Mem. Descr. Carta Geol. d'It.
105 (2020), pp. 77-83;
figg. 2

Mud volcanoes and seafloor fluid seepage on the Calabrian accretionary prism (Ionian Sea)

Vulcani di fango ed emissioni fluide nel prisma di accrezione della Calabria (*Mar Ionio*)

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ABSTRACT - The occurrence of mud volcanoes (MVs) in the deep Ionian Sea was first recognised in the early 1980s from the recovery of cores of mud breccia, initially hypothesised to record tectonic or diapiric processes, but eventually shown to record a long (> 1 Ma) history of seafloor extrusion from the accretionary prisms along the Europe-Africa subduction zone. Provinces of MVs were identified along the crest of the Mediterranean Ridge south and west of Greece, but few data were available from the Calabrian offshore until early in this century when new geophysical and geological data were acquired in the context of European-funded programmes. The acquisition of regional multibeam bathymetric and backscatter data, as well as seismic reflection profiles and cores from selected features, resulted in the discovery of a new province of MVs on the Calabrian accretionary prism (CAP), as well as insights into their activity through time. A total of 54 MVs were identified on the inner CAP across water depths of 150-2750 m from their distinctive morphologies and/or high backscatter character, in several cases proven by coring. Seismic reflection grids across two proven MVs showed them to record a history of activity dating back to an interpreted mid-Pliocene unconformity, one of the longest known records of extrusion. Sediment cores indicate recurrent eruptive episodes during the last glacial-interglacial cycle (<56 ka). Seafloor investigations of several MVs were undertaken using Autonomous Underwater Vehicles (AUVs) and Remotely Operated Vehicles (ROVs), which found evidence of phases of mud breccia extrusion and ongoing seepage of gas-rich fluids to support the growth of authigenic carbonate structures, chemosynthetic ecosystems and possible gas hydrate formation. The Calabrian deep-sea MV province is an active system in which extrusive episodes potentially constitute recurrent geohazards, separated by longer periods of quiescence in which fluid seepage drives geosphere-biosphere coupling.

KEY WORDS: fluid emission, ocean floors, mud volcanoes, gas, continental margin

RIASSUNTO - La presenza di vulcani di fango (MV) nelle acque profonde del Mar Ionio è stata riconosciuta all'inizio degli anni '80 dalla presenza di brecce di fango in carotaggi. Inizialmente si era ipotizzato che questa litologia indicasse processi tettonici o diapirici, mentre successivamente la sua genesi è stata attribuita ad un lungo (> 1 Ma) processo di estrusione sul fondo marino avvenuto nei prismi di accrezione nella zona di subduzione Europa-Africa. Province di MV sono state identificate lungo la cresta del *Mediterranean Ridge* a sud e a ovest della Grecia, ma pochi dati relativi all'*offshore* calabrese sono stati disponibili fino all'inizio di questo secolo, quando nuovi dati geofisici e geologici sono stati acquisiti nel contesto di programmi finanziati dall'UE. L'acquisizione dei dati batimetrici e di *backscatter multibeam*, così come profili di sismica a riflessione e carotaggi hanno portato alla scoperta di una nuova provincia di MV sul prisma di accrezione calabrese (CAP), insieme a informazioni sulla loro attività nel tempo. Sulla CAP interna sono stati identificati 54 MV, a profondità comprese tra 150 e 2750 metri, identificati sulla base delle caratteristiche morfologiche e/o dell'elevato *backscatter*, supportati in diversi casi da carotaggi. Le registrazioni sismiche eseguite in corrispondenza di due MV hanno mostrato tracce di attività risalente a una discordanza del Pliocene medio, uno dei record di estrusione fra i più antichi. I campioni di sedimento indicano episodi eruttivi ricorrenti durante l'ultimo ciclo glaciale-interglaciale (<56 ka). Le indagini su diversi MV sommersi sono state realizzate utilizzando strumenti autonomi sottomarini (AUV) e strumenti teleguidati (ROV), che hanno identificato tracce di estrusione di brecce di fango e infiltrazioni di fluidi ricchi di gas associate a strutture carbonatiche autigene, ecosistemi chemiosintetici e probabile formazione di gas-idrati. La provincia di MV nelle acque profonde della Calabria è un sistema attivo in cui gli episodi di estrusione possono dare origine a *geohazard* ricorrenti, separati da periodi più lunghi di quiescenza durante i quali la fuoriuscita di fluidi crea un collegamento tra geosfera e biosfera.

PAROLE CHIAVE: emissione fluida, fondale marino, vulcano di fango, gas, margine continentale

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1. - INTRODUCTION

Mud volcanism is a form of extrusive activity driven by the upward migration of overpressured fluids within sedimentary successions, so as to cause the liquefaction of mud-rich units and the episodic extrusion of solids, liquids and gases (Deville *et alii*, 2003; Planke *et alii*, 2003; León *et alii*, 2007). This process may result in a wide range of extrusive edifices, including cones, pies, ridges and calderas, typically composed of a sedimentary diamict commonly referred to as mud breccia (Brown & Westbrook, 1988; Kopf, 2002; Dimitrov, 2002). Mud volcanoes (MVs) are characteristically linked to hydrocarbon systems at depth (Etiope *et alii*, 2009), and in submarine settings may act as hosts to gas hydrates and to chemosynthetic ecosystems that mediate the release of greenhouse gases to the oceans (e.g. Foucher *et alii*, 2009). MVs are found within sedimentary successions on both passive and active margins, but most commonly form within accretionary wedges along convergent plate boundaries (Higgins & Saunders, 1974; Kopf, 2002; Dimitrov, 2002).

2. - PREVIOUS STUDIES

Submarine MVs are abundant in the eastern Mediterranean Sea, particularly along the accretionary prisms of the Africa-Europe subduction zone where they have received great attention (Kopf, 2002; Dimitrov, 2002). Mud breccias were first identified over 30 years ago in cores from the Prometheus Dome (Cita *et alii*, 1981), one of a number of 2-5 km wide semi-circular anomalies observed on GLORIA long-range sidescan sonar imagery. The anomalies were initially interpreted as halokinetic features but recognised to be MVs due to their high acoustic backscatter and irregular mainly positive relief (Belderson *et alii,* 1978; see Fusi & Kenyon, 1996). Scientific drilling of two features, the Milano and Napoli MVs, showed them to have recorded the extrusion of mud breccias over at least 1.75 Ma (Robertson *et alii*, 1996; Robertson & Kopf, 1998). Sediment cores obtained on the MVs showed mud breccias covered by a variable thickness of hemipelagic sediments (e.g. Cita *et alii*, 1981; Camerlenghi, *et alii* 1992), while seafloor video transects revealed small-scale fluid escape features, authigenic carbonate crusts, and biological systems (Limonov *et alii*, 1996; Volgin & Woodside, 1996; Cronin *et alii*, 1997; Huguen *et alii*, 2005; Zitter *et alii*, 2005; Foucher *et alii*, 2009). Regional multibeam coverage obtained by French scientists revealed a belt over 1.000 km long containing hundreds of backscatter anomalies of varying size and morphology (Huguen *et alii*, 2004, 2005; Chamot-Rooke *et alii*, 2005a,b; Mascle *et alii*, 2014). A quantitative analysis of backscatter anomalies south and west of Greece revealed 215 features (averaging 2-9 km^2). Sediment coring documented mud breccias within 2.25 m of the seabed inferred to record eruptions over the last ≤60 ka, whereby over 90% of the MVs were located within a 70 km wide band along the prism-backstop boundary (Rabaute & Chamot-Rooke, 2007). The anomalous concentration of MVs within the inner, older part of the prism has been proposed to reflect a combination of the presence of a Messinian evaporite layer, and different forms of tectonism along the backstop boundary (Camerlenghi *et alii*, 1995; Robertson & Kopf, 1998; Chamot-Rooke *et alii*, 2005a; Rabaute & Chamot-Rooke, 2007).

3. - CALABRIAN ACCRETIONARY PRISM

The Calabrian accretionary prism (CAP) is contiguous with the larger Mediterranean Ridge (fig. 1), but had received little attention in regard to mud volcanism prior to this century. In 1981, two cores containing 'pebbly mudstones' were recovered from a seismically unstratified body on the inner prism (fig. 1; Morlotti *et alii*, 1982; Barbieri *et alii*, 1982), but mud diapirism as proposed by Cita *et alii* (1981) was rejected in favour of a process of tectonic chaoticisation along thrusts (Morlotti *et alii*, 1982; Rossi & Sartori, 1981). Partial coverage of the prism by long-rangeside-scan imagery had revealed several backscatter anomalies (Belderson *et alii*, 1978), later reassessed as mud volcanoes (Fusi & Kenyon, 1996). No new data were available from the Calabrian offshore for over two decades, but it became apparent that mud volcanoes were likely to be found (Sartori, 2003). This was confirmed during the HERMES-HYDRAMED campaign of the OGS Explora in 2005, which obtained the first regional multibeam coverage (including backscatter) of the CAP (fig. 1), and resulted in the identification of mud volcanoes at two sites (Ceramicola *et alii*, 2006; Praeg *et alii*, 2009; Ceramicola *et alii*, 2014). Investigations of two bathymetric targets yielded cores of mud breccia from the Madonna dello Ionio and Pythagoras MVs (fig. 1), while seismic reflection grids across both features showed them to be the tops of buried extrusive edifices. These are >1 km thick and interfinger with sediments above a regional unconformity inferred to be of mid-Pliocene age (3-3.5 Ma), making these edifices among the longest-lived mud volcanoes on record (Praeg *et alii*, 2009; Somoza *et alii*, 2012). The two extrusive structures were further investigated during HERMES campaigns equipped with ROVs, which found geological and biological evidence of seabed seepage (Foucher *et alii*, 2009).

4. - NEW INTERPRETATIONS

Several authors subsequently suggested that mound-like seabed features might be mud volcanoes (Fusi *et alii*, 2006; Morelli *et alii*, 2011; Volpi *et alii*, 2011), although these studies were not supported by backscatter imagery. The

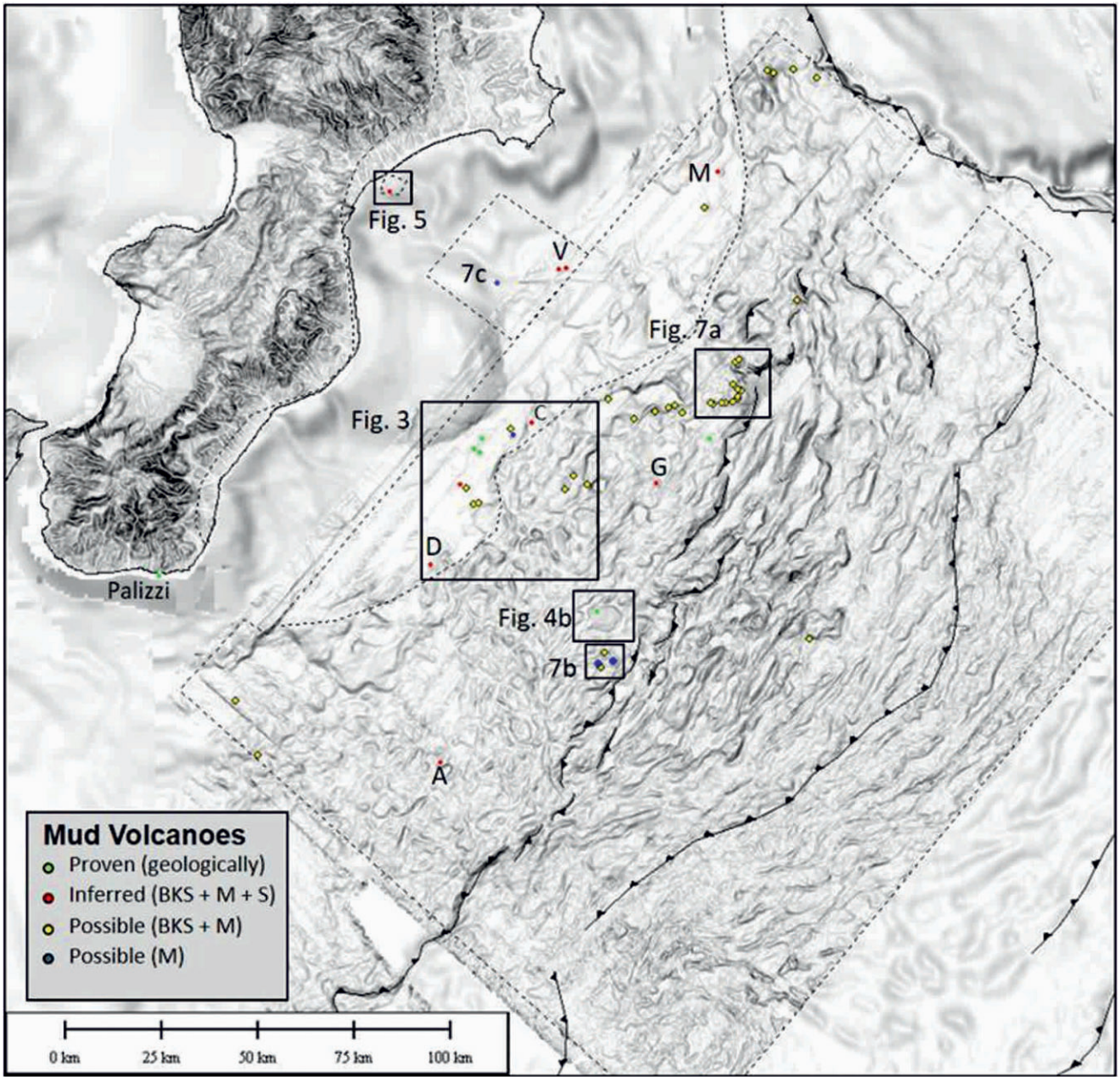

Fig. 1 - Map showing the regional distribution of mud volcanoes in relation to the main tectonic features of the Calabrian accretionary prism seen from shaded-relief bathymetry (from CERAMICOLA *et alii*, 2014). The study was based on the first regional multibeam bathymetry/backscatter datasets acquired in the area by OGS in 2005 and in 2009, as well as *chirp* subbottom profiles and cores from selected sites. These data allowed the identification of proven, inferred and possible mud volcanoes across the inner accretionary prism and fore-arc basins. Sedimentation rates in cores were used to argue that high backscatter areas record episodic extrusions of mud breccia over the last <56 ka.

- *La mappa mostra la distribuzione regionale dei vulcani di fango in relazione alle principali caratteristiche tettoniche del prisma d'accrescimento calabrese sulla base della batimetria a rilievo ombreggiato (da* CERAMICOLA *et alii, 2014). Lo studio si è basato sui primi* dataset *regionali di batimetria/*backscatter multibeam *acquisiti nell'area da OGS nel 2005 e nel 2009, così come su profili di subbottom chirp e campionamenti mirati. Questi dati hanno permesso l'identificazione di vulcani di fango certi, dedotti e probabili attraverso il prisma d'accrezione interno e i bacini di* fore-arc. *I tassi di sedimentazione, studiati attraverso i carotaggi, confermano che le aree di alto* backscatter *identificano estrusioni episodiche di brecce di fango negli ultimi 56 ka.*

'chaotic tectonites' cored by MORLOTTI *et alii* (1982) were reinterpreted as mud breccias (PANIERI *et alii*, 2013). Separately, seismic reflection studies revealed evidence of significant out-of-sequence tectonism within the pre-Messinian accretionary prism (MINELLI & FACCENNA, 2010) and it was suggested that the post-Messinian thrusts may have provided pathways for fluid flow and mud volcanism (POLONIA *et alii*, 2011; PANIERI *et alii*, 2013).

5. - DATA COLLECTION

During the HERMES HYDRAMED campaign high backscatter patches were detected on the seafloor, and sediment cores proved the existence of a new province of mud volcanoes (PRAEG *et alii*, 2009 CERAMICOLA *et alii*, 2014). The acquisition was carried out in the framework of the projects HERMES (Hotspot Ecosystem research along the Margins of European seas)

and HYDRAMED (Marie Curie Individual fellowship), both funded by the EC. A total of 54 MVs were identified across water depths of 150-2750 m using up to four geophysical criteria: distinctive morphology, high backscatter, unstratified subbottom facies and, in one case, a hydroacoustic anomaly in the water-column (Ceramicola *et alii*, 2014). Fourteen MVs were identified from 3-4 criteria, of which five were previously proven by cores containing mud breccia beneath up to 1.6 m of hemipelagic sediments (Madonna dello Ionio MVs 1-3, Pythagoras MV, and the newly named Sartori MV), while nine others were identified for the first time (Athena, Catanzaro, Cerere, Diana, Giunone, Minerva, 'right foot', Venere 1 and 2). Forty other as yet unnamed MVs were inferred from 1-2 geophysical criteria (three from distinctive morphology alone). All but one possible MV lay on the inner plateau of the CAP, landwards of the Calabrian Escarpment in a zone up to 120 km wide that includes the inner pre-Messinian wedge and the fore-arc basins, where they were interpreted to record the ascent from depth of overpressured fluids that interacted with tectonic structures and with evaporitic or shale seals within the fore-arc basins (Ceramicola *et alii*, 2014). The rise of fluids may have been triggered by post-Messinian out-of-sequence tectonism that affected the entire pre-Messinian prism, but Plio-Quaternary sedimentation rates and depositional styles supported the inference that significant mud volcanism has taken place only on the inner plateau. Sedimentation rates across the CAP applied to a 12 khz sonar detection depth of 225 cm imply that all MVs with backscatter signatures (50 of 54) have extruded mud breccias within the last 56 ka, and within the last 12.5 ka in the fore-arc basins. Ages of extrusion estimated from the depth of cored mud breccias at five MVs, and a seismo-stratigraphic relationship at a sixth, indicate extrusive episodes at the last glacial maximum ca. 20 ka BP and during the postglacial period. Extrusive episodes within the Calabrian MV province constitute recurrent geohazards, separated by longer periods of quiescent (subdued) fluid seepage that are likely to support gas hydrate formation and chemosynthetic ecosystems.

6. - DISCUSSION

Based on the results above, a group led by G. Bohrmann of MARUM, collaborating with a team from OGS, carried out further investigations of MVs on the Ionian Calabrian margin during campaigns of the R/V METEOR (Bohrmann *et alii*, 2015) and the R/V POSEIDON (Bohrmann *et alii*, 2016). These campaigns resulted in a wealth of acoustic data providing high resolution imagery of the seafloor as well as of the water column, surveying almost all of the MVs identified by OGS in order to detect gas bubbles rising from the seafloor. During both campaigns a Kongsberg EM2040 (300 kHz) system was mounted on an autonomous underwater vehicle (AUV), the MARUM-SEAL 5000, and revealed morphological details of the Ionian Sea MVs at resolutions of up to 1.6 m lateral and decimetre-scale vertical (Loher *et alii*, 2018a). Particular attention was focused on Venere MV (fig. 2), the only feature on the Calabrian margin observed to be emitting gas to the watercolumn. The 100 m high twin cones of Venere mud volcano with a subsidence caldera composed of inward-dipping ring faults, are situated at 1,600 m water depth within the Squillace Canyon. Sites of gas bubble emissions and chemosynthesis-based ecosystems have been documented at several sites along the periphery of the caldera. The molecular composition of hydrocarbons and isotopic composition of methane indicate a thermogenic origin of hydrocarbons emitted at Venere MV and together with the presence of strongly freshened pore water in recently extruded mud breccia, point to fluid sources located deep (>3 km) within the forearc basins of the CAP (Loher *et alii*, 2018). Seafloor bathymetry and backscatter data obtained by a ship-based system and an autonomous underwater vehicle (AUV) allowed mapping of mudflow deposits of the mud volcano as well as of bedforms in the surrounding canyon. Repeated surveying by AUV documented active mud movement at the western summit between 2014 and 2016 (Loher *et alii*, 2018a). Through sediment coring and the ages of buried ash layers (tephrochronology), it was possible to date buried mudflow deposits based on sedimentation rates in overlying hemipelagic sediments. An average extrusion rate of 27,000 m^3/yr over the last 882 years was estimated. These findings supported a three-stage evolutionary model of Venere mud volcano during the last 4,000 years, which includes i) the onset of quiescence at the eastern cone (after 2,200 years ago), ii) erosive events in Squillace Canyon (prior to 882 years ago), and iii) mud flows from the eastern cone (since 882 years). This study revealed new interactions between a mud volcano and a deep sea canyon and the potential geohazards associated with them.

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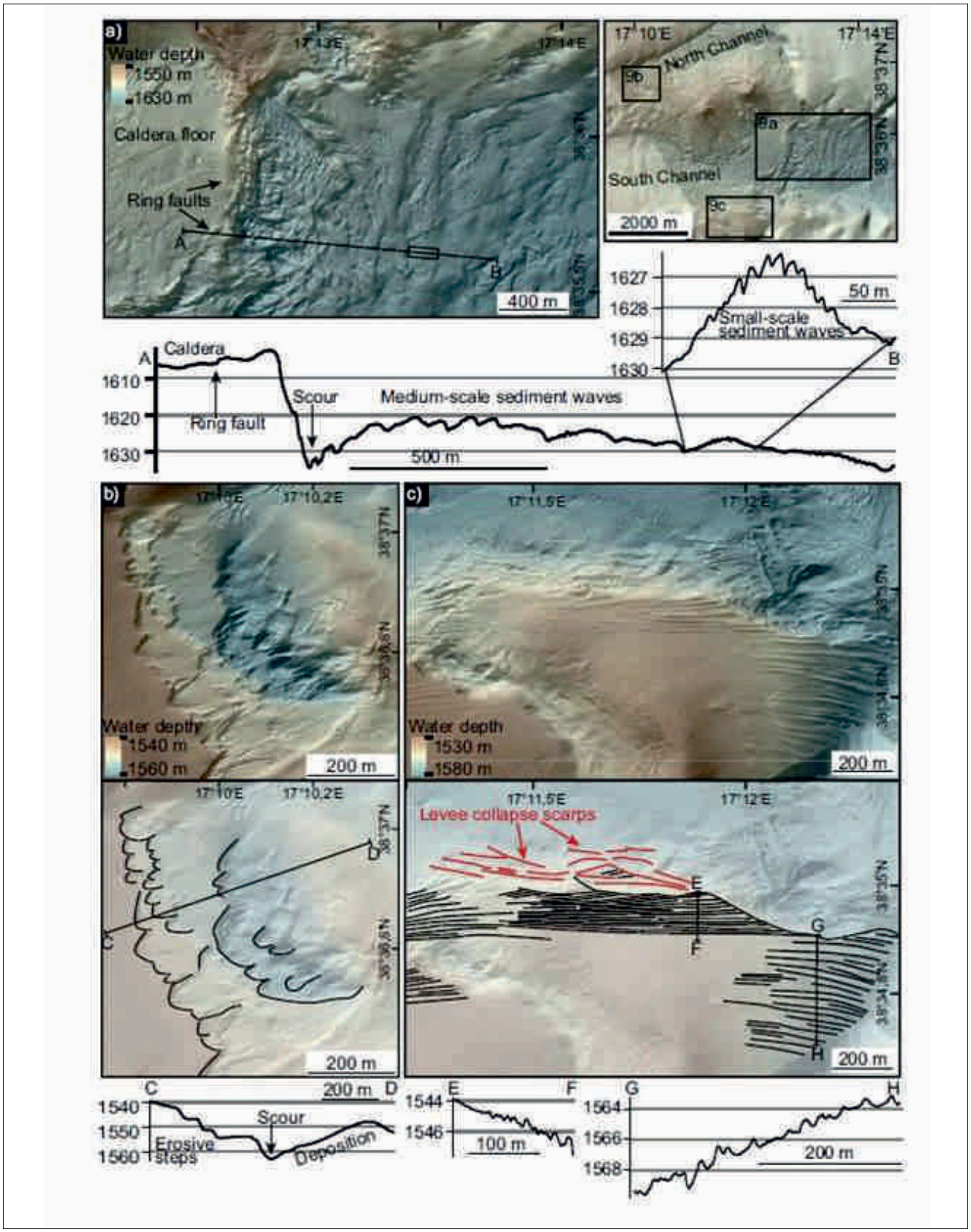

Fig. 2 - Detailed AUV-derived bathymetric maps, interpreted seafloor features and topographic cross-sections in the vicinity of Venere mud volcanoes (see V in fig. 1 for location), a: Grooves covering the southern levee of Squillace Canyon; b: Scour along the northern channel of Squillace Canyon; c: Scour at the downslope edge of the caldera giving way to medium-scale sediment waves, which are overprinted by small-scale sediment waves. Figure modified from Loher *et alii* (2018a).

- *Mappe batimetriche di dettaglio derivate da registrazioni AUV, interpretate, e sezioni topografiche nelle vicinanze dei vulcani di fango Venere* (*V in figura 1*), a: *solchi lungo l'argine meridionale del Canyon di Squillace*; b: Scour *lungo il canale settentrionale del Canyon di Squillace*; c: Scour *lungo il versante della caldera passano a onde di sedimento di media grandezza, sovrastate da onde di sedimento minori. Figura modificata da* Loher *et alii* (*2018a*).

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