A pockmark field in the Patras Gulf (Greece) and its activation during the 14/7/93 seismic event

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1. Introduction

At 15.32 on July 14th, 1993 an earthquake of magnitude $M=5.4$ on the Richter scale resulted from a shallow rupture (4.5 km focal depth) in the active Patras graben in western Greece (Fig. 1a). This was one of the largest earthquakes to have occurred in the vicinity of Patras Harbour (Fig. 1) during the 20th century. In this paper the findings from a set of oceanographical and geological data, which were collected over a pockmark field before and after the earthquake, are reported. The study area is located at the southeastern termination of the graben in the vicinity of the city of Patras (Fig. 1). It covers an area of 11 km$^2$ and extends from the 15 to 80 m isobath (Fig. 1).
2. Geological and oceanographical setting

The Gulf of Patras is an actively subsiding Pliocene-Quaternary graben controlled by WSW-ESE faulting (Ferentinos et al., 1985). Quaternary evolution of the gulf is a consequence of interaction between active tectonic subsidence, rapid supply of river sediment and global sea-level changes (Chronis et al., 1991).

The seafloor in the gulf is covered by an almost acoustically transparent layer whose thickness ranges from 20 to 30 m and unconformably overlies a tilted and faulted earlier sequence (Ferentinos et al., 1985). Ferentinos et al. (1985) and Papatheodorou et al. (1993) attributed this unconformity to the Holocene/Pleistocene boundary. Chronis et al. (1991) suggests that the unconformity represents the isotopic stage 2 (Würm) marine lowstand when the gulf was subaerially exposed.

Gas in the sediment of the Quaternary sequence
The data presented in this paper were collected during an environmental oceanographical/geological survey specifically planned for: (1) the study of the morphological and geological features on the seabed for the safe construction of a sewage outfall for the city of Patras and (2) the study of the water circulation and the effluent dispersion in the vicinity of the outfall.

The geophysical survey was carried out using a 200 kHz J.V.C. echo-sounder, a 3.5 kHz GEOPULSE subbottom profiler and a E.G.G. 260 side scan sonar. Positioning was by Differential G.P.S. model "TRIMBLE 4000 II" with an accuracy of 2-3 m and by G.P.S. model "MAGNAVOX MX 200" with an accuracy of 50 m. The survey was undertaken on July 24th, 10 days after the earthquake. The oceanographical survey was carried out using a SENSORDATA 2000 current-meter, which recorded the current velocity and water temperature every 8 minutes, and a SENSORDATA 202 temperature/salinity probe. The current-meter was installed at a water depth of 35 m within the bottom layer, 10 m above the seabed (Fig. 1). It was installed on July 13th (30 h before the earthquake) and was recovered on July 17th (60 h after the earthquake). During the survey wind data (direction and speed) were also taken from the nearby station in Patras harbour and analysed.

4. Data presentation

4.1. Oceanography

Examination of the temporal and spatial distribution of the data collected by the temperature and salinity probe over the investigated area has shown that the water column is divided into two layers (Fig. 2). The upper layer has a thickness of about 12 m and a temperature of 23.5°C. The bottom layer which extends to the seabed has a thickness of 17 m and a temperature of 16.6°C. The two layers were separated by a sharp thermo-
Fig. 3. Temperature variation versus time in the current-meter station, 10 m above the seabed, from July 13th (30 h before the earthquake) to July 17th (60 h after the earthquake). The straight line after the three peaks indicates the time of the earthquake.

cline with a gradient of 1.3°C/m. The salinity of the upper layer varied between 38.3‰ and 39.1‰ and in the bottom layer varied between 38.9‰ and 39.1‰. In the bottom layer, during the 4 day recording period, the temperature varied slightly from 16.5 to 17.5°C but there were three sudden and sharp temperature changes (Fig. 3). The first sharp temperature increase was recorded at 22.40 on July 13th when the water temperature rose from 16.8°C to 19.3°C for a duration of 1 h 20 min. The second increase was recorded at 01.30 on July 14th, when the water temperature rose from 16.8°C to 23°C for 5 h 25 min. The third increase occurred at 10.00 on July 14th and the temperature rose from 17°C to 22°C for 5 h. During the same period the sea was calm, the wind was blowing from variable directions and was less than force 3.

4.2. Geology

Examination of high resolution seismic profiles and sonar images in the investigated area have shown the existence of a variety of anomalous acoustic characters indicative of the presence of gas in the sediments and gas escape features in the seabed.

The seismic profiles show an acoustically transparent sequence with few and weak internal reflectors (Holocene sequence) overlying a highly reflective surface that blocks further seismic penetration (Fig. 4). This highly reflective surface represents the Pleistocene/Holocene boundary (Chronis et al., 1991; Papatheodorou et al., 1993). The strong acoustic character of this surface can be attributed to one or more of the following: (1) sharp contrast in sediment types and (2) gas charged sediments.

Five shallow borings (maximum depth 35 m) which have been drilled within the studied area have shown that the Holocene sequence consists of silts and localised sandy silt horizons. The silts in engineering terms are soft and on average are characterised by liquidity index values greater than 1 (LI>100%), dry apparent unit weight of 1.35 T/m³ and standard penetration test (SPT) values of N=2. The upper parts of the Pleistocene sequence consist similarly of silts but they are somewhat stiffer, having on average LI=85%, dry apparent unit weight of 1.45 T/m³ and SPT values N=4–5. In one of the borings underneath the Holocene sequence a 20 m thick, sandy gravel layer was detected.

The aforementioned together with the presence of gas-related features in the seabed suggest that the highly reflective surface is a result of (1) a change in the geotechnical properties of the sediments and (2) the presence of gas in the lower sequence. Therefore, the Pleistocene/Holocene boundary can be considered as a gas accumulative horizon.

The appearance of enhanced reflectors within
the Holocene sequence indicate an upward migration of gas and its entrapment in porous horizons within the transparent sequence. This suggests that the Holocene sequence cannot completely restrain the vertical migration of gas.

Synsedimentary active faults affect the Quaternary sequence, forming rotated blocks (Fig. 4). In each individual fault block the gas appears to migrate up-dip along the Pleistocene/Holocene boundary trying to reach the summit of the tilted block. There it is halted and accumulates forming in some cases gas pockets as the Pleistocene porous layers through which the gas percolates come in contact with the impermeable Holocene layer due to the fault offset (Fig. 4a and b). At the up-dip end of the tilted blocks very small and shallow pockmarks have sometimes been observed on the seafloor (Fig. 4c). The existence of acoustically turbid sediments within the transparent sequence between the base of the pockmark and the enhanced reflector in the summit of the tilted block (Fig. 4c) suggests that the gas which flows up-dip the boundary is not fully trapped, but at the termination of the tilted block turns and flows upward through the fault zone thus forming the pockmark.

Dome shaped reflectors have been detected in many locations and are indicative of low relief intrasedimentary and seabed doming which is being raised about 1–2 m relative to the surroundings (Fig. 5). These domes have probably been formed by “high pressure” gas build up at the Pleistocene/Holocene boundary. Similar domes have also been observed in other areas of the world (Hovland and Judd, 1988) and their formation has been attributed to the same mechanism.
Very often the flexured layers are broken by the doming (Fig. 5).

Conical and dish shaped incisions observed in the seismic records, truncating the layering of the upper sequence are pockmarks (Fig. 6). The pockmarks form an extensive field (Fig. 1) which occupies an area of 1.7 km² and are confined between the 15 and 35 m isobaths. The pockmarks occur in a wide variety of sizes and shapes most of which are composite and a few single. Single pockmarks are usually symmetric in profile and circular in plan view while others are asymmetric. The composite pockmarks are formed by the amalgamation of single pockmarks (Fig. 7) which on the side scan sonar images are shown as one overlapping the other.

The single pockmarks have a diameter ranging from 25 to 130 m whilst the diameter of the composite pockmarks can be as long as 250 m. A rough estimate of the average diameter is about 98 m. The depth of the pockmarks ranges from 0.5 to 4 m for the small ones and from 10 to 15

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**Fig. 5.** 3.5 kHz profile showing gas pockets (GP) in the Holocene sedimentary cover associated with faulting (F) and doming (D) in the seabed. ATZ = Acoustic Turbid Zone; HOL/PL = Holocene/Pleistocene boundary.

**Fig. 6.** 3.5 kHz seismic profiles showing pockmarks at which some of the features described in the text are demonstrated: (a) a large pockmark whose floor reaches the Holocene/Pleistocene (HOL/PL) gas accumulative interface; (b) and (c) pockmarks surrounded by a chimney-like zone of transparent acoustic character (TR) indicating that gas venting takes place all over the pockmark floor. ATZ = Acoustic Turbid Zone.
m for the larger ones with an average of 8.8 m. The side walls of the pockmarks are very steep and in many cases the gradient ranges from 22° to 23° (40–43%).

The base of the largest pockmarks usually reaches the Pleistocene/Holocene interface (Fig. 6a) whilst the base of the smaller pockmarks is located at a distance of 5 to 10 m above the interface (Fig. 6b and c). Many of the pockmarks are characterised by the existence of an acoustically turbid zone which is located under the base of the pockmark and sometimes extends down to the interface (Fig. 8). In other pockmarks there is a chimney like zone which is characterised by an incoherent or transparent acoustic character (Fig. 6b and c). This zone is not just confined under the base of the pockmarks but also extends under the sidewall.

The existence of an acoustic turbid zone underneath the pockmarks suggest that there is a continuous supply of gas from below towards the pockmarks and that at present the sediments within the migration path are gas-charged. The coherent or transparent acoustic character under the base and the sidewalls of most of the pockmarks probably suggests that (a) the gas venting is not restricted only to the centre of the pockmark but also takes place under the sidewalls (b) the sediment texture has been disturbed by the gas venting and (c) the sediments within the migration paths are at present gas-free due to the loss of gas through recent out-gassing. Once the sediments within the migration paths are filled with gas and gas pressure builds-up, another venting (of gas) takes place. According to the theory of pockmark formation (Hovland and Judd, 1988) the initial escape of gas is enhanced as a new migration path will have to be established, so it is believed that this acoustic character is formed in the first stages of (single) pockmark development. The release of gas under the sidewalls allows continuous mass wasting and re-working all around the crater and causes the maintenance of steep slopes. The very loose nature of the sediment may also have helped this process to take place.

The sidewalls of some pockmarks are affected by gravitative mass movements (Fig. 8). Profile -a- (Fig. 8a) which run across the largest composite pockmark observed shows a rotational slide affecting the sidewall and a detached block resting on the bottom of the pockmark. The sliding plane of the rotational slide is a gas accumulative horizon as is indicated by the acoustic turbidity. Profile -b- (Fig. 8b) shows a single pockmark whose floor seems to be capped by a detached block whilst profiles -c- and -d- (Fig. 8c and d) show small mass flows lying over the pockmarks floor. The sediment movement and flows can be induced by
Fig. 8. 3.5 kHz seismic profiles showing pockmarks at which some of the mass movement features described in the text are demonstrated: (a) a rotational slide (SI) affects the sidewall of a composite pockmark and a detached block (DB) rests on the pockmark floor; (b) a detached block (DB) rests on the pockmark floor; (c) and (d) small size mass flows (MF) unconformably cover the pockmark floor. A columnar-like shape acoustic turbid zone (ATZ) underneath the pockmark’s floor indicate the existence of a gas migration path rising from the Holocene/Pleistocene boundary and that the sediments within the path are gas-charged.

GS = Gas Seepage; ER = Enhanced Reflector.

(1) the oscillatory loading of wave motion on the bottom which causes shear failure in soft sediments (2) earthquakes and (3) tsunamis.

The presence of mass movements covering the floor of the pockmarks suggests that gas-venting can be temporally blocked. This may either lead to a rapid establishment of a new migration path(s) through which gas is gently emanating or to a more abrupt gas emission if large volumes of gas accumulates and no slow seepage occurs for a long period. The above-mentioned process is probably a matter of the volume of the mass flow/slide, the available gas and the rate at which it accumulates and of the physical properties of the sediments. The aforementioned suggest that the pockmarks have grown in size through a combined process of sediment displacement by gas and slumping, thus modifying the depression to a more complex form.
The majority of the pockmarks were active during the survey a few days after the earthquake, as sharp-edged, highly reflective patches (gas plumes) were detected in the echo-sounder, side scan sonar and 3.5 kHz records above the seafloor indicating bubbles ascending in the water (Fig. 9). In two or three pockmarks the extremely high reflectivity of the plumes shown on the sonargraphs (Fig. 9) is interpreted as being due either to the high concentration of gas bubbles in the water column or/and to sediment suspension caused by the ascending gas bubbles.

5. Discussion

Data collected during previous surveys has shown that gas charged Quaternary sediments cover about 70% of the seafloor of the Patras Gulf, which has an area of 800 km² (Chronis et al., 1991). The presence of gas was identified by mapping acoustic anomalies associated with gas in over 450 km of shallow reflection profiles recorded within the gulf.

The present detailed study was restricted near Patras harbour in the southeastern coastline of the Gulf over an area of about 11 km² (Fig. 1). The study has shown the existence on the seafloor of gas related features similar to those described for the whole gulf by Chronis et al. (1991) and Papatheodorou et al. (1993). It further showed within this area the existence of a pockmark field which extends over an area of about 1.7 km².

The pockmarks have an average diameter of 98 m, ranging from 25 to about 250 m. The average depth of the pockmarks is 8.8 m, ranging from 0.5 to 15 m. The density of the pockmarks found is 80 per km², however dense clusters of up to 150 per km² locally exist. The pockmarks found in Patras Gulf, based on the aforementioned parameters can be considered to be amongst the largest and deepest observed (Hovland and Judd, 1988).

The size and apparent variations in density of the pockmarks are controlled not only by the volume of the causative gas available which as mentioned before is abundant all over the Gulf, but also by the characteristics of the containment sediments, such as grain size distribution and shear strength. The silty and sandy-silty sediments together with the very soft (low strength) nature of the seabed are considered as important factors in the formation of pockmarks.

There is no conclusive evidence as to the origin of the gas in the area. The vertical extent of the gas cannot be assessed due to the acoustic masking of the gas. However, taking into consideration
that the gas has accumulated within the upper layers of the upper Pleistocene sequence, it is most likely that the gas originated in the deeper parts of the Pleistocene sequence and migrated upwards through the porous Pleistocene layers. Therefore it can be suggested that the upper Pleistocene silts and the high water content Holocene silts restrain the upward migration of gas.

The presence of gas-plumes in the water column which are closely related to the large number of pockmarks, indicate that during the survey most of the pockmarks were active. Further, the detection of only one buried pockmark within the entire pockmark field together with the fact that the pockmarks are located in very shallow waters where sediment on the seafloor can be suspended and transported by the wave regime in the Gulf and therefore filling the pockmarks, suggest a long-term static activity of the pockmark. The fact that, most of the pockmarks exhibit sharply defined morphology with steep slopes and the high density in which they occur are also indicative of long-term and continuing activity.

The existence of pockmarks on the seafloor and the presence of actively seeping gas in the vicinity the measured intermittent and abrupt temperature anomalies in the water column indicate a probable causative relationship. It is considered that the three abrupt temperature increases in the bottom water layer, observed at the current-meter station (which was installed inside the pockmark field) were probably the result of upward migrating gas bubbles in the water column whose temperature was much higher than the ambient water temperature. A causative relation of the intermittent temperature anomalies observed, with the formation of downwelling condition along the coastal zone should be excluded, as during the survey the prevailing wind pattern was not favourable for the development of downwelling.

The detection of gas-bubbles over a large number of pockmarks, suggests that the three intermittent events of temperature increase recorded in the current-meter station were not of local occurrence restricted to the vicinity of the station but were of a much wider occurrence probably from the entire pockmark field. For such large changes to occur in the bottom water temperature, the average thickness of which is about 15 m and extends to an area of about 1.7 km², an enormous amount of heat would have been required. Therefore it is considered that huge quantities of hot gas were intermittently emitted through the pockmarks.

The three abrupt intermittent gas release events might have been caused by respective changes in the stress regime prior to the earthquake which then resulted in the destabilization of the granular framework and thus in a tendency for closer packing leading to reduction of the pore volume in the sediments. This volume reduction was then followed by an upward migration of gas which had previously been trapped within the pores.

The escape of biogenic gas from the sediments is perhaps, the most probable cause of the anomalous acoustic characters in the sediments, the pockmarks and the intermittent temperature anomalies, which are described in this paper. However, other fluids such as ground water, thermogenic (petroleum) fluids and volcanic or hydrothermal gas, can also be considered as being potentially responsible. Fresh hot water ground seeps (geothermal springs) can be ruled out as a probable liquid, responsible for the occurrence of the above-mentioned features, as no salinity anomalies were observed within the craters. Similarly thermogenic and hydrothermal fluids should also be ruled out as there is no geological evidence from the surrounding area to support their presence in the deeper layers.

Similar phenomena, to that described in the present paper have been reported during the last two centuries from two adjacent sites. In the vicinity of Aegion harbour which is about 40 km to the east of Patras (Fig. 1a), Pouqueville, a French geographer reported that during an earthquake event in 1817, the seawater became hot enough to burn the hands of the fishermen and "bubbles together with smoke came out" of the sea (Papazachos and Papazachou, 1989). A pockmark field was detected over the same area on the seafloor in 1992 (S. Soter, pers. commun.).

At Mesologhi lagoon (Fig. 1a) on the northeastern part of Patras Gulf, during an earthquake event in 1882, gas bubbles appeared on the sea surface whilst at the same time a strong odour
rather like that of rotten eggs pervaded the air (Papazachos and Papazachou, 1989). This smell could most probably be attributed to the emission of methane and hydrogen sulfide from the sediments and resulted in the death of many fish in the lagoon.

The same phenomenon of gas bubble emission with the simultaneous pervasion of the air with the smell of rotten eggs, occurred in 1990. No earthquake was recorded during that period nor was another potential triggering mechanism like tsunami or storm observed which can temporarily reduce the confining pressure on the seabed and result in gas release. This gas emission can therefore be attributed to the gradual build up of gas pressure in the sediments of the lagoon.

Triggering of gas seepage by earthquakes has also been documented at Malibu point in California (Clifton et al., 1971) whilst Field and Jennings (1987) have documented the formation of low relief mounds and craters at Klamath river in California after an earthquake. The above examples demonstrate clearly that earthquakes activate gas venting. If the gas venting is steady, then earthquakes may enhance the rates of gas emission as observed in the present study. However enhanced gas venting may also be activated by prolonged elevated pressure due to gas accumulation.

Earthquakes of magnitude over 4R occur in Patras Gulf on average every 10 years, therefore it is expected that such large quantities of gas release events may have a 10 year cycle. The enhanced pockmark activity which occurred a few hours before the earthquake may prove a promising and inexpensive tool for predicting earthquakes in areas where pockmark fields occur.

The volume of sediments removed from an average sized cone shaped pockmark in Patras Gulf, represents about 22,000 m\(^3\) of sediment while a conservative estimate of the volume of sediment removed from a composite pockmark is at least 360,000 m\(^3\). Therefore it can be assumed that a vast quantity of sediments, roughly estimated from the mean values of the dimensions of the pockmarks to be about 1,760,000 m\(^3\), have been redistributed by gas venting and have reshaped the seabed morphology.

The overall parallel character of the faint reflectors in between the pockmarked Holocene succession suggests that during the Holocene a low energy and uniform sedimentation regime prevailed in the area indicating that the large volume of sediments lifted and suspended by the gas venting has been uniformly spread over the wider area by waves and currents. Therefore it is suggested that the pockmarks have been formed by a more or less steady and continuous gas venting after the stronger initial gas escape, which is being interrupted by short-duration events of enhanced gas emission due to earthquakes. This mechanism of pockmark formation is further supported by the fact that the near surface sediments are unconsolidated as would be expected from the continuous seepage (Nelson et al., 1979). The absence of mound type deposits on the surrounding seabed suggests that the short duration enhanced emission events do not create violent eruptions intense enough to lift instantaneously huge sediment volumes.

The described changes in temperature and the increased concentration of gas in the water due to the gas venting were only observed in a small percentage area of Patras Gulf which was surveyed. However, as about 70% of the seafloor of the Gulf contains gas-charged sediments, it is quite possible that the phenomenon occurred Gulf-wide. It is also possible that such sudden and short-term changes in the physical and chemical properties of the water column all over the Gulf would have caused stress or death to some living organisms.

References


