, in which karst is limited) and do not exceed 10 MPa, as is known from tunneling and mining (Panet, 1969; Stiros and Kontogianni, 2009). Failure of such voids, especially as a chain effect through induced/transferred stresses, in analogy to tunnels and mines (Kontogianni and Stiros, 2005; Stiros and Kontogianni, 2009) can explain the swarms of micro-earthquakes felt locally in the area of the dam for years (Fig. 2b). Grouting in combination with collapse of karstic voids has not prevented leakage which remains a threat for the dam and has prevented the reservoir from reaching its design level (130 m instead of 138 m), limiting its storage potential to 85% (Pytharouli, 2007; Pytharouli and Stiros, 2009).

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

Conclusions

We suggest that within the framework of the regional tectonic context and the local hydrogeology, the M~6 earthquakes which occurred in western Greece in 1966 are likely to represent cases of ordinary (tectonic, background) seismicity as proposed previously in the international literature (e.g. Stein et al., 1982; Ambraseys and Jackson, 1990). More specifically, we note that the occurrence of big earthquakes (M > 5.8) at large distances (> 20 – 30 km) from the areas of high hydraulic loading, in different tectonic regimes and in highly fragmented crust, cannot be characterized as RIS. This conclusion challenges the previously held assumption that these events were RIS/RTS activity and highlights the fact that earthquake occurrence within the proximity of reservoirs or close to impoundment time cannot always be assumed to be reservoir induced or reservoir triggered activity. On the other hand, we provide new evidence for induced seismicity, associated with collapse of karstic voids (implosions). This seismicity has a pattern, magnitude range and physical origin very different to the postulated RTS before, and explains ignored, non-instrumentally recorded, micro-earthquakes at the Kremasta dam. This seismicity is broadly related to leakage, which, despite an extensive program of grouting through adits and boreholes, it still represents a threat for the structural integrity of the dam.

Data and Resources

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

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Figure Captions

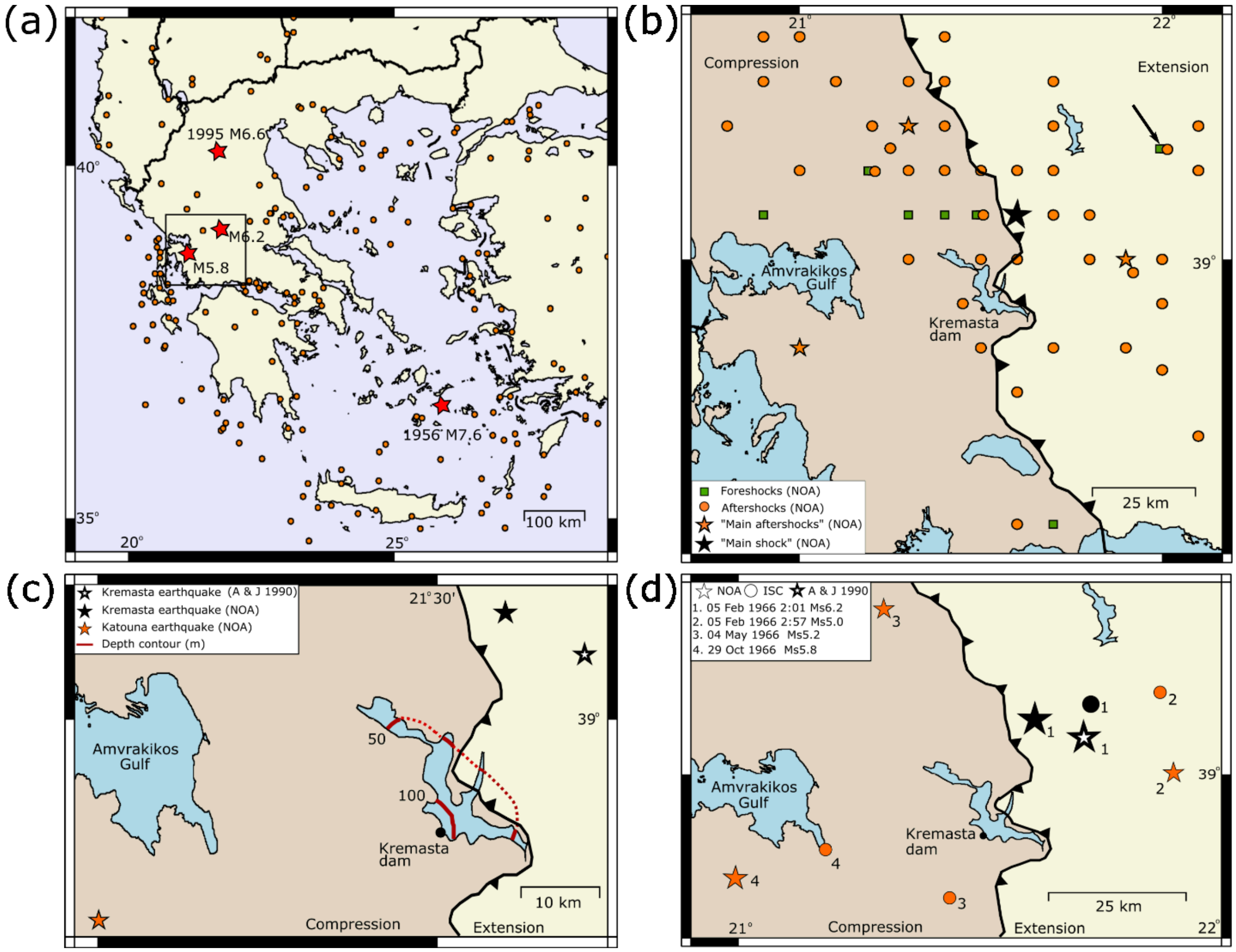

Figure 1. Seismicity in the wider area of the Kremasta dam in 1965-1966.

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

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

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

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

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

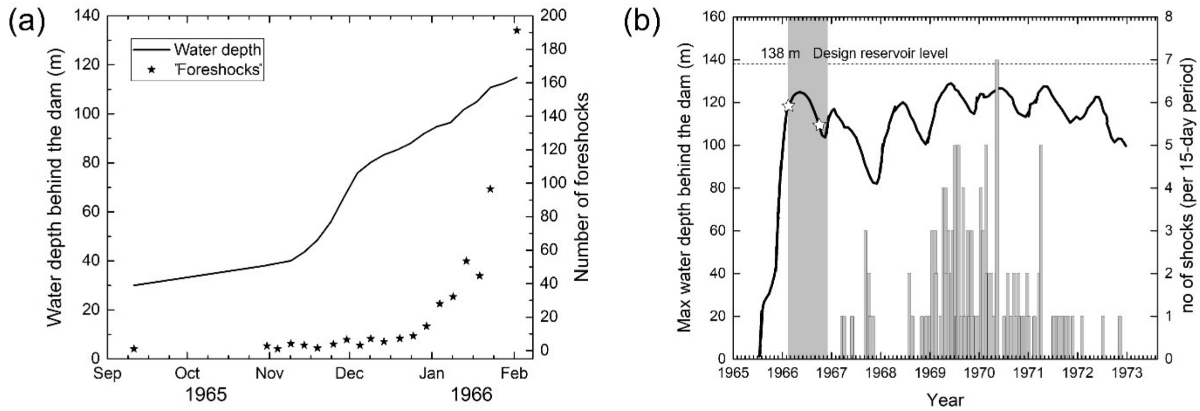

Figure 2. Water level fluctuations in the Kremasta reservoir and seismicity in the broader area (a) The number of foreshocks (stars) seems to correlate with the maximum reservoir depth before the main shock (modified after Comninakis et al., 1968). However, this apparent correlation does not reflect a causative relationship, as analyzed in the text. (b) Relationship between the reservoir level fluctuations and empirically recorded local aftershocks next to the dam, between 1967 – 1973 and reservoir level fluctuations (partly based on Therianos, 1974). A shaded zone indicates the interval of aftershocks of the Kremasta main event, according to Comninakis et al. (1968). Two stars indicate the timing of the assumed main shock (Kremasta earthquake, 05.02.1996) and of the assumed main delayed aftershock (Katouna earthquake, 29.10.1966). The maximum design water depth of the reservoir, 138m, was never attempted, for fear of excessive leakage.

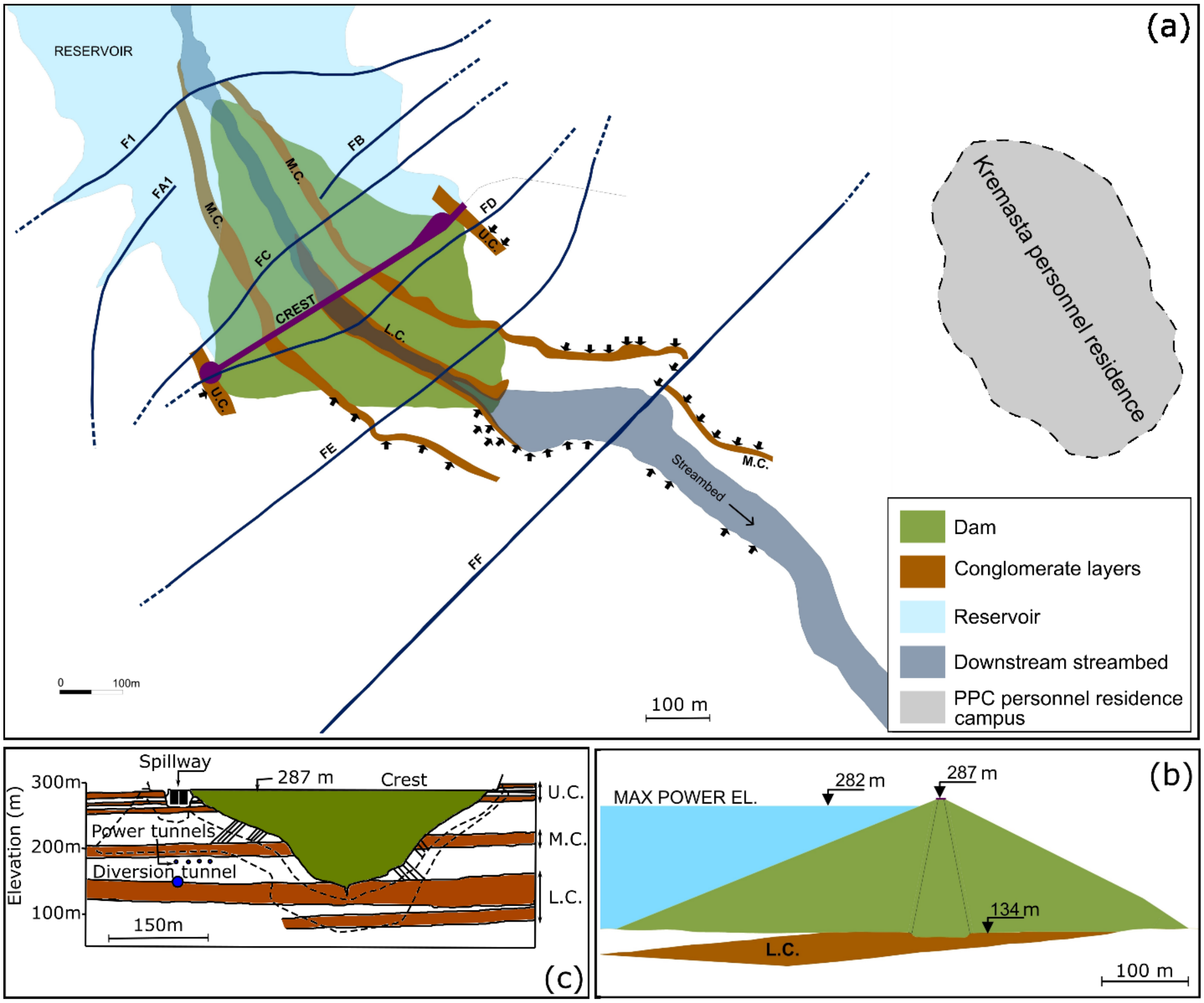

Figure 3. Distribution of conglomerates with karstic voids in the foundations and abutments of the Kremasta dam. The scale is the same on both axes unless otherwise indicated. (a) Plan view, (b), cross-section and (c) longitudinal cross-section of the Kremasta dam, showing three layers of highly karstified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

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

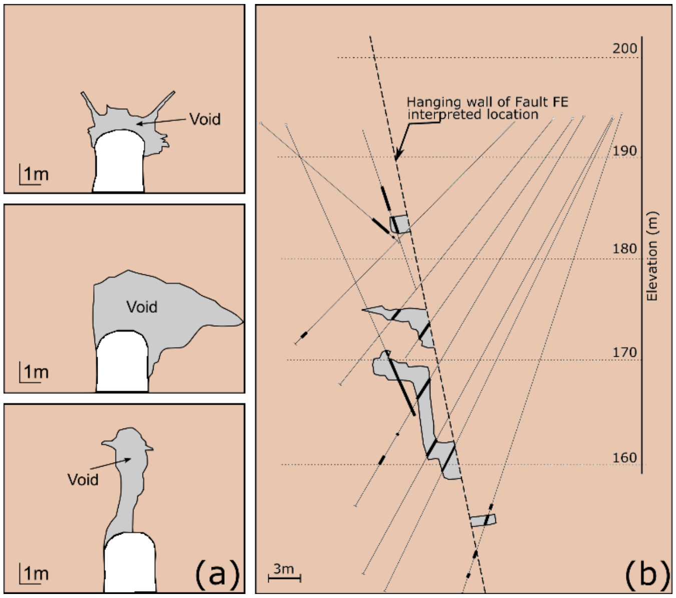

Figure 4. (a) Observed and (b) borehole modelled cavities in the abutments and foundations of the Kremasta dam. (a) Representative cavities found along an adit (in white), excavated along Fault FE and the lower conglomerate (L.C.; for location see Fig. 3) to control leakage through extensive grouting. Light shading above the tunnel section indicates the main shape of the void. Void in the form of fissures (‘open channel”) extends all along the fault and was partly filled with soft sediments. (b) A representative vertical cross-section showing a curtain of boreholes (Ø101 mm) and their segments crossing voids (thick lines), used to model karstic voids along a fault (dashed line). Modified after ECI (1974). The overall pattern is representative of the wider area. Voids were found in different levels within the three conglomerate layers, mostly where crossed by faults.