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Fluid flow systems of the Malta Plateau, Central Mediterranean Sea

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ABSTRACT

The Malta Plateau is a shallow, asymmetric, north–south striking ridge located between Sicily and the Maltese Islands. New 2D seismic and side scan sonar data sets, sub-bottom profiles and seabed samples are investigated to characterize fluid flow systems on the Malta Plateau, determine their origin, and improve our general understanding of fluid flow focusing in terms of structural and stratigraphic controls. We demonstrate that fluid flow systems across the Malta Plateau are numerous, widespread and active. Two types of fluid flow systems are identified. The first type can be observed in the shallower parts of the western Malta Plateau. It consists of a shallow system where fluids ascend from gas-charged Plio-Pleistocene sediments and actively seep at the seafloor in the form of gas flares. The fluid migrating in this kind of system is likely autochthonous, biogenic gas (probably methane) forming at shallow depth. The second type comprises deep systems that can be observed in the central and eastern parts of the Malta Plateau. In these deep systems, fluids generated in Late Mesozoic sediments ascend through Late Cretaceous, Tertiary and Plio-Pleistocene units, and are expelled at the seafloor in the form of pockmarks. Late Mesozoic faults, Early Miocene to recent faults, and pipe structures constitute the preferred migration pathways. The migrating fluids are likely of thermogenic origin, possibly leaking from Mesozoic hydrocarbon reservoirs. Particularly in the north of Malta there is evidence that fluid migration is driven by overpressure at depth resulting from compressive events during the Late Cretaceous–Early Tertiary. Since the tectonic regime across the Malta Plateau is currently extensional, we propose that recent fluid migration and expulsion are at least partly driven by old overpressures and sustained by more recent normal faults. Our results show that fluid migration must be taken into account when assessing seabed stability on the Malta Plateau. Our results also indicate where chemosynthetic ecosystems may be located, and they improve our understanding of the petroleum geology of the Malta Plateau.

1. Introduction

The Malta Plateau is a ~10 700 km^2 large, asymmetric, north–south striking ridge on the Pelagian Platform between Sicily and the Maltese Islands (Fig. 1). The recent discovery of mud volcanoes in the northwest of the Malta Plateau (Holland et al., 2003; Savini et al., 2009) indicates that this poorly studied zone of the Mediterranean Sea must have at least one active fluid flow system, but so far the driving mechanism is little understood. The adjacent Calabrian Arc is known to have several compression-related fluid flow systems (Praeg et al., 2009) similar to those on the Central Mediterranean Ridge (Huguen et al., 2005). Elsewhere in the Mediterranean Sea, fluid flow focusing in relation to Messinian Salt deposits has been observed (Lastras et al., 2004; Zitter et al., 2005; Camerlenghi and Pini, 2009; Hübscher et al., 2009).

The investigation of fluid flow systems in the Malta Plateau is important for at least three reasons. First, numerous offshore platforms and submarine cables have been installed across the Malta Plateau. Shallow gas is known to pose a potential hazard to offshore infrastructures (Davis, 1992); gas escaping naturally to the surface or during drilling can cause collapse of structures and undermine foundations. Shallow gas is also acknowledged to have a significant effect on the engineering behavior of sediments by altering their geotechnical characteristics (Sills and Wheeler, 1992). As a result, high sedimentary fluid content and gas emissions also pose serious hazards to settlements along the Maltese and Sicilian coastlines because they can cause slope failures and related tsunamis (Orange et al., 2001). Secondly, long-term seeping gasses through the seafloor are the primary energy source for chemosynthetic benthic ecosystems (Dando et al., 1991). Apart from showing high biomass and productivity, these little studied communities play an important role in controlling greenhouse gasses, and they may be important breeding grounds for fish populations (Sibuet and Olu-Le Roy, 2003). Nevertheless, the distribution of these communities across the Malta Plateau is still unknown. Thirdly, since fluid escape features can be a direct consequence of reservoir leakage (Heggland, 1998), their study is useful to assess the petroleum potential of the Malta Plateau. The detailed study of the seep sites allows the prediction of hydrocarbon

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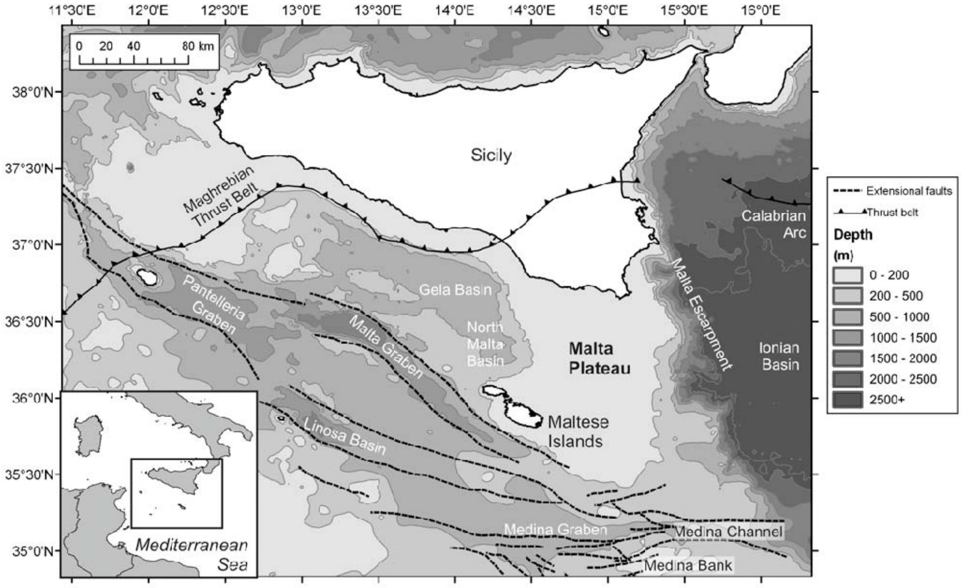

Fig. 1. Bathymetric map of the northern section of the Pelagian Platform in the Central Mediterranean, showing the Malta Plateau and the principal morphological and structural features in the region.
Sources: Smith and Sandwell (1997); Catalano et al. (2008); Lipparini et al. (2009).

migration patterns in the subsurface, optimization of well tracks and modeling of the economics of petroleum reservoirs.

During the last decade there has been an increasing availability of high resolution seabed data, associated with the surge in telecommunication cable installations, as well as new regional seismic reflection data for petroleum exploration across the Malta Plateau. In this paper we analyze new geophysical data sets to investigate the nature and origin of shallow and deep fluid flow systems on the Malta Plateau. The objectives of our study are: (i) to characterize fluid flow systems on the Malta Plateau and determine their origin, and (ii) to improve our general understanding of fluid flow focusing in terms of structural and stratigraphic controls.

2. Regional setting

The central Mediterranean region is dominated by the Pelagian Platform (Fig. 1), a structural element of the African continent that comprises a shallow shelf between the south of Sicily and the north-west of Libya. The Pelagian Platform consists of a sequence of Meso-Cenozoic carbonate rocks and volcanic deposits that is wedged in the overall compressive system between the African and European continental plates. The present day structural setting of the Pelagian Platform is characterized by thrust faulting at its northern and western margins, and a complex array of shallow shelves and intervening, elongated, fault-controlled rift basins of Miocene–Pliocene age in its center (Reuther and Eisbacher, 1985). At its eastern margin, the Pelagian Platform is separated from the deep Ionian Basin by the Malta Escarpment.

The Malta Plateau, located in the north-eastern part of the Pelagian Platform (Fig. 1), has been a structurally elevated area relative to its surroundings since at least the Late Triassic (Bishop and Debono, 1996). The Malta Plateau is bound by the Hyblean Plateau to the north, the Malta Escarpment to the east, the Gela and North Malta Basins to the west, and the Medina Channel to the south. The Malta Plateau is composed of thick continental crust. Wells drilled to the east of Malta indicate that the stratigraphic framework of the plateau mainly consists of >4500 m of limestones and dolomites, with intercalated volcanic rocks at several stratigraphic levels from the Upper Triassic to the Quaternary (Patacca et al., 1979; Jongsma et al., 1985; Torelli et al., 1995). The Tertiary succession consists of shallow marine and pelagic limestones and marls, whereas pre-Tertiary rocks mainly consist of dolomites and limestones dating back to the Lower Cretaceous and possibly the Jurassic (Jongsma et al., 1985) (Fig. 2). The youngest limestone formations are cut by a series of regional syndepositional NE–SW trending normal faults, which were active intermittently from Early Miocene to mid-Pliocene times (Pedley, 1990; Gardiner et al., 1995). NW–SE and ENE–WSW trending normal faults, on the other hand, were formed or re-activated in the late Pliocene to Quaternary periods (Gardiner et al., 1993). These three generations of faults are closely related to the development of the Malta Graben to the west of the Malta Plateau (Illies, 1981). The most recent sediments covering the Tertiary succession comprise up to 300 m-thick conformable, parallel-bedded units of Plio-Pleistocene terrestrial, pelagic and hemipelagic sediments (Fig. 2) (Max et al., 1993; Osler and Algan, 1999). The Plio-Pleistocene sediments have been divided into six continuous units based on seismic character and stratigraphy (Max et al., 1993; Osler and Algan, 1999), which show that their deposition was synchronous with sea level rise during the last eustatic hemicycle (Ruddiman and McIntyre, 1981). No faults are generally observed cutting the Plio-Pleistocene sediments. Messinian low-stand strata, which were exposed to subaerial erosion during the Messinian Salinity Crisis, comprise the basement surface for the Plio-Pleistocene sedimentary succession (Finetti, 1984; Osler and Algan, 1999). The seabed across the Malta Plateau is generally smooth and gently sloping, except where the underlying Messinian basement crops out (Max et al., 1993). Across the majority of the Malta Plateau, the bathymetric depth varies between 100 m and 150 m (Fig. 3). The dominant types of sedimentation across the Malta Plateau today are pelagic and hemipelagic.

3. Data and methods

The first data set used in this study was collected during a cable route survey carried out by Fugro for Melita plc between September and October 2008. The surveyed area consists of a 93 km long and 0.5 km wide corridor between Bahar ic-Caghaq, off the north-eastern coast of Malta, and Pozzallo, off the southern coast of Sicily (Fig. 3). The data collected during the survey, which include bathymetry, side

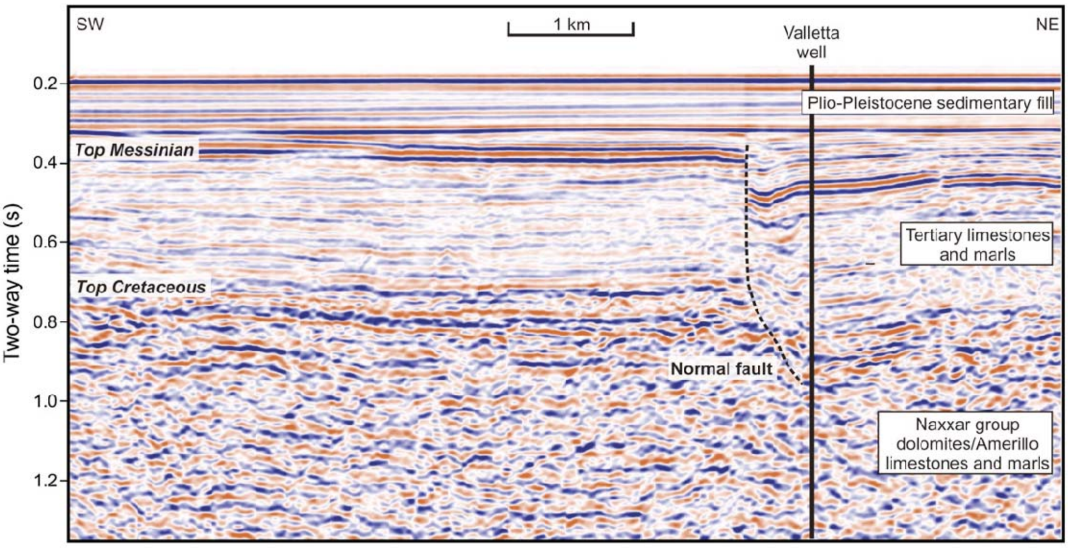

Fig. 2. Seismic stratigraphy of the Malta Plateau, interpreted from seismic line MSC02-450. The interpretation is based on seismic sections, stratigraphic information and well data (Valletta and Alexia) presented in Jongsma et al. (1985), Dart et al. (1993), Gardiner et al. (1993) and Bishop and Debono (1996). The location of the seismic line and the wells is shown in Fig. 3.

scan sonar, sub-bottom profiles and seabed samples (17 gravity core and 12 grab samples, Supplementary material—Fig. 1), were acquired by the *SV Fugro Gauss* and *SV Navigator*. The equipment on board the *SV Fugro Gauss* comprised: (i) a hull-mounted Reson SeaBat 8101 DR multibeam echo sounder, (ii) a GeoAcoustics dual frequency 100/400 kHz transceiver in connection with a GeoAcoustics side scan sonar towfish (SS942/136 S), and (iii) a Benthos Datasonics CAP 6600 Chirp II Acoustic Profiling System. On board the *SV Navigator*, the following equipment was used: (i) a Kongsberg Simrad EM 3000 multibeam echo sounder, (ii) a GeoAcoustics 159D side scan sonar and (iii) a Sonar Equipment Services Ltd Probe 5000S. Accurate surface positioning was achieved using the Fugro Starfix XP/HP DGPS.

The second data set was acquired during a survey carried out by TGS-NOPEC Geophysical Company (TGS) between December 2000 and March 2001. The data coverage includes the Malta Plateau, the Pantelleria-Linosa-Malta rift, the Medina Graben and Channel, and the

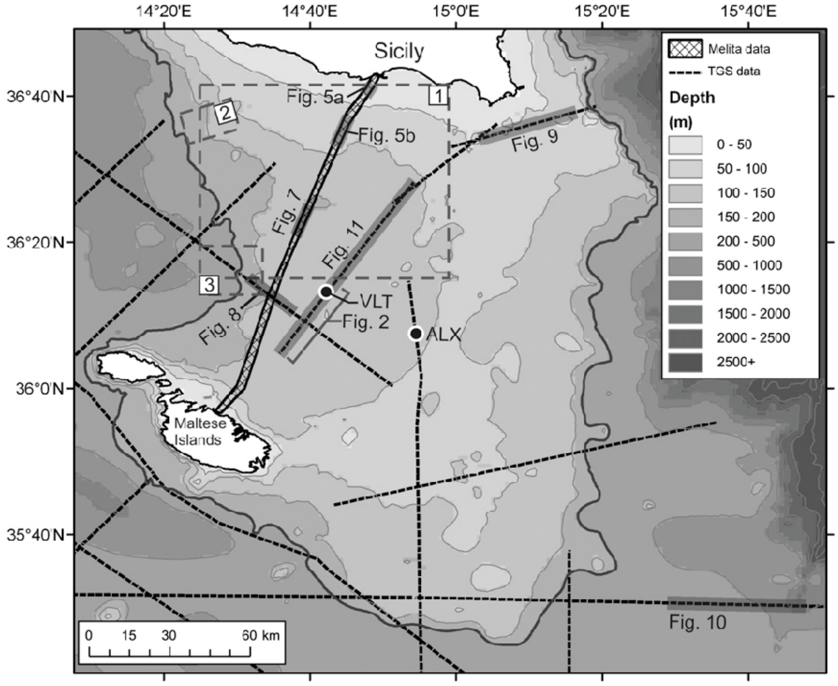

Fig. 3. Spatial coverage of the Melita seismic and high resolution acoustic data sets, and TGS seismic data set. The location of the Melita sub-bottom profiler data and TGS seismic lines, shown in Figs. 2, 5, and 7–11, is indicated. Also shown are the locations where mud volcanoes and gas venting described by Holland et al. (2003) (box 1), the domes and ridges, attributed to mud volcanism and documented by Savini et al. (2009) (box 2), and the pockmarks identified by Max et al. (1993) and Prior (2005) (box 3) have been discovered. 'VLT' and 'ALX' refer to exploration wells 'Valletta' and 'Alexia'. The 200 m isobath is denoted in bold.
Sources: Bishop and Debono (1996); Smith and Sandwell (1997).

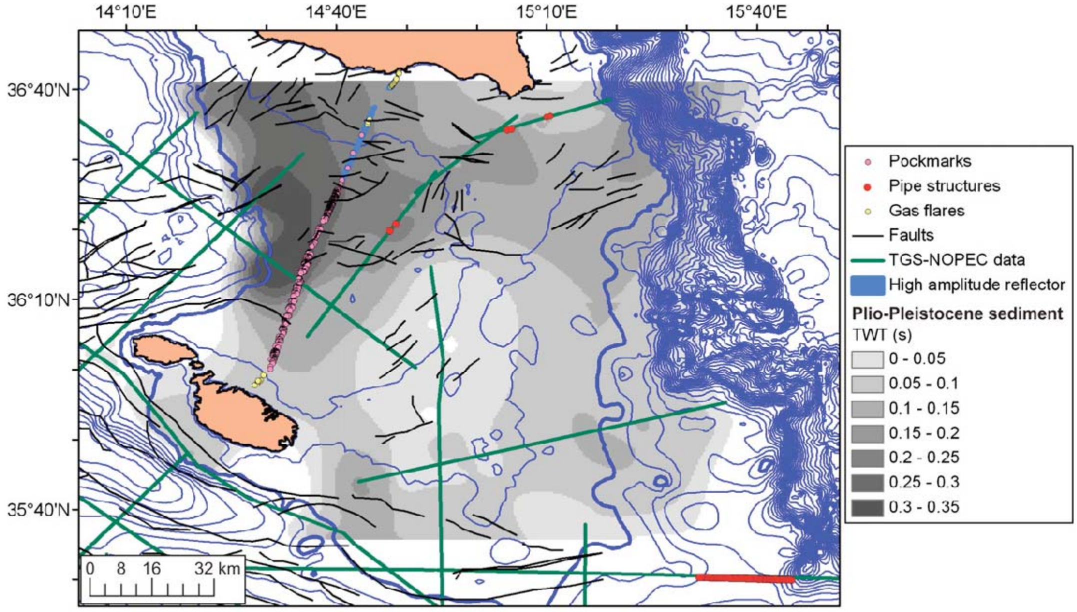

Fig. 4. Map of fluid flow features, identified in the TGS 2D seismic data and in the Melita side scan and sub-bottom profile data, overlain on an isopach map of Plio-Pleistocene sediments. Also included are the bathymetric contours at 100 m intervals (in blue), and the Late Miocene–Pliocene faults mapped by Gardiner et al. (1995). The 200 m isobath is denoted in bold.
Source: Smith and Sandwell (1997).

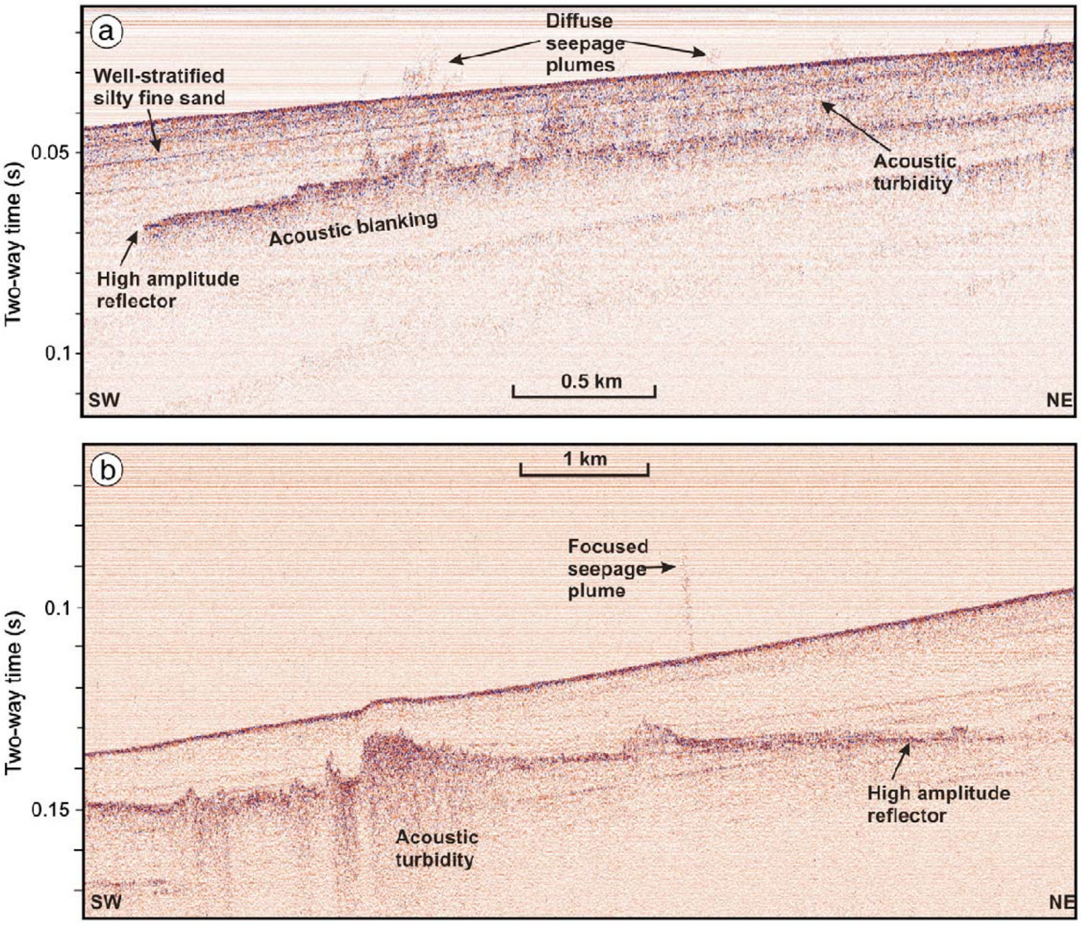

Fig. 5. Acoustic anomalies, in the form of gas flares, high amplitude reflectors, acoustic turbidity and blanking, which are indicative of the occurrence of shallow gas within the seafloor sediments of the Malta Plateau: (a) sub-bottom profile SB-20080926092407; and (b) sub-bottom profile SB-20080926062647. The location of the profiles is shown in Fig. 3.

Malta Escarpment (Fig. 3). The data set, acquired by the MV Zephyr using a Syntrak 960-24 bit system, consists of 3325 km of 2D seismic reflection data (HDM-00, HDMK00, MSC-01 and MSC-02). The seismic lines were shot using a 2800 cubic inch Tuned bolt array, a shot point interval of 37.5 m, a 6000 m long streamer, 480 recording channels, a sample interval of 2 ms and a group interval of 12.5 m. The processing of the seismic data included Parabolic Radon Transform filtering, f-k filtering, Stolt f-k migration, square root recovery scaling, predictive deconvolution, FX deconvolution, Provisional Kirchhoff migration, time-variant filtering and time-variant scaling.

For this study, the Melita bathymetric and side scan sonar data were processed, visualized and interpreted using IFREMER's Caraibes software. The Melita sub-bottom profiler and TGS seismic data were visualized and interpreted using the KingdomSuite software.

4. Results

4.1. Seabed sediment

The seabed sediments collected across the Melita survey area are predominantly sandy clays to silty fine sands (Supplementary material—Table 1). These results are comparable to the grab and core samples of Plio-Pleistocene sediments from the central Malta Plateau described in Tonarelli et al. (1993), which consist of fine, silty sand to silt with small fractions of clay. We therefore infer that the sediments sampled across the Melita survey area are Plio-Pleistocene terrigenous sediments mixed with pelagic and hemipelagic sediments.

The Messinian basement was interpreted across the Malta Plateau from the TGS seismic data and combined with published well and seismic data to construct an isopach map of the Plio-Pleistocene sedimentary fill (Fig. 4). The map shows that the Plio-Pleistocene sediments thicken towards the west of the Malta Plateau, attaining their maximum thickness within the North Malta Basin. The sedimentary cover is thinnest in the southern central part of the Malta Plateau where the Messinian basement is exposed at the sea floor.

4.2. Shallow gas

A number of acoustic anomalies (following the terminology in Judd and Hovland, 1992) observed in the Melita sub-bottom profile data provide direct evidence of the occurrence of shallow gas across the Malta Plateau (Figs. 4 and 5).

The first acoustic anomaly is a shallow, sharp, coherent, non-continuous high amplitude seismic reflector. Extending laterally up to 20 km, and located at a maximum depth of 0.025 s (TWT) below the seabed (Fig. 4), this reflector tends to cross-cut other reflectors (Fig. 5b). The reflector is interpreted as the top of an accumulation of gas within porous sediments, resulting from the enhancement of the impedance contrast between gas-charged layers and gas-free layers.

The second acoustic anomaly is acoustic blanking, which consists of faint or absent reflections that can be observed below the high amplitude reflector (Fig. 5a). Acoustic blanking occurs due to absorption of the highly frequent acoustic energy by the overlying gas-charged sediments, which lowers the seismic amplitude and masks internal layering below (Davis, 1992).

The third acoustic anomaly is acoustic turbidity in the form of diffuse and chaotic reflections occurring above and below the high amplitude reflector (Fig. 5). In some instances, acoustic turbidity extends vertically from the high amplitude reflector to the seabed where gas flares are found in the water column. Acoustic turbidity is attributed to the scattering of acoustic energy by interstitial gas in the sediments.

The fourth acoustic anomaly consists of straight and inclined reflections that can be observed in the water column at a number of points along the Melita survey area. In analogy with Sauter et al. (2006), we interpret these disturbances as gas flares due to active seepage of gas from the seabed. The gas flares, which are either diffuse or focused (Fig. 5), reach a height of 10–15 m above the seabed. Gas flares tend to occur in groups located at depths shallower than 90 m (Fig. 6b). The gas flares are spatially correlated with the high amplitude reflectors (Fig. 4). The majority of the gas flares are located where the Plio-Pleistocene sediments are thinner than 0.17 s (TWT) (Fig. 4).

4.3. Pockmarks

Pockmarks, sub-circular depressions formed by escaping fluids (Judd and Hovland, 1992), are expressions of present or former fluid migration and seepage through the seabed (Hovland et al., 1985). 500 pockmarks have been mapped between Sicily and the Maltese Islands from the Melita side scan sonar data, which are limited to the cable route survey corridor and do not represent a homogenous data set over the entire Malta Plateau. Pockmarks have been identified as circular or ellipsoidal zones of low backscatter fringed by a crescent of high backscatter (Fig. 7). The pockmarks have a median area of 13.2 m^2 (Fig. 6a) and a mean depth of 0.6 m; the maximum pockmark diameter recorded is 22 m. Pockmarks extend over a length of 65 km across the Malta Plateau, and they are concentrated at seabed depths of 140–150 m (Figs. 4 and 6b). The pockmarks have a clustered distribution; whereas the mean density of pockmarks is 10.8/km^2, the pockmark density can reach values of 42/km^2 at a distance of 36 km south–south-west of the Sicilian coastline. Areas with high densities of pockmarks coincide with Late Miocene faults and indications for pipe structures, which intersect the Tertiary limestone and marl sequence (Figs. 4 and 8). The orientation of the pockmarks is predominantly NW–SE, which is parallel to the orientation of the faults. The majority of the pockmarks are located where the thickness of the Plio-Pleistocene sediment is 0.26–0.27 s (TWT). Only a few of the shallowest pockmarks correlate spatially with the high amplitude

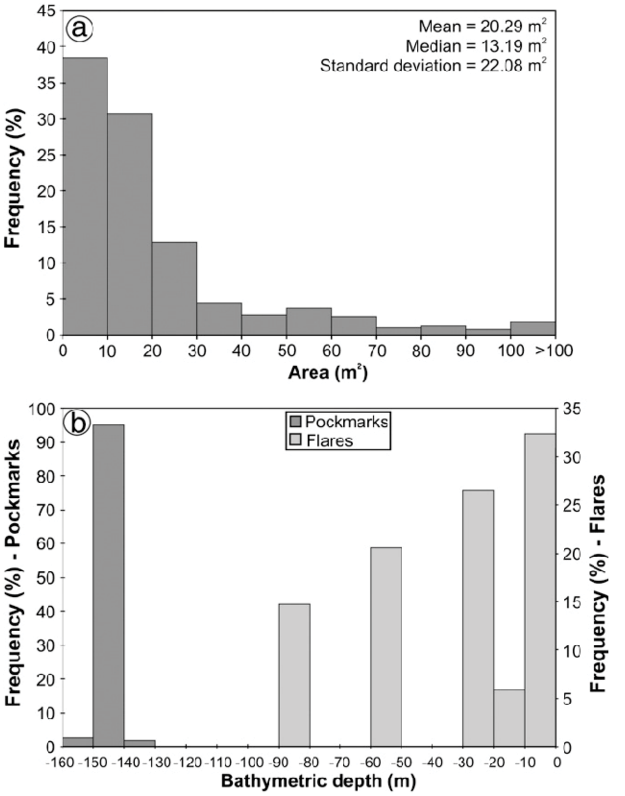

Fig. 6. (a) Histogram and descriptive statistics of the area of the mapped pockmarks. (b) Frequency distribution of the bathymetric depths of the mapped pockmarks and gas flares.

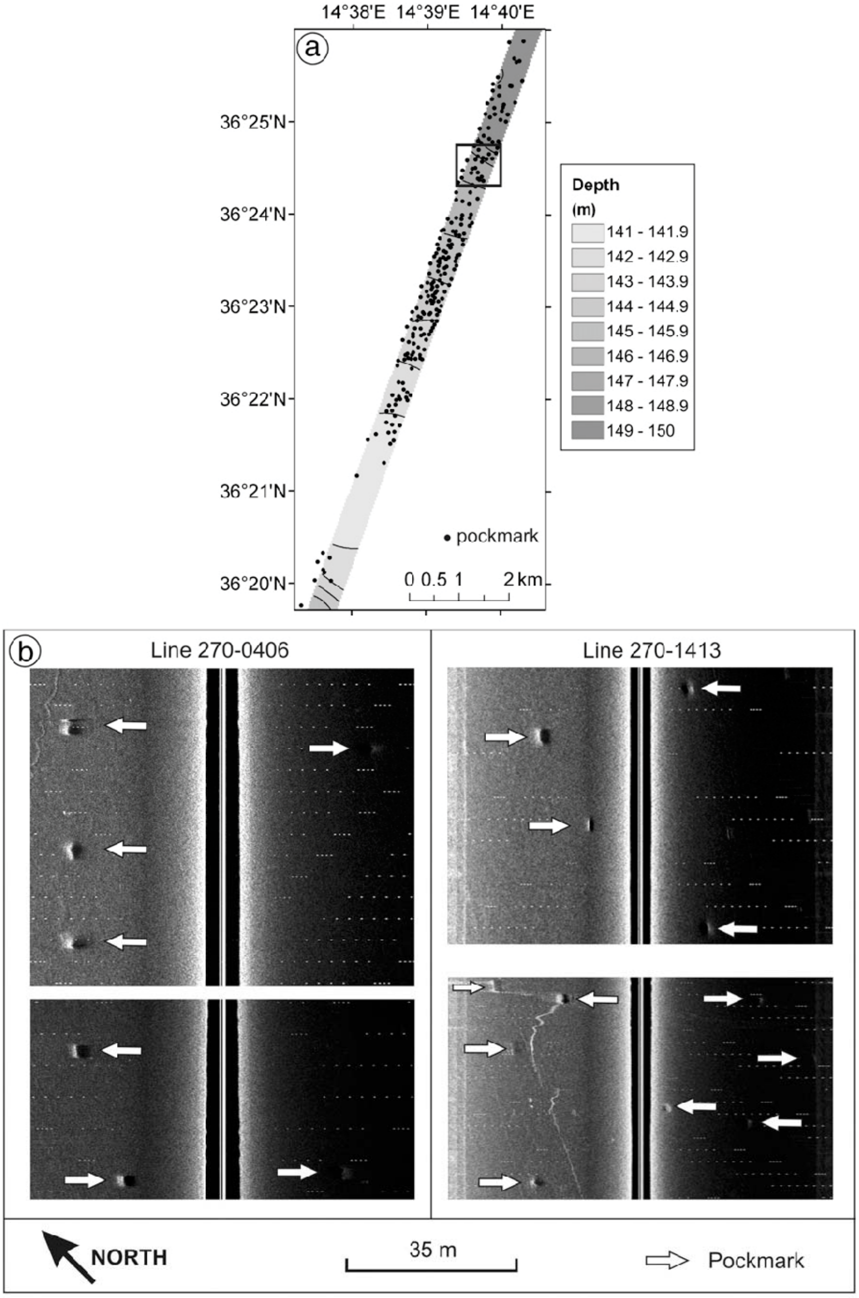

Fig. 7. (a) Bathymetric and pockmark location map between latitudes 36°24′N and 36°25′N. (b) Melita side scan sonar imagery along lines 270-0406 and 270-1413 showing ellipsoidal pockmarks (bright = high backscatter; dark = low backscatter). The pockmarks are denoted by white arrows.

reflector shown in Fig. 5, and none of the pockmarks is associated with gas flares (Fig. 4).

4.4. Evidence of fluid flow systems in TGS 2D seismic data

We interpret acoustic anomalies in the TGS 2D seismic data as representative of four fluid flow systems.

The first system is located 7.5–8 km south of Sicily, at a water depth of ~60 m (Fig. 9a). In this area, two vertical and 100–150 m wide zones of decreased seismic amplitude, commonly referred to as pipe structures (e.g. Løseth et al., 2001, Berndt et al., 2003), can be observed rising from a depth of 0.25 s (TWT) and disturbing the Plio-Pleistocene sediments in the west–south-western section of the line (Fig. 9b). At the seabed, the pipe structures are evident as local depressions. These depressions are likely to be pockmarks, which are in some instances associated with pipe structures (Berndt et al., 2003). Two additional vertical acoustic disturbances, also interpreted as pipe structures, can be observed rising from a depth of 0.4 s (TWT) in the central section of the line (Fig. 9a). The sedimentary succession underneath all these pipe structures is characterized by intensely faulted Tertiary limestones/marls and Late Mesozoic limestones/dolomites. The strata below the Top Cretaceous have been deformed into a series of crests and troughs that display a range of dips and that extend continuously over a distance of at least 15 km. This deformation is interpreted as asymmetrical folding.

The second system is located on the south-eastern part of the Malta Plateau, 95–115 km south-east of the Maltese Islands and close to the

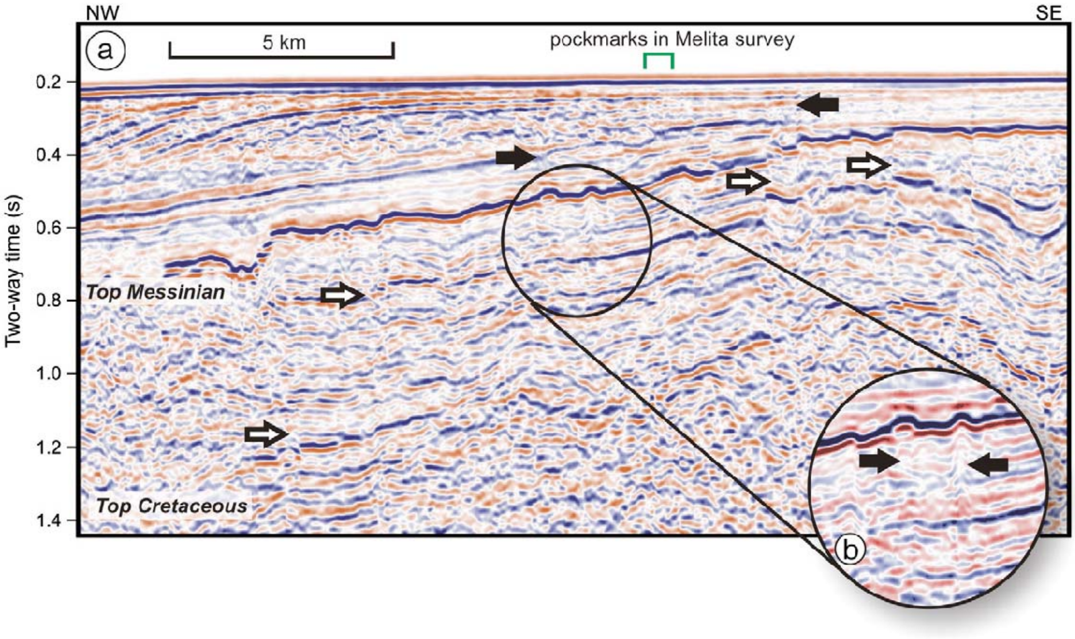

Fig. 8. (a) TGS 2D seismic line MSC01-301, 55–60 km south-west of Sicily, showing faults (denoted by white arrows) and pipe structures (denoted by black arrows) disrupting the Tertiary limestones/marls underneath a mapped pockmark field. The location of the seismic line is shown in Fig. 3. (b) Enlarged section of the pipe structures in the center of seismic line MSC01-301.

Malta Escarpment at a water depth of ~430 m (Fig. 10). Numerous vertical pipe structures are observed cutting through the 0.2–0.25 s (TWT) thick Pliocene to Quaternary surface sediments. These features rise from the Top Messinian to the seafloor, where a number of depressions, interpreted as pockmarks, are located. The base of the vertical pipe structures corresponds to an intensely-faulted Tertiary limestone graben.

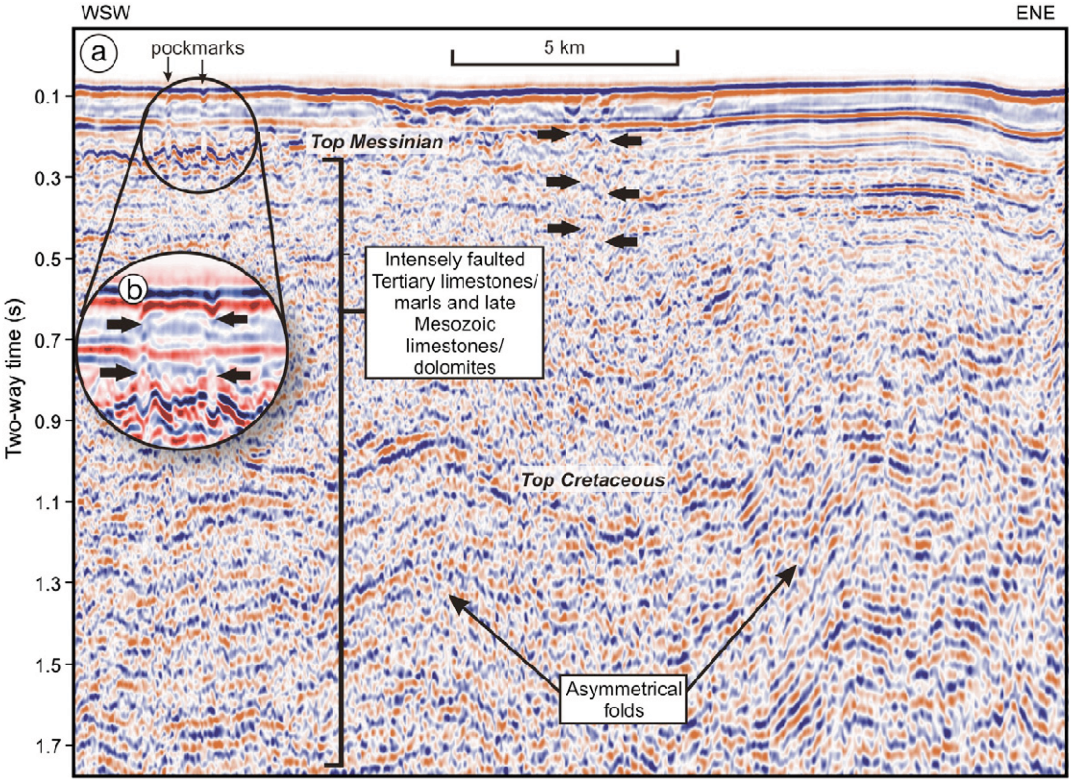

Fig. 9. Fluid flow system 1: (a) vertical pipe structures (denoted by black arrows) overlying intensely faulted Tertiary limestones/marls and Late Mesozoic limestones/dolomites. (b) Zoomed section of the pipe structures in the WSW of the seismic line. These acoustic anomalies are observed in TGS 2D seismic line MSC02-451A, 7.5–8 km south of Sicily. The location of the seismic line is shown in Fig. 3.

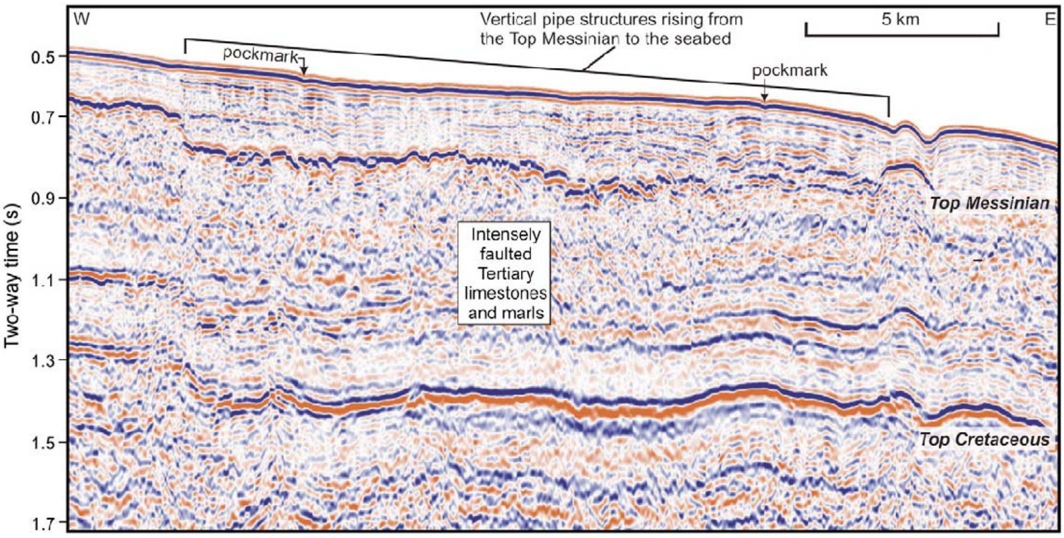

Fig. 10. Seismic expression of fluid flow system 2, located 95–115 km to the south-east of the Malta Plateau (TGS 2D seismic line MB01-101). The location of the seismic line is shown in Fig. 3.

The third system is located 25–75 km south of Sicily (Fig. 11). Three types of acoustic disturbance can be observed. The first is a vertical zone of acoustic turbidity, extending from well below the Top Cretaceous to the Top Messinian, which narrows upwards. Up-bended seismic reflectors are visible along the edges of this vertical zone. This feature is interpreted as a shear zone along a fault where upward migration of fluid has occurred. The second type of acoustic disturbance is an extensive zone of acoustic turbidity located in the south-west of the seismic line (Fig. 11), which denotes the presence of gas. The third type of disturbance consists of a number of vertical pipe structures rising from the Cretaceous to the Top Messinian (Fig. 11).

The fourth system is located 130 km south-east of the Maltese Islands, in an area that does not form part of the Malta Plateau (Fig. 12). We identify a high amplitude, inverse polarity seismic reflector intersected by a normal fault. We interpret this reflector as indicative of an accumulation of gas that has migrated upwards from the deeper Late Mesozoic limestones/dolomites along the normal fault. The lack of intermediate seals is evident in the seismic data (Fig. 12).

4.5. Spatial correlation of fluid migration features with structure and stratigraphy

Pockmarks across the seabed of the Malta Plateau tend to be linked with underlying vertical pipe structures (Figs. 9 and 10). These vertical pipe structures are located in the central and north-eastern part of the Malta Plateau, and to the south-east of the Malta Plateau in proximity of the Malta Escarpment. These structures typically intersect the Plio-Pleistocene sediments, as well as the Tertiary limestone/marl sequence (Figs. 9–11).

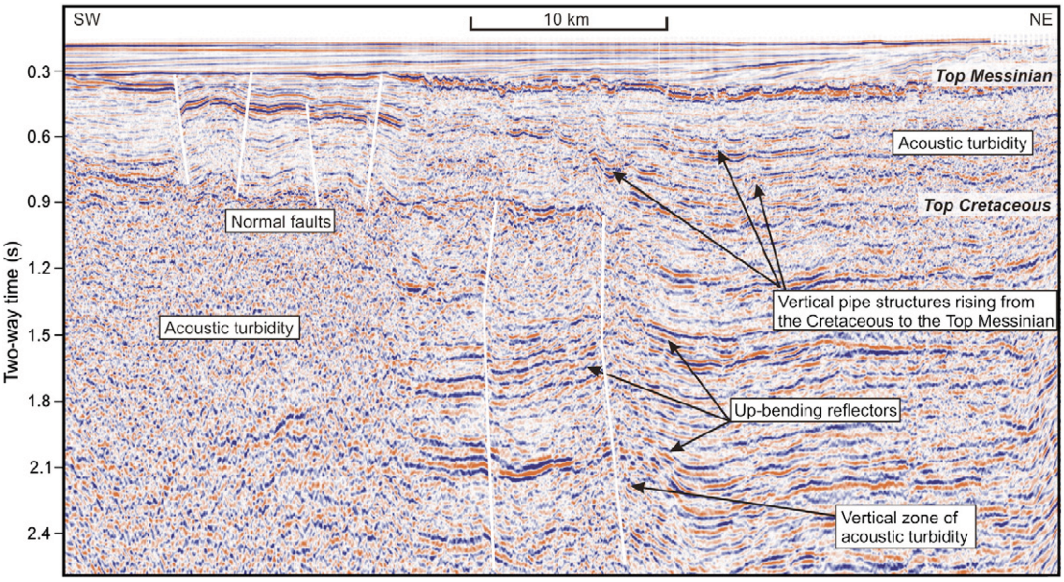

Fig. 11. Three forms of acoustic disturbance associated with fluid flow system 3 (TGS 2D seismic line MSC02-450, 25–75 km south of Sicily): (i) vertical zone of acoustic turbidity and up-bended reflectors, interpreted as a fault shear zone where upward migration of fluid has occurred; (ii) acoustic turbidity in the south-west of line that is attributed to the presence of gas; (iii) vertical pipe structures from the Cretaceous to the Top Messinian. The location of the seismic line is shown in Fig. 3.

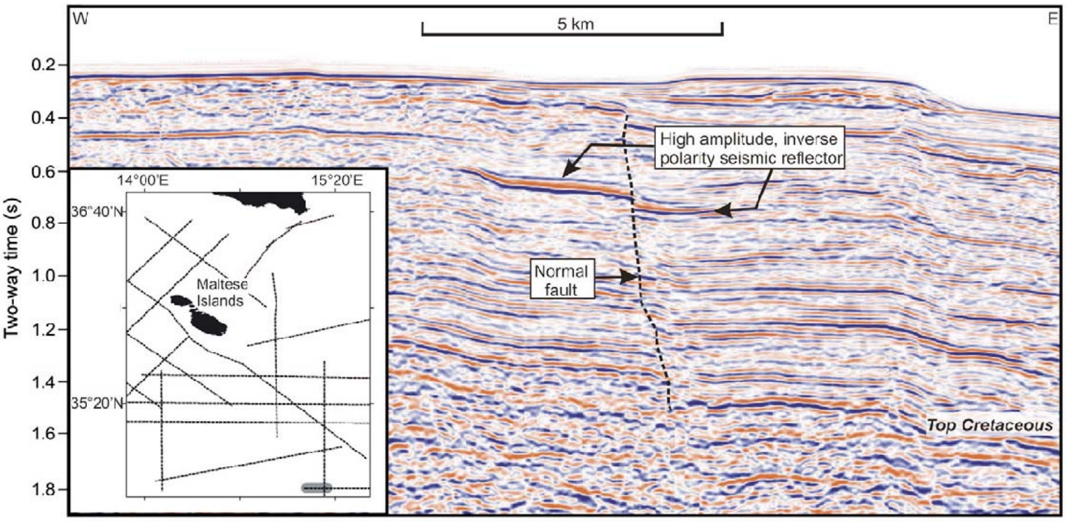

Fig. 12. Fluid flow system 4: a high amplitude, inverse polarity seismic reflector intersected by a normal fault in TGS 2D seismic line MB01-111. We interpret this reflector as indicative of an accumulation of gas that has migrated upwards from the Late Mesozoic limestones/dolomites. The lack of intermediate seals is evident in the seismic data. The seismic line (denoted by a thick gray line in the inset map) is located to the south-east of the Maltese Islands, outside of the Malta Plateau proper.

The majority of the vertical pipe structures and pockmarks are associated with faults and fractures planes, which tend to occur across the entire Malta Plateau. These faults can be divided into two groups: the first group disrupts the underlying Tertiary limestones and marl sequence (Figs. 4, 8 and 10) and corresponds to the Early Miocene to mid-Pliocene NE–SW series of faults and the Late Pliocene to recent NW–SE faults (Gardiner et al., 1995). The second group disrupts the Late Mesozoic sequences and most probably consists of a NNW–SSE trending fault system, formed during the Cretaceous rifting episodes and well-documented across the Pelagian Platform (Torelli et al., 1995) (Figs. 9 and 11). The exact depth of the base of these deeper faults is difficult to determine from our data.

5. Discussion

5.1. Fluid flow systems of the Malta Plateau: Characteristics and distribution

The data presented in this study yield evidence of two types of fluid flow systems across the Malta Plateau (Fig. 13):

(a) Shallow fluid flow system: This consists of shallow, Plio-Pleistocene gas-charged sediments, and the migration and active seepage of gas at the seafloor in the form of gas flares. This type of system can be observed in the shallower parts (at depths <90 m) of the western Malta Plateau.

(b) Deep fluid flow system: This consists of the upward migration of fluids through Plio-Pleistocene sediments, Tertiary and older sedimentary units, and the expulsion of the fluids at the seafloor in the form of pockmarks. This type of fluid flow system can be observed in the Melita data between Malta and Sicily at depths >140 m, and in the TGS 2D seismic data 7.5 km south of Sicily, 95–115 km south-east of the Maltese Islands and 25–75 km south of Sicily.

Direct evidence of fluid flow and seepage systems has been reported in other parts of the Malta Plateau. Some pockmarks were observed on side scan sonographs from the western Malta Plateau by Max et al. (1993), although no enhanced acoustic anomalies were reported in their seismic data (Fig. 3). More recently Holland et al. (2003) discovered diapiric structures 16 km south of Sicily and at water depths of 70–170 m, along faults adjacent to the Scicli fracture zone (Fig. 3), which they have interpreted as active mud volcanoes. Active gas venting was observed from most of these structures. Domes and ridges, attributed to mud volcanism and influenced by active seeps, were documented by Savini et al. (2009) in the north of the

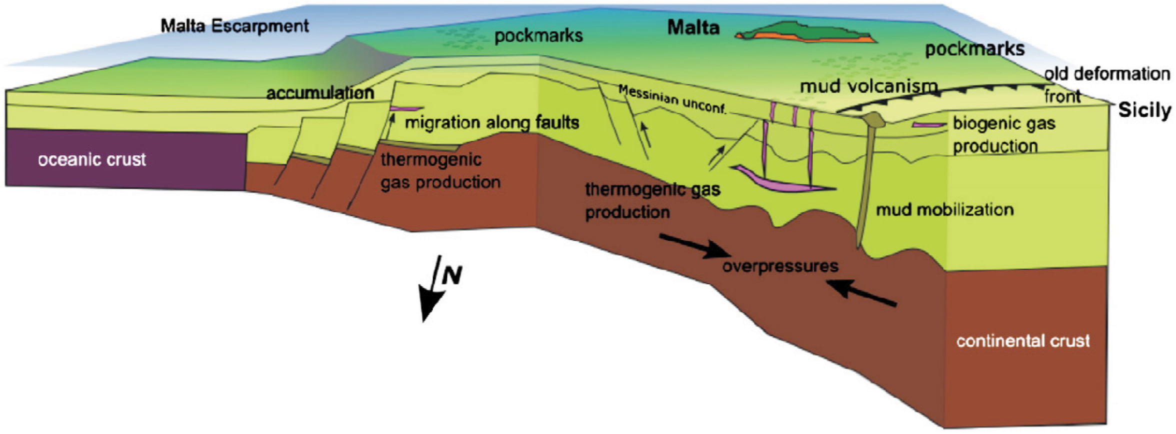

Fig. 13. Schematic model of the shallow and deep fluid flow systems identified across the Malta Plateau.

North Malta Basin, in depths of 140–170 m (Fig. 3). Indirect evidence of sediment-borne gas and pockmarks is observed in the reflection measurements and scatterer maps published by Holland et al. (2004) and Prior (2005) for the Malta Plateau (Fig. 3).

5.2. Processes of formation

5.2.1. Shallow fluid flow system

Acoustic turbidity and acoustic blanking in the Melita sub-bottom profile data provide evidence of the occurrence of gas in the shallow sediments. This gas is sourced by gas-charged layers that are shallow and cross-cut sediment strata, and is released at the seabed in the form of focused and diffuse gas flares. In accordance with Fleischer et al. (2001), we infer that the fluid migrating in such a shallow system is autochthonous and biogenic (Fig. 13). The gas is most probably methane, originating from bacterial degradation of organic matter at low temperatures, which is the most common biogenic gas in surficial shallow water sediment (Judd and Hovland, 2007). The ideal environment for the formation of biogenic methane is areas of rapidly accumulating, fine-grained muddy sediments rich in organic matter (Rice and Claypool, 1981; Hovland et al., 1993). The western edge of the Malta Plateau, where the Plio-Pleistocene sediments thicken within the North Malta basinal area, marks the position of the relative sea level during the Last Glacial Maximum (Vai and Cantelli, 2004). High-resolution seismic reflection data of Plio-Pleistocene sediments covering the western Malta Plateau demonstrate that, at different points during the last 10 000 years, this area was a lagoon and a deltaic environment (Max et al., 1993; Osler and Algan, 1999). Both depositional environments are conducive to biogenic gas formation.

5.2.2. Deep fluid flow system

The formation process of the deep fluid flow system is more difficult to determine. The vertical migration of fluid, which is expelled at the seabed surface in the form of pockmarks, seems to be taking place via two discrete migration pathways (Fig. 13):

(i) Pipe structures: The association of the pipe structures with seabed pockmarks implies that the pipe structures represent the acoustic imprint of highly focused, cross-stratal fluid migration, and that fluid flow along these vertical structures must have been active until recently. A direct link between pockmarks and vertical pipe structures has also been documented in the Niger Delta (Løseth et al., 2001), mid-Norwegian continental margin (Berndt et al., 2003; Hustoft et al., 2007) and the Gulf of Mexico (Gay et al., 2011). The geological processes leading to the formation of these pipes are still not very well understood—pipes may either be vertical migration pathways for water and gas (Evans et al., 1996), or they may correspond to mud diapirs with defined zones of vertically deflected sediment layering due to the confined front of ascending gaseous fluids (Hustoft et al., 2007).

(ii) Faults and fractures: As the majority of the vertical pipe structures and pockmarks are associated with faults and fractures planes, we infer that fluids from the deeper layers have migrated vertically upwards along the Late Mesozoic and Tertiary faults to feed the overlying vertical pipe structures and reach the seabed to form pockmarks. Faults are characterized by greater shear strain, which results in greater dilation and better connectivity, and they have been shown to be good migration pathways for fluids from deeper layers in a variety of settings (Vogt et al., 1994; Aydin, 2000; Berndt, 2005; Gay and Berndt, 2007; Savini et al., 2009).

We can thus infer that these two types of discrete fluid migration pathways are connected and sourced by sedimentary sequences of at least Late Mesozoic age. The main driving force promoting fluid migration along these pathways is overpressure at depth (Kopf, 2002; Judd and Hovland, 2007). The fluids may either be ancient pore waters or they can have a thermogenic origin. Thermogenic fluids are produced from organic precursors at high temperature and pressure, originating from depths greater than 1000 m (Davis, 1992). The Malta Plateau lies adjacent to an important petroleum province, with a number of Sicilian oil fields producing hydrocarbon from Triassic dolomites and Lower Jurassic–Oligocene carbonate sequences (Chierici et al., 1979; Matavalli and Novelli, 1990). Methane has also been detected at a number of shallow seep-related seafloor features and mud volcanoes located close to the Vega oil field (Holland et al., 2006; Savini et al., 2009). Upper Cretaceous and Jurassic hydrocarbon-generative source rocks are also known to occur south of the Malta Plateau (Lipparini et al., 2009). We thus infer that the migrating fluids have a thermogenic origin, possibly leaking from Mesozoic hydrocarbon reservoirs. The lack of intermediate seals, which is typical of the Malta Plateau and the surrounding areas (Pedley, 1990; Lipparini et al., 2009), could have facilitated the vertical migration of fluids from the Mesozoic source rocks to the surface along faults and pipe structures (Figs. 12 and 13).

Overpressure in fluids arises due to a combination of tectonic stresses (principally due to tectonic loading at convergent margins) and overburden stresses (due to sedimentary loading and compaction) that are transmitted to the pore fluids, and which may be enhanced by thermobaric processes such as hydrocarbon generation (Brown, 1990; Kopf and Behrmann, 2000; Milkov, 2000). A wealth of studies attests that the fluid migration features observed across the Malta Plateau are typical of collisional settings (Kopf, 2002): e.g. Costa Rica (Hensen et al., 2004); Caspian Sea (Planke et al., 2003); Alaska (Suess et al., 1998); Trinidad (Deville et al., 2003); and Hellenic subduction zone (Huguen et al., 2005). Mud volcanism, reported in the north-west of the Malta Plateau (Holland et al., 2003; Savini et al., 2009), is also generally tectonically-driven and favored by compressional regimes (Kopf, 2002; Judd and Hovland, 2007; Praeg et al., 2009). Asymmetrical folding, observed in the Late Mesozoic sedimentary units underneath vertical pipe structures (Fig. 9), is typical of collisional settings. On the other hand, sedimentation rates across the Malta Plateau were never high enough to create significant overpressures due to overburden stress (Bishop and Debono, 1996). We therefore conclude that the process generating overpressure of fluids at depth is principally compression at a convergent plate margin setting (Fig. 13).

Compressive events across the Malta Plateau are restricted to Late Cretaceous to Early Tertiary times; they produced uplift, folding and reverse faulting, and partly reactivated Lower Cretaceous extensional structures (Lipparini et al., 2009). As the asymmetrical folding observed in Fig. 9 is also of Late Cretaceous age, we conclude that compression during the Late Cretaceous to early Tertiary created the overpressure necessary to activate the deep fluid flow system (Fig. 13). The tectonic regime across the Malta Plateau became extensional between the Late Miocene and Late Quaternary, supporting the rifting mechanism of the Sicily Channel (Jongsma et al., 1985; Grasso, 1993; Goes et al., 2004). Thus, the principal mechanism generating fluid overpressure is no longer active. This inference is supported by the observation that some of the deeper pipe structures do not extend to the sea bed (Fig. 11). The fact that fluid migration and expulsion have taken place until recently means that fluid flow across the Malta Plateau is being driven by old overpressures. The normal faults located across the Malta Plateau, which predominantly formed during the more recent extensional regime, constitute important conduits that have sustained fluid migration.

5.3. Implications

There are a number of important implications associated with the discovery of these fluid flow systems across the Malta Plateau. First, the occurrence of widespread fluid flow systems highlights the potential of the Malta Plateau as a hydrocarbon prone area. On the other hand, the numerous fluid escape features observed across the Malta Plateau indicate that seals are frequently absent or breached (Figs. 2, and 8–12). This may be attributed to continuous carbonate deposition since the Triassic (Bishop and Debono, 1996), as well as the presence of normal faults. This may explain why the search for reservoirs with commercial quantities of hydrocarbons in the central and eastern Malta Plateau has proven unsuccessful so far. Furthermore, this would also indicate that the deep plays of neighboring Tunisia do not work for the Maltese Islands. On the other hand, observation of direct hydrocarbon indicators southwest of Malta show the presence of structural traps, and other plays may possibly be valid (Lipparini et al., 2009). Our results also demonstrate that normal faults represent a principal risk to hydrocarbon preservation and trap integrity, and that a detailed investigation of such faults is important in assessing the petroleum potential of an area.

Secondly, the upward migration of fluid has been identified as a factor conducive to frequent failure of the continental slope of the Gela Basin, located to the west of the Malta Plateau (Minisini and Trincardi, 2009). Small-scale landslides have been observed in proximity of fluid escape features in scatterer maps and side scan sonar surveys across the western and eastern Malta Plateau (Alcatel Submarine Networks, 2003; Prior, 2005). Our results may thus indicate that several other areas across the Malta Plateau could also be potentially unstable and thus pose a risk to seafloor infrastructure and coastal communities. This should be taken into account when assessing slope stability based on geotechnical studies.

Thirdly, authigenic carbonate crusts have recently been documented in the mud volcano field to the north of the North Malta Basin (Cangemi et al., 2010). These crusts are the results of the activity of anaerobic methane-oxidizing micro-organisms and sulfate-reducing bacteria, which form the basis of a food chain that reaches from the sediment to larger predators (Boetius et al., 2000; Sibuet and Olu-Le Roy, 2003). Our results indicate where similar chemosynthetic ecosystems may be located across the Malta Plateau.

6. Conclusions

Fluid flow systems are numerous, widespread and active across the Malta Plateau. Two types of fluid flow systems have been identified. The first type, which can be observed in the shallower parts of the western Malta Plateau, is a shallow system consisting of fluid migrating from gas-charged Plio-Pleistocene sediments and their active seepage at the seafloor in the form of gas flares. The fluid migrating in such a system is inferred to be autochthonous, biogenic gas (probably methane) formed at lower sea levels in lagoon and deltaic depositional environments during the last 10 000 years. The second type comprises deep systems that can be observed between Malta and Sicily at depths >140 m, 7.5 km south of Sicily, 95–115 km south-east of the Maltese Islands and 25–75 km south of Sicily. In these deep systems, fluids sourced by Late Mesozoic sedimentary units ascend through Late Cretaceous, Tertiary and Plio-Pleistocene units and are expelled at the seafloor in the form of pockmarks. Late Mesozoic faults, Early Miocene to recent faults, and vertical pipe structures constitute the preferred migration pathways. The migrating fluids are inferred to have a thermogenic origin, possibly leaking from Mesozoic hydrocarbon reservoirs. Fluid migration is driven by overpressure at depth resulting from compression events during the Late Cretaceous–Early Tertiary. Since the tectonic regime across the Malta Plateau is currently extensional, we conclude that recent fluid migration and expulsion are being driven by old overpressures and sustained by more recent normal faults.

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