



Deciphering the 3D structure and development of the Venere mud volcano (southern Italy) using integrated geophysical methods

Michael Riedel^{a,*}, Cord Papenberg^a, Anne Krabbenhoef^a, Joerg Bialas^a,
Gerhard Bohrmann^b, Miriam Römer^b, Silvia Ceramicola^c

^a GEOMAR, Helmholtz Centre for Ocean Research Kiel, Kiel, Germany

^b MARUM Center for Marine Environmental Sciences and Faculty of Geosciences, University of Bremen, Bremen, Germany

^c OGS, National Institute of Oceanography and Applied Geophysics, Trieste, Italy

ARTICLE INFO

Keywords:

Mud volcanoes
Calabrian arc
Seismic imaging methods
Ocean-bottom-seismic data
Multichannel seismic data

ABSTRACT

Mud volcanoes (MVs) have been found in various geological settings on passive and active margins. Here, we present results from Venere MV located at the southern rim of the Crotona forearc basin of the Calabrian Arc, offshore southern Italy at ~1500 m water depth. The near-circular dimension of Venere MV from its bathymetric expression is ~4 km in diameter and has two cones. To contribute to the knowledge of the internal structure across Venere MV, we conducted a geophysical study using multichannel and wide-angle seismic data constraining the P-wave velocity variation. The upper 200 m below the seafloor consist of sub-parallel layers, while a prominent reflection at that depth is a regionally occurring unconformity representing the onset of the Calabrian uplift. The seismic data and the P-wave velocity indicate two separate feeder conduits of the cones. Seismic imaging yields subseafloor dimensions of Venere MV that exceed its seafloor dimensions by at least twice. Combining the wide-angle and reflection data allowed a reconstruction of the history of Venere MV's structural change over time. An initial phase of mud volcanism formed a semi-circular mound with rigid rims and an internal mud-pie. After a period of quiescence associated with subsidence, this mud-pie was covered with hemipelagic sediments. A second phase formed the double-cone structure re-mobilizing previously extruded mud and creating a complex pattern of overlapping mud flows. The formation of steep cones instead of a mud-pie indicates a change in viscosity of the extruded mud during the second phase of mud volcanism.

1. Introduction

Mud volcanoes (MVs) are deeply-rooted structures where surface mud-extrusion is driven by rising fluids along focused conduits that may extend to depths of several kilometres (e.g. Deville et al., 2006; Planke et al., 2003; Mazzini and Etiope, 2017; Kopf, 2002). Often, mud volcanoes are made up of one or more mud chambers at intermittent depths above zones of geologic overpressure (e.g. Dimitrov, 2002; Kopf, 2002). Although MVs are widespread worldwide (see e.g. a recent inventory by Napoli et al., 2025a), they are concentrated in specific geological regions including convergent margins and accretionary complexes (e.g. Brown, 1990; Brown and Westbrook, 1988; Xu et al., 2021), but also passive continental margins with high sedimentation rates such as sedimentary fans in the extension of river deltas (e.g. Aslan et al., 2001; Loncke et al., 2004; Paull et al., 2015), sedimentary basins associated with hydrocarbon deposits (e.g. Guliyev et al., 2023; Yusubov et al.,

2024), or linked to salt-tectonics (Kirkham and Cartwright, 2022). The presence of more than 600 MV structures has been recorded on land (Mazzini and Etiope, 2017), although the number of underwater MVs is likely to be far greater, and recent improvements in seafloor mapping have led to the discovery of many MVs in all oceans.

Specifically, in the eastern Mediterranean Sea more than 500 MVs are known from several regions (Masche et al., 2014) like the Mediterranean Ridge (e.g. Camerlenghi et al., 1992, 1995; Huguen et al., 2005), the Anaximander seamounts (Lykousis et al., 2009; Pape et al., 2010) and Florence Rise, the Nile deep-sea fan area (Dupré et al., 2008; Feseker et al., 2010), and the Calabrian arc (Praeg et al., 2009; Ceramicola et al., 2014; Doll et al., 2025). Many of the marine MVs in the Mediterranean Sea are rooted within accretionary prisms (e.g. Camerlenghi and Pini, 2009; Ceramicola et al., 2014) and the location of MV is often linked to major thrust faults (e.g. Ceramicola et al., 2014; Rabaute and Chamot-Rooke, 2007). The tectonically active region of the

* Corresponding author.

E-mail address: mriedel@geomar.de (M. Riedel).

<https://doi.org/10.1016/j.marge.2026.207656>

Received 10 July 2025; Received in revised form 8 January 2026; Accepted 3 February 2026

Available online 13 February 2026

3117-5775/© 2026 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

Mediterranean Sea is also strongly influenced by earthquakes which may trigger upward fluid migration and MV eruptions (e.g. Aliyev et al., 2001; Mellors et al., 2007; Menapace et al., 2017).

Within the framework of several European projects, scientists from Italy, Germany, France, and other countries collected over the last 10 years numerous multibeam and echosounder data from the inner and outer Calabrian arc (Gutscher et al., 2017). By combining seafloor bathymetry and backscatter imagery, integrated with sub-bottom profiles

and locally proven from geological sampling, a total of 54 MVs have been identified in a sector of 35,600 km² within the Calabrian Arc (Ceramicola et al., 2014, Fig. 1b). Within the Calabrian Accretionary Prism, three MVs have received particular attention including seismic imaging and sediment sampling: Madonna dello Ionio (e.g. Praeg et al., 2009), Sartori (e.g. Doll et al., 2023, 2025), and Venere MV (e.g. Loher et al., 2018a, b, c). To date, Venere MV is known as the only MV within the Calabrian Arc with active gas seepage, chemosynthetic

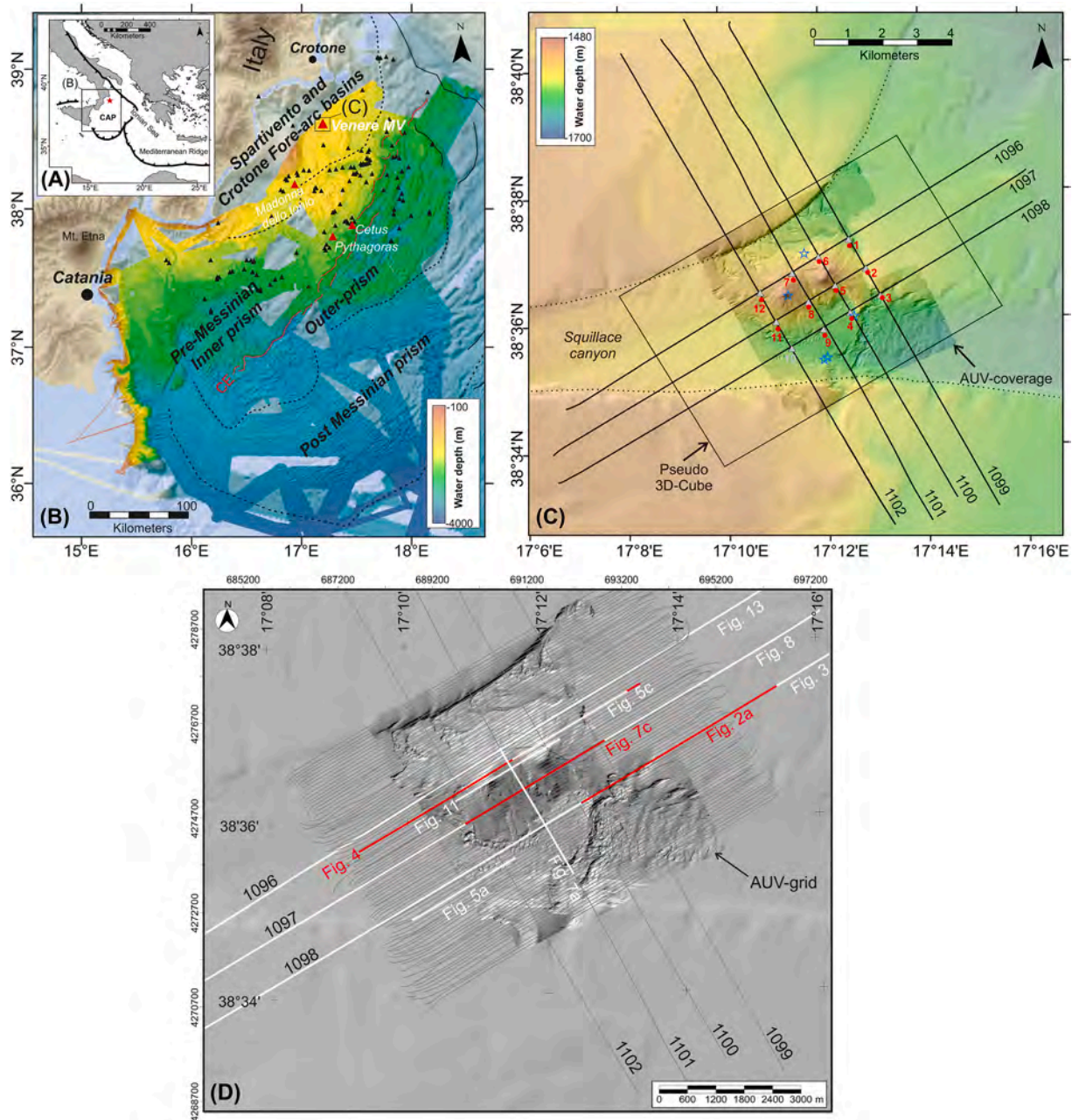


Fig. 1. Overview Map with tectonic setting of the Calabrian accretionary prism (CAP) and study area at Venere mud volcano (MV) (red star). (A) Regional plate-tectonic regime of the central and eastern Mediterranean Sea. (B) Morphobathymetric map of the CAP and major tectonic boundaries. Other locations of MVs are indicated by black triangles (Loher et al., 2018a). Two MVs described by Praeg et al. (2009) with a reference stratigraphic interpretation (Pythagoras MV, Madonna dello Ionio MV) and Cetus MV for comparison are highlighted as red-colored triangles. (C) Detailed bathymetry around Venere MV inside Squillace Canyon (side-walls indicated by dotted black line). High-resolution multibeam data from Autonomous Underwater Vehicle (AUV, Loher et al., 2018a). Solid thick black lines are multichannel seismic (MCS) profiles used for P-wave velocity (Vp) analyses. Black numbers annotate seismic line numbers. Grey triangles show Ocean-bottom seismometer (OBS) deployment positions and red dots and numbers show relocated OBS positions and station numbers (note, OBS 10 was recovered but had recorded no data). Black box outlines survey region for interpolated pseudo-3D reflection seismic imaging from combining 95 shorter MCS reflection profiles. Blue stars are known gas seeps (Loher et al., 2018b). (D) Location of multichannel seismic (MCS) lines used in this study above the hill-shaded bathymetry around Venere MV. CE = Calabrian Escarpment. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

communities, and authigenic carbonates at the seafloor (Loher et al., 2018b). Two seepage domains associated with hydrocarbon venting were defined: shallow-rooted (possibly <1 km) gas venting is linked to ring faults whereas mud extrusion and hydrocarbon migration are linked to sources at depths exceeding 3 km (Loher et al., 2018b). Venere MV is located within the Crotona forearc basin (Fig. 1a and b), in a water depth of ~1600 m. The MV is situated inside a major channel system (Fig. 1c) of the Squillace Canyon (e.g. Capozzi et al., 2012; Coste, 2014). The channel splits into two sub-channels as mapped by Loher et al. (2018a) east of the Venere MV and the channel floor is showing a network of alternating scours and sediment waves, locally covered by numerous small-scale mud flows. The northern rim of the channel is a marked edge with a nearly vertical headwall of ~30 height. The activity of Venere MV has been shown to bifurcate the main branch of the Squillace Canyon (Loher et al., 2018b).

To contribute to the knowledge of submarine MVs, in particular the internal structure across Venere MV, we conducted a multi-geophysical imaging approach during expedition POS515 with the German research vessel POSEIDON (Riedel et al., 2017). High resolution multibeam bathymetry constraining the seafloor morphology of the MV (Loher et al., 2018a, 2018b) was used to guide new multichannel seismic (MCS) and wide-angle ocean-bottom seismometer (OBS) data acquisition. The Vp structure obtained from our OBS-analyses are the fundamental base for all subsequent analyses including migration of the OBS data. The overall aim of this study is to present a 3D structural model of Venere MV as best constrained by available seismic imaging. An additional objective is to tie the Venere MV structures and seismically imaged stratigraphic units into existing geological models and to define an overall timing of activity of Venere MV. With the available velocity-control and depth-conversion from wide-angle seismic data, an additional objective is to estimate a first-order volume of mud extruded at Venere MV. From the depth-converted data, constraints on the volumetric mud-extrusion history were made, expanding on the initial results from Loher et al. (2018b). Using assumptions on the amount of gas present within the extruded material (Loher et al., 2018b), a total volume of methane emissions over the geologic history of Venere MV in the Pleistocene was made. Thus, this study provides a step forward in our understanding of the role of submarine MV as contributor in global greenhouse gas emissions.

2. Tectonic setting

The Calabrian Accretionary Prism (CAP) is 300 km wide and extends almost 300 km from elevations of ca. 1950 m in Calabria to a frontal thrust intersecting the Mediterranean Ridge in water depths of ca. 4000 m (Fig. 1a; Chamot-Rooke et al., 2005). The CAP lies at the SE tip of the arcuate Apennine-Maghrebide subduction system (Fig. 1a), a product of rapid rollback of a NW dipping oceanic slab over the last ca. 30 Ma (Neogene) to open back-arc basins in the western Mediterranean Sea (Malinverno and Ryan, 1986). Since ca. 10 Ma (late Miocene), slab retreat has driven the pulsed opening of back-arc basins in the Tyrrhenian Sea during migration of the accretionary system up to 380 km towards the Ionian domain (Faccenna et al., 2004). Consumption of the slab, and its fragmentation during episodes of tearing beneath bordering continental margins, has narrowed the subduction zone to a tongue of Ionian lithosphere confined between the Maltese and Apulian escarpments, descending NW into the mantle beneath the Aeolian volcanic arc (Faccenna et al., 2004). Rollback of the subducting slab has slowed or ceased following a regional plate tectonic reorganization at ca. 0.8-0.5 Ma (Goes et al., 2004). Over the same time period, Calabria has undergone a rapid km-scale uplift (Zecchin et al., 2012), argued to be a response to mantle circulation around a slab window beneath the southern Apennines (Faccenna et al., 2011). In the Ionian Sea, Rossi and Sartori (1981) showed the seaward-thinning accretionary prism to contain three main morpho-structural zones (Fig. 1b), recognized in all subsequent work and corresponding to the fore-arc basin and pre- and

post-Messinian (internal/external) wedges (e.g. Praeg et al., 2009; Polonia et al., 2011).

Detailed seismic imaging and interpretation of regional-scale seismic data defined the large-scale seismo-stratigraphic units of the CAP and revealed a series of thrust faults within the pre- and post-Messinian wedge (e.g. Polonia et al., 2011; Maesano et al., 2017 and references therein). Shallow thrust-type seismic activity is though lacking across the Calabrian Arc; yet, the presence of active deformation of the shallow sedimentary units at the wedge front implies that subduction could still be active but possibly aseismic or with a locked mega-thrust fault plane (Polonia et al., 2011). Utilizing turbidite deposits across the CAP, Polonia et al. (2023) defined a possible recurrence rate of 2-3 ka for such subduction-related plate-interface earthquakes. Whether the main slab or shallower thrust fault splays may be linked to individual MV activity remains unclear and beyond the scope of this study. However, the onset of mud volcanism on the inner prism (NW of the Calabrian Escarpment, Fig. 1b) has been linked to the mid-Pliocene at around 3.6 Ma, and upward fluid and mud migration is suggested to have been triggered by post-Messinian (<5.3 Ma) slab retreat with arc migration and simultaneous back-arc extension (e.g. Praeg et al., 2009). In a detailed study combining acoustic imaging with sediment analyses, Ceramicola et al. (2014) showed that the vast majority of MVs in the CAP erupted within the past 56 ka. Furthermore, Doll et al. (2025) showed at Sartori MV a very detailed chronology of individual mud flows where mud flow activity and extruded volume have progressively decreased for the past ~56 ka.

3. Data and methods

3.1. Multibeam bathymetry

Several multi-resolution bathymetric datasets from a number of research expeditions in the region are available for our study and are combined in one regional grid with a resolution of 40 m by 40 m (Gutscher et al., 2017). In addition, Autonomous Underwater Vehicle (AUV) seafloor bathymetry and backscatter data were acquired across Venere MV and Cetus MV (R/V POSEIDON cruise POS499 (Bohrmann et al., 2016) and R/V METEOR cruise M112 (Bohrmann et al., 2015)). These high-resolution data were used to guide the OBS deployment and MCS data acquisition during R/V POSEIDON cruise POS515. Details of AUV data acquisition and processing can be found in Loher et al. (2018a) and Bohrmann et al. (2016; 2015).

3.2. Multichannel seismic (MCS) data

Short-offset MCS data were acquired during cruise POS515 with a total of twelve streamer sections (each 12.5 m long and containing 8 recording channels) combined into a 150 m long streamer of 96 channels total. The seismic source was a single GI Gun (volume of 210 in³, or ~3.4 l; dominant frequency ~ 100 Hz) towed at a nominal depth of ~4 m below sea surface for the seven long OBS refraction survey lines. The injector is fired with a delay of 50 ms after the generator. Firing interval between consecutive airgun shots was 10 s for the acquisition of wide-angle data. Processing of the MCS data post-expedition was done using the software VISTA. Processing included after geometry definition, an initial frequency bandpass filter, debias, and noise-removal. Due to several dead channels in the streamer, trace interpolation to achieve full fold was included. After binning into common-mid-points (CMP), data were corrected for normal moveout (NMO). Due to the small total offset of 150 m in water depth >1500 m, a simple NMO-velocity function was initially used to generate a brute-stack. The overall warm Mediterranean water temperatures and salinities yield an average water-velocity of ~1520 m/s. Frequency-wavenumber (FK) time-migration with a single velocity of 1520 m/s and a 1-D velocity depth-conversion was conducted on the brute-stack to guide the OBS modeling. This was followed by a second processing sequence including

new NMO correction and 2D FK time-migration using the final 2D OBS-based velocity grid. The post-stack migrated seismic data were then depth-converted with the OBS-based velocities for display-purposes as overlay to the velocity-results. Seven MCS profiles across the OBS stations were acquired with distances large enough to observe refracted arrivals (lines 1096 – 1102, Fig. 1c). These seven profiles were used for OBS-based velocity analyses (see below). Additional 95 parallel lines (with a spacing of ~50 m) were acquired in a pseudo-3D grid pattern for higher resolution seismic imaging of the Venere MV. These lines were acquired with the same streamer configuration, but at faster shot-interval of 5 s to increase lateral resolution. The location of individual MCS lines shown in subsequent figures is given in Fig. 1d.

The 95 lines acquired with a 5 s shot-interval were interpolated and binned into a regular grid (9375 m SW-NE by 5762.5 m NW-SE) generating a 3D cube with a resolution of 3.125 m (inline, main shooting-direction) by 12.5 m (crossline direction after interpolation). Using the original 95 lines and the interpolated 3D cube, fault traces were hand-picked and verified using the similarity attribute calculated on the interpolated 3D grid. However, the similarity attribute can be aliased for structures smaller in extent than twice the interpolation step-size (i.e. < 25 m laterally) and thus is not uniformly useful across the entire data set.

3.3. Ocean bottom seismometer (OBS) data

A total of twelve OBS instruments were deployed at Venere MV in a rectangular grid across the two main cones. Although all instruments were recovered at the end of the survey, one OBS (Station 10) did not record any data. From the remaining eleven instruments, all data were recovered and corrected for the internal clock time-drift (Riedel et al., 2017). To compensate for the physical drift of the instruments on the way from the sea surface to the seafloor upon deployment, we re-located their positions on the seafloor iteratively, using the direct arrival travel-times, measured water velocity, and locations of known airgun shots minimizing observed and computed travel-times. All OBS instruments drifted to the south-east for a minimum of ~110 m (OBS03) and maximum of ~210 m (OBS05) from their deployment positions (Fig. 1c).

The program Pasteup (Fujie et al., 2008) was used to pick the reflection and refraction travel-time data from the hydrophone and/or vertical geophone component. All OBS data are of high quality (see

Supplement Fig. S1 as an example of the record of OBS station 09) and processing prior to picking only included some frequency-filtering. Reflections can be better identified including high frequencies (full range), while refractions are better highlighted limiting the data to low frequencies (<50 Hz). Picking accuracy is 5 ms for the shallower reflections and increase up to 20 ms for the deepest reflection and the refractions. Picking of reflections was guided by horizons identified on coincident MCS lines. Major horizons were matched in time/depth at the crossings of individual MCS lines. Also included are the first multiple of selected reflections, the direct wave and its multiple arrival, as well as one multiple refracted arrival (Table 1). All multiple arrivals were incorporated in building the velocity model, but with a pick-uncertainty of 20 ms.

3.3.1. Top to bottom approach for velocity-model definition

The dense OBS network and quasi-3D grid of seismic lines, with a large amount of reflections (9 reflections within the upper ~0.6 s, corresponding to ~0.5 km below the seafloor, bsf) allowed us to obtain the Vp-depth distribution with travel-time forward modeling and inversion. We used the Modeling program Pasteup (Fujie et al., 2008) in a top to bottom approach. After the travel-time curve of the first reflection was fitted to the travel-time picks within the range of picking accuracy at all OBS stations along the seismic lines, we successively fitted all travel-time curves for deeper reflections in an iterative manner. Results were thereby matched successively between all crossing lines and OBS stations for each reflection. Wide-angle refractions constrain the velocity for the deeper layers in ~2.4 km depth at the center of the seismic lines (Supplement Fig. S1). Refractions were modeled as turning rays helping to constrain the velocity gradient below the corresponding layers. After the final best-fit forward model was defined, velocity of each layer was refined through iterative inversion minimizing the misfit between picked and predicted first-arrivals (Zelt and Smith, 1992; see Supplement Fig. S2 as example of modeled arrival times compared to manual picks along line 1098). The final velocity grid was used to predict the arrival times of the first water-multiple reflections and refractions in an effort to determine robustness of the velocity information. With diminishing depth penetration of our high-resolution seismic experiment, the velocity models are terminated at 4 km depth with an assumed velocity value of 3.0 km/s.

Table 1

Simplified average 1D P-wave velocity (Vp) for all layers identified, modeled ray-type (reflection (Rc), refraction (Rfrc)), number of picks used, pick-uncertainty, final RMS-misfit and normalized χ^2 values along all seven lines analyzed. Modeling-statistics are given for primary and first multiple arrivals (where identified).

Layer	Primary (P) Multiple (M)	Type	Vp (km/s)	Pick-uncertainty (ms)	RMS-misfit (ms)	Normalized χ^2	Total number of picks used	Remarks
1	P	-	1.52	5	4.1	0.53	2871	direct arrival
2	P	Rc	1.53 – 1.53	5	3.7	0.59	2712	
3	P	Rc	1.54 – 1.55	5	4	0.68	2862	
4	P	Rc	1.56 – 1.57	5	4	0.64	2677	base of unit 3b
5	P	Rc	1.58 – 1.59	5	3.7	0.58	2419	
6	P	Rc	1.63 – 1.65	5	4.1	0.71	2538	
7	P	Rc	1.68 – 1.70	5	3.9	0.58	2831	
8	P	Rc	1.80 – 1.83	5	4.3	0.75	2494	base of unit 3a
9	P	Rc	1.85 – 1.88	5	3.6	0.55	1756	
10	P	Rc	1.90 – 1.95	5	6.4	0.45	1605	base of Unit 2b
11	P	Rc	2.10 – 2.40	20	12.9	0.45	609	basement (Unit 1)
8	P	Rfrc	1.80 – 1.83	20	14.3	0.43	599	base of unit 3a
10	P	Rfrc	1.90 – 1.95	20	14	0.5	446	base of unit 2b
11	P	Rfrc	2.10 – 2.40	20	17.3	0.59	929	basement (Unit 1)
1	M	-		20	18.4	0.55	3179	direct arrival
7	M	Rc		20	18.4	0.91	1207	
8	M	Rc		20	15.9	0.68	469	base of unit 3a
9	M	Rc		20	17.8	0.73	194	
10	M	Rc		20	13.9	0.58	358	base of unit 2b
10	M	Rfrc		20	16.8	0.39	255	base of unit 2b
11	M	Rc		20	18.4	0.9	501	basement (Unit 1)
11	M	Rfrc		20	34.8	1.5	193	basement (Unit 1)

3.3.2. Mirror-imaging of ocean bottom seismometer data

The mirror imaging technique (e.g. [Grion et al., 2007](#)) utilizes the first multiple of the arrivals for imaging, providing larger aperture than the direct (first) reflections, thus horizontally widening the regional coverage. Using OBS data also allows recovering deeper frequencies than what is recorded on the 2D MCS streamer and thus this technique could provide deeper penetration and the ability to possibly overcome subsurface-related attenuation from topographic irregularities of the near vertical-incidence reflected MCS data. For successfully applying the OBS mirror imaging technique, it is important to have separation between the direct arrivals and reflections and the multiple. This is optimally achieved at Venere MV ([Supplement Fig. S3](#)) where the primary energy is sufficiently reduced in amplitude at the arrival of the multiple. The mirror imaging code was successfully applied previously to OBS data acquired at the Sevastopol MV ([Krabbenhoef et al., 2016](#); [Papenberg et al., 2016](#)). We conducted mirror imaging using the hydrophone component of each OBS (from now on we refer to this data set as ocean-bottom-hydrophone data, OBH) along the seven longer profiles (lines 1096 - 1102). Each line was first migrated for each of the coinciding OBH individually, thereby projecting the data after

re-localization onto a 2D crooked line. Combining multiple OBH and stacking the data along the lines (i.e. two stations at line 1102, three stations for lines 1099, 1100, 1101, and four stations for lines 1096, 1097, and 1098, respectively) yield a partially degraded result due to de-stacking of coherent signals from Vp related distortions at the edges of each line and slightly different signal-coherency of each individual OBS/H. Especially OBS locations 02 and 04 were too noisy to constructively add in stacking, but still did yield valuable 2D velocity information.

Each OBS did continuously record the wave-field emitted by the airgun during the entire experiment, including all turns made while we kept the airgun active. After instrument re-localization, we implemented a full 3D mirror time-migration of each OBH followed by stacking of all data from all stations (excluding stations OBS02 and OBS04 of very low signal-to-noise ratio). The objective of this 3D OBH migration is to aid in the interpretation of the MCS data that are compromised by shortcomings in the reflection seismic imaging capacity from near-seafloor irregularities yielding apparent blanking zones and from the complex 3D nature of the MV cones resulting in potentially artificial images when assuming 2D migration algorithms only, as well as side-echoes from

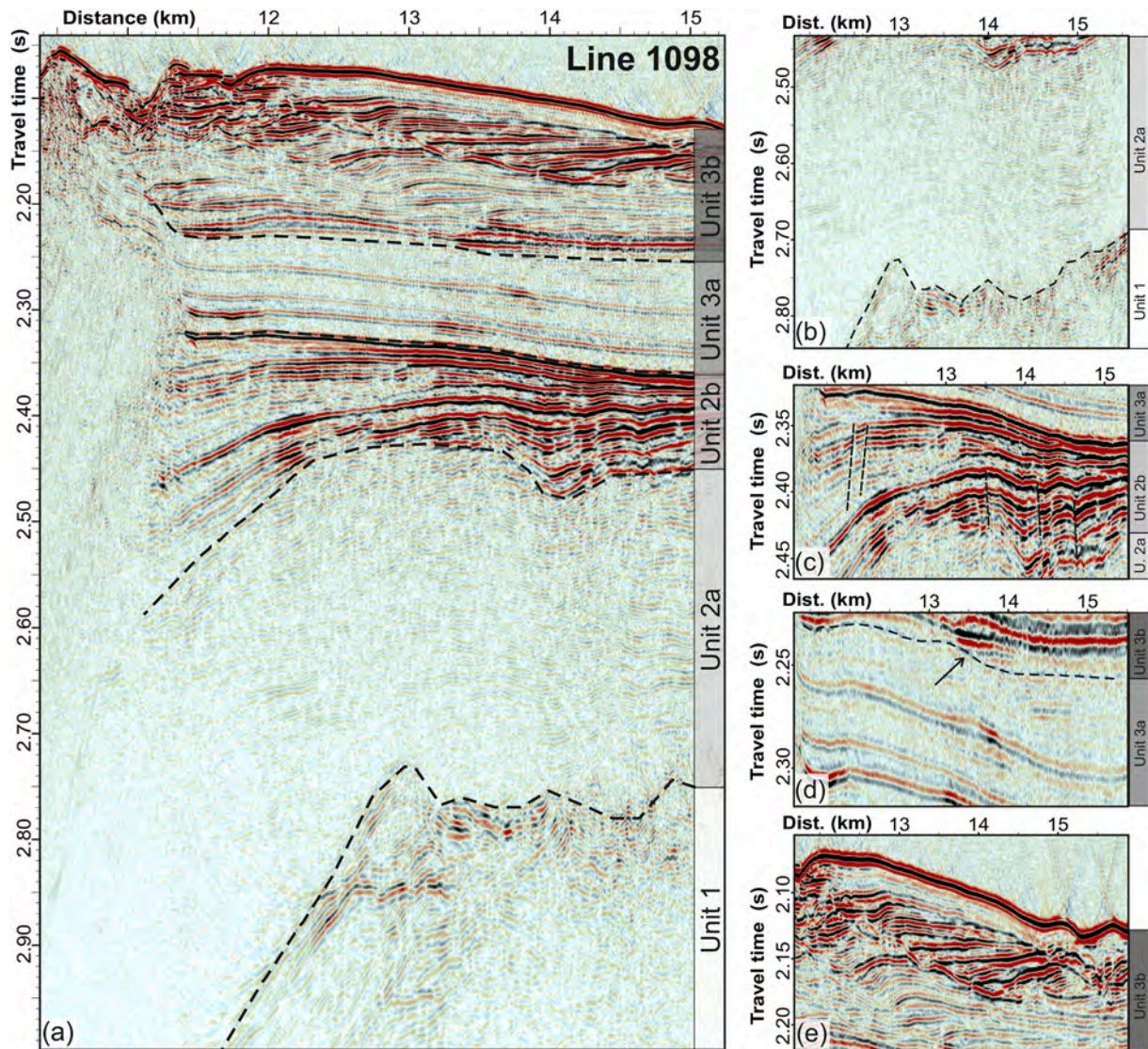


Fig. 2. Section of MCS line 1098 (2D FK time migration) showing main stratigraphic units imaged by the reflection data (a). From bottom to top: Unit 1 is the acoustic basement with rough topography and piece-wise high reflection patches (b). Unit 2 is divided into two sub-units with sub-unit 2a being of very low reflection amplitude but piece-wise semi-parallel reflections (b). Sub-unit 2b shows high reflection amplitude marked by an unconformity at the top (c). Unit 3 is divided into sub-unit 3a with low-amplitude and mostly parallel reflections (d), and sub-unit 3b with high amplitude reflections of undulating nature (e).

steep topography. The full 3D OBH migration also allows mapping of the mudflows in the central portion of Venere MV at much higher resolution than what is possible with the parallel 2D MCS data.

4. Results

4.1. The sub-seafloor regional stratigraphy from seismic reflection imaging

The MCS reflection data image the sediment sequence up to a depth of ~1000 m below seafloor. This sequence away from the main MV structure was divided into three main sedimentary units (Fig. 2a).

4.1.1. Stratigraphic Unit 1

The top of the deepest Unit 1 is identified as “acoustic basement” beneath which reflection imaging is often reduced (Fig. 2b). The surface of the acoustic basement reflection is rough but generally strong in amplitude. Beneath the central portion of the Venere MV, seismic data do not image a basement reflection. Across the study region, basement topography changes significantly and varies by up to 600 m along the seismic lines. Basement is shallowest towards the north-eastern portion of all seismic lines and dips towards the central portion of the MV (towards the south-west). The basement reflection is typically the deepest below seafloor on the north-western portion of the lines (outside the channel region).

4.1.2. Stratigraphic Unit 2

Above the acoustic basement, a well-stratified unit is deposited (Unit 2, Fig. 2b). This unit shows some normal faulting with the majority of faults terminating at the upper limit of the unit. The normal faults show varying dip direction but have two predominantly strike directions: north and south of the channel incision, faults strike at ~60° from North but in the western portion of the region, faults strike at an oblique angle ~135° from North. Sediments within Unit 2 can be subdivided into two sub-units. The lower sub-unit 2a (Fig. 2b) shows lower reflection amplitude compared to the overlying sub-unit 2b (Fig. 2c). All sedimentary layers within Unit 2 dip towards the centre of the MV. Dip progressively increases with depth and towards the centre of the MV. The top of Unit 2 is a regional unconformity that can be easily recognized in all seismic profiles.

4.1.3. Stratigraphic Unit 3

Above this regional unconformity, sedimentary layers of Unit 3 are showing nearly no sign of normal faulting (Fig. 2a). Unit 3 was divided into two sub-units based on the internal reflection character of the sediments. Sediments of Unit 3a (Fig. 2d) are nearly flat and uniformly deposited on top of the unconformity. Layers imaged within this sub-unit are of overall low reflection amplitude. This is in stark contrast to the uppermost sediment layers of sub-unit 3b that show a laterally changing and undulating nature (Fig. 2e). The reflection strength of these layers is much larger and more variable. The base of sub-unit 3b is an erosional unconformity (see arrow in Fig. 2d).

4.2. P-wave velocity (V_p) distribution from wide-angle OBS data

The upper 200 m (sub-) parallel layers below the seafloor (bsf) show V_p values gradually increasing from 1.53 to 1.7 km/s (Table 1). At the prominent reflection of the unconformity ~200 m bsf a sudden increase of V_p from 1.7 to 1.8 km/s marks a change in the otherwise homogeneous velocity field. Beneath the unconformity, reflections dip and V_p laterally decreases towards the centre of Venere MV in a circular symmetric pattern. The deep root of the MV is beyond achievable depth penetration. The lack of reflections beneath the central portion of the MV reduces the reliability of velocity definition, as only few rays cover this region. The reflections from the acoustic basement vary from 500 m to 800 m bsf and few reflections can be identified in the OBS data from

greater depth. Thus, we are unable to further constrain the velocity beneath the acoustic basement and a constant gradient is used to the final depth of the velocity field with a maximum velocity of 3 km/s. One example of the resulting V_p model superimposed on the coincident MCS reflection image of line 1098 is shown in Fig. 3. All remaining examples are given in the Supplementary information (Fig. S4–S9). The root-mean-square (rms) misfit and normalized χ^2 -values for all modeled reflections and refractions for the final velocity models are summarized in Table 1.

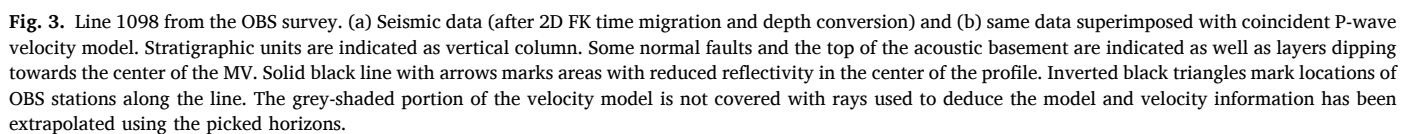
4.3. Seismic reflection character of Venere MV

4.3.1. Ring-structure

Seismic reflection imaging reveals two nearly symmetrically located zones of reduced reflectivity underneath Venere MV (Fig. 4a) protruding as bulges above the regional unconformity marking the boundary between stratigraphic Unit 3a and Unit 2b. Sedimentary reflections of Unit 2b underneath the unconformity are dipping into the centre of Venere MV but cannot be imaged entirely underneath the two cones with the 2D streamer data set. The degree of dip increases for deeper reflections, especially pronounced on the eastern margin of the MV. Above the unconformity continuous reflections are seen (Unit 3a) that gradually cover the zones of reduced reflectivity and the two bulges and can partially be traced into the inner depocentre. At both outer edges of the two bulges, several short reflection-segments are dipping towards the centre of the structure, marking the typical Christmas-tree shape as a result of overlapping extruding mud with regular (hemipelagic) sediments (Fig. 5). Similar features are identified below the unconformity.

In all the different seismic data types, a ring-like or donut-shaped structure of low- and high-reflectivity (with corresponding low and high similarity) beneath the MV is imaged (Fig. 6). The ring structure can be seen starting below a depth of ~2.17 s two-way travel-time (tw) (2000 m total depth below sea surface), widening with depth and reaching a maximum horizontal extent at a depth of 2.34 s twt (~2200 m below sea surface). The ring of low reflectivity is wider than the surface expression of the two cones at Venere MV. The inner circular region of high reflectivity and high similarity is bound on the outer rim by the ring faults mapped by [Loher et al. \(2018b\)](#). The ring structure is thus not just a feature in the MCS data and an artifact from poor imaging in the near-vertical incidence range of the data, but exists as true low-amplitude zone as imaged with the OBH and wide-angle reflections that undershoot the complex surface topography of Venere MV. The region between the two bulges of reduced reflection strength (i.e. inside the low-amplitude ring-feature) forms a bowl-shaped mini-basin with higher reflection strength (Fig. 4), but often only short reflection segments are imaged, thus creating a chaotic overall seismic image as seen on the time-slices (Fig. 6).

Near the west cone of Venere MV the subsurface structure within this mini-basin changes its character. A package of reflections is strongly warped upwards (dragged) forming a finger-like structure with bright reflections at the top (Fig. 7a, b, c, d), likely representing the feeder-channel of mud from greater depth. Reflection polarity of the top reflection appears opposite to that of the seafloor in the OBH data (Fig. 7e), but polarity remains obscured in the 2D MCS data. Imaging of the steep reflections is limited but the package is approximately 80 ms twt thick, equivalent to ~60 m, if those sediments were horizontally deposited. At the same time, a portion of the sedimentary layers deposited in the mini-basin form clear onlap-structures onto the package of warped sediments. The deepest onlap was identified at a depth of 250 ms twt bsf or ~200 m bsf. The up-warped finger had evolved after some sediments had already accumulated in the mini-basin and gradually grew upwards simultaneously with ongoing sedimentation and newly emitted mud flows from the west cone. A similar feature may also exist at the south-western edge of the mini-basin related to the east cone (Fig. 7b–e). However, seismic imaging is not definitive and the nearby fault may have altered the sediment-layering too strongly to clearly



A striking detail in our Vp model is the velocity-distribution in the ring structure and feeder-channel close to the west cone (Fig. 8a). While the Vp outside the main structure of Venere MV is increasing with depth and remains laterally homogeneous reflecting burial depth (i.e. age), the velocity structure inside the MV is laterally rather variable. The symmetric ring of low reflectivity is associated with a much higher velocity than the surrounding sediment at comparable depths. As outlined along MCS line 1097, the velocity within the two bulges is ~ 1690 m/s, whereas the region outside shows velocity values of ~ 1580 m/s. Additionally, the zone of strongly upwards bending reflections underneath the west cone shows velocity values of up to 1750 m/s for the same burial depth. Combining the results of all seven long MCS lines shot for seismic refraction velocity analyses in a time-slice reveals the consistency of elevated velocities within the ring structure and feeder-channel (Fig. 8b).

components of the data with major impedance changes in the subsurface). We also followed in the picking process the boundaries of the finger of warped sediments at the west cone. Outside the ring structure the surface was continued parallel to the unconformity between Units 3a and 2b for display purposes. The resulting surface was smoothed to avoid striping in the picks from the parallel 2D nature of data acquisition (footprint) and was then gridded using a 10×10 m cell-size (with minimum curvature constraint). The resulting surface is shown in Fig. 9a in a 3D-view together with inline 4848 and a time-slice at 2.38 s twt from the pseudo-3D MCS data to show the ring of low amplitude below the bulges. The depth of the picked horizon is also displayed as 2D map (with contour-lines) in Fig. 9b. On the north-western region of the structure, the height of the circular bulge is less tall and almost reaches the depth of the surrounding unconformity. Whether this is an erosional effect or the ring had in the past collapsed remains unresolvable. The inner portion of the ring structure forms a depression (mini-basin) that reaches a maximum depth of 400 ms twt bsf, equivalent to ~ 320 m bsf. The depression is slightly asymmetrically shaped with steeper slopes on the eastern and southern margin, linked to the inner ring fault and the

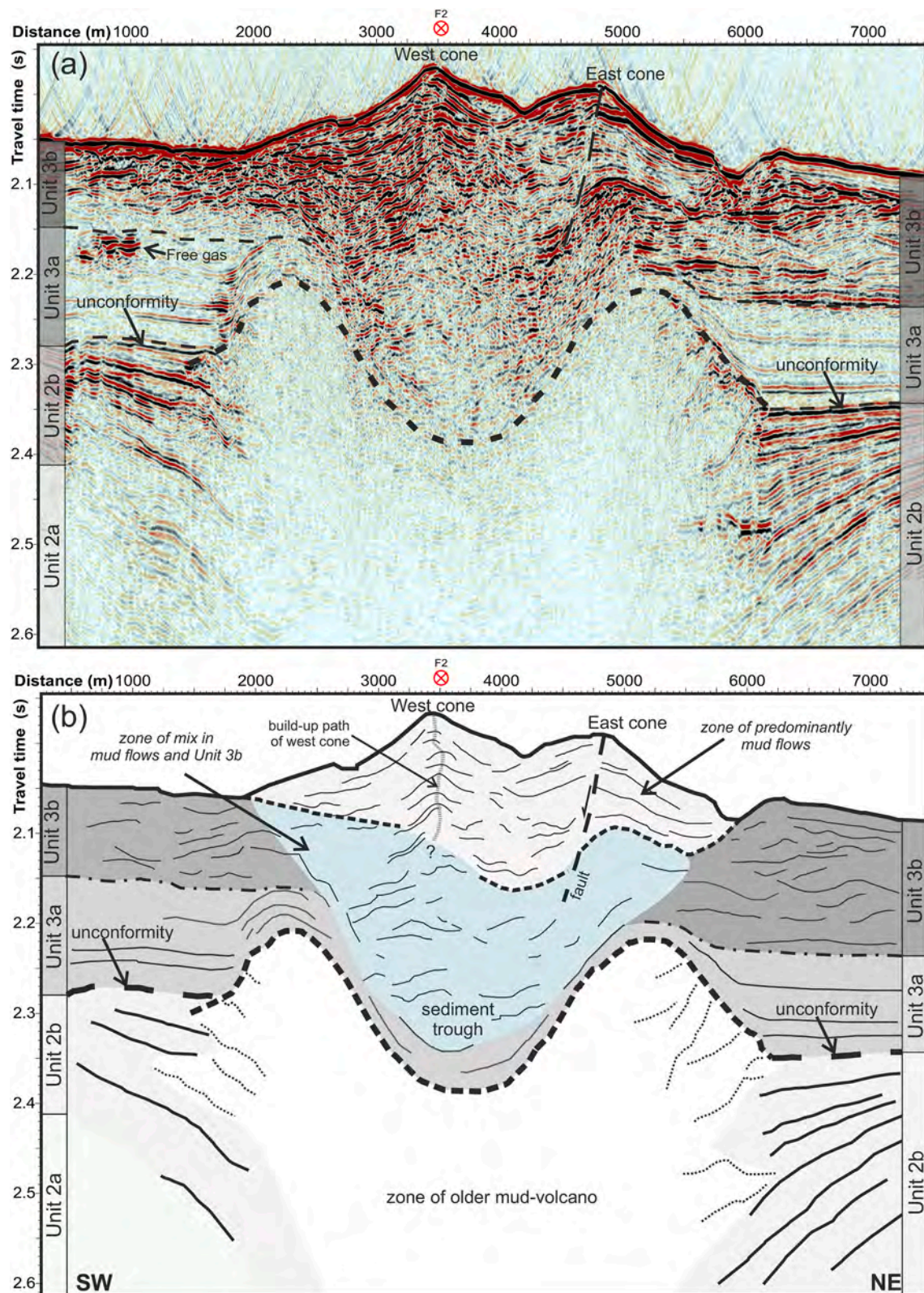


Fig. 4. (a) Image from seismic line 1031 (after 2D FK time migration) showing two bulges of reduced seismic reflection amplitude in between a filled sediment trough (depocenter, or mini-basin). Above this structure the two cones of Venere MV are located. (b) Interpreted line-drawing of section shown in (a).

collapse of the east cone as described by [Loher et al. \(2018a\)](#).

The central portion of Venere MV beneath the unconformity between stratigraphic Unit 2b and Unit 3a is characterized by dipping reflectors where the dip progressively increases towards the central region beneath the MV (Fig. 4). The stratigraphic Unit 2b is thereby of much

higher reflection amplitude than the bounding units above (Unit 3a) and below (Unit 2a). That reflection character and remarkable dip can be traced away from the centre of Venere MV up to a distance of ~6 km (Fig. 9b). At the outer edge of this feature, sediment reflections suddenly increase in reflection strength (Fig. 9c and d). Following the reflections

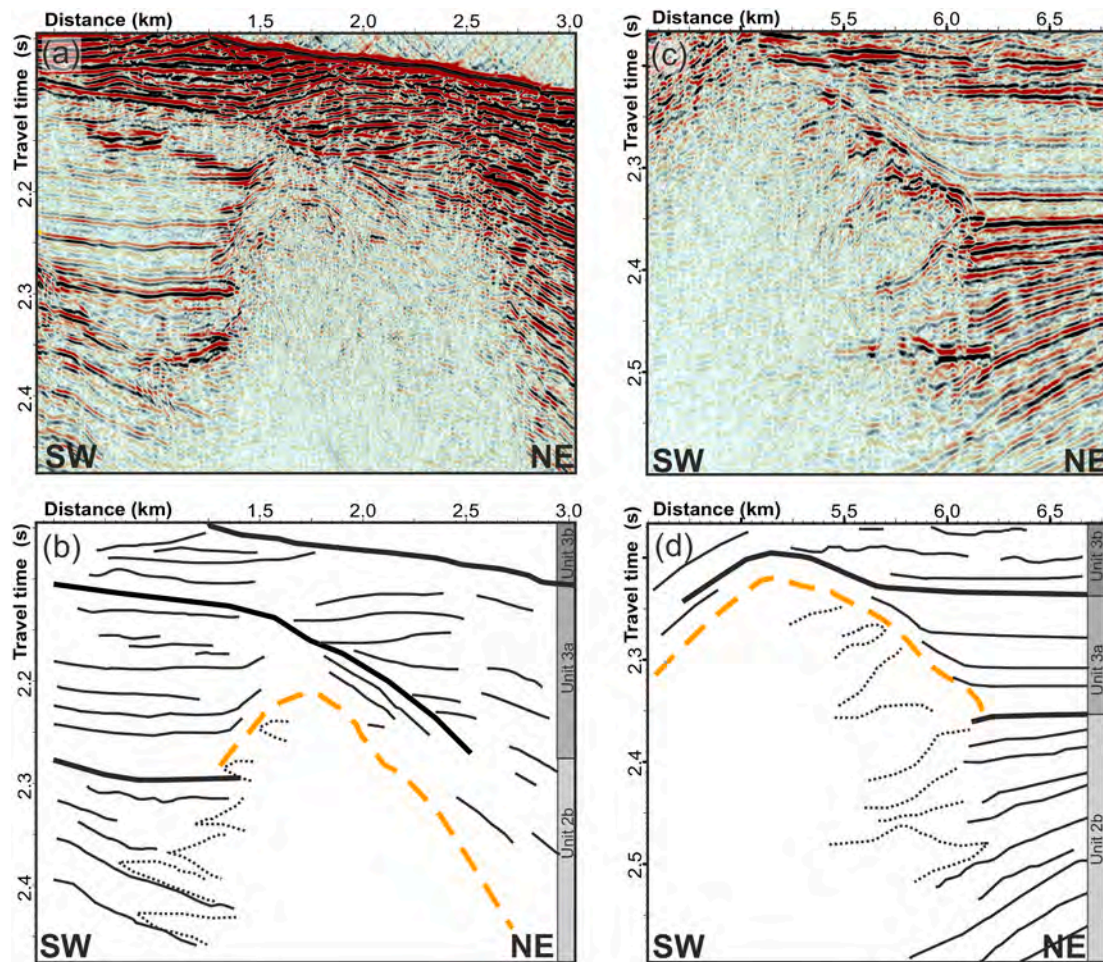


Fig. 5. Detailed view on the Christmas-tree structure at the two outer bulges of the ring-like structure beneath Venere MV as imaged with the MCS data (after 2D FK time migration). (a) and (b) are from the western bulge (line 1062), (c) and (d) are from the eastern bulge (line 1098).

towards the main Venere MV they remain at such high amplitude. The next deeper reflections also show the same behaviour but the onset of relative higher reflection strengths is shifted towards Venere MV, thus giving an overall impression of a wedge or “inverted triangle”. The sediments within this wedge are additionally faulted, and with one exception, these faults do not penetrate shallower than the unconformity between stratigraphic units 3a and 2b, i.e. the top of the wedge-like feature.

4.3.2. Ring faults

High-resolution bathymetric mapping of the Venere MV has revealed a series of ring faults that develop around the two cones and partially cut several mud flows (faults marked in red in Fig. 10a), especially those emanating from the east cone (Loher et al., 2018b). These ring faults are also associated with fluid seepage identified from prominent gas bubble release into the water column (Loher et al., 2018b). However, the prominent ring faults identified in the seafloor bathymetry can be seen – if at all – in the seismic data only for short depths and are imaged only within the upper 20 m bsf. Due to the lack of coherent reflectivity and steep slopes over much of the cone structures, faults are difficult to recognize at greater depth in the seismic data. However, they may extend to larger depths as indicated by the fluid composition described by Loher et al. (2018b). The seafloor offset of the ring-fault traces are ~2 m and thus at the resolution limit of the reflection seismic data.

Using the 2D MCS reflection data, we picked fault traces at greater sub-seafloor depth and verified these with the similarity attribute calculated from the interpolated pseudo-3D MCS cube and 3D OBH

cube. Several normal faults are well developed in the sediments of Unit 2 (Figs. 4 and 9, Supplement Fig. S4–S9). Most of these faults do not penetrate to shallower depths to the base of Unit 3b and are confined to Unit 2. The faults truncate at the unconformity, with a prominent exception seen in the region south-west of Venere MV with these few faults penetrating to ~100 m bsf. Connecting fault picks made on individual MCS lines, a pattern of ring-faulting emerges (Fig. 10) at a radial distance of 2 – 4 km outside the previously imaged ring faults by Loher et al. (2018b).

One of the unique features observed hydroacoustically and visually with an ROV at Venere MV was the occurrence of free gas bubbles in the water column. Five gas flares (F1 – F5) were mapped (Loher et al., 2018a) and are seen either at the summit of the west cone or associated with the ring-fault system (Fig. 10a). Chemical analyses of the gas point to a mixture of possible sources including a thermogenic origin from greater depth and a shallow microbial methane source. We used the seismic data to scan the records for evidence of free gas within the depth interval imaged using two distinct characteristics for free gas signatures: (i) bright-spots with a polarity opposite to the seafloor from a P-impedance reversal, and (ii) pull-down of sedimentary layers beneath bright-spots possibly but not necessarily linked with acoustic blanking. Two bright-spots with a top-reflection of inversed polarity to the seafloor and free-gas related down-warping were observed outside the Venere MV cone structures (Fig. 10). These two bright-spots are linked to faults reaching from below the unconformity to within stratigraphic Unit 3a. Within the inner ring of Venere MV, the 2D reflection data did not indicate clear evidence for the presence of free gas; however, the 3D

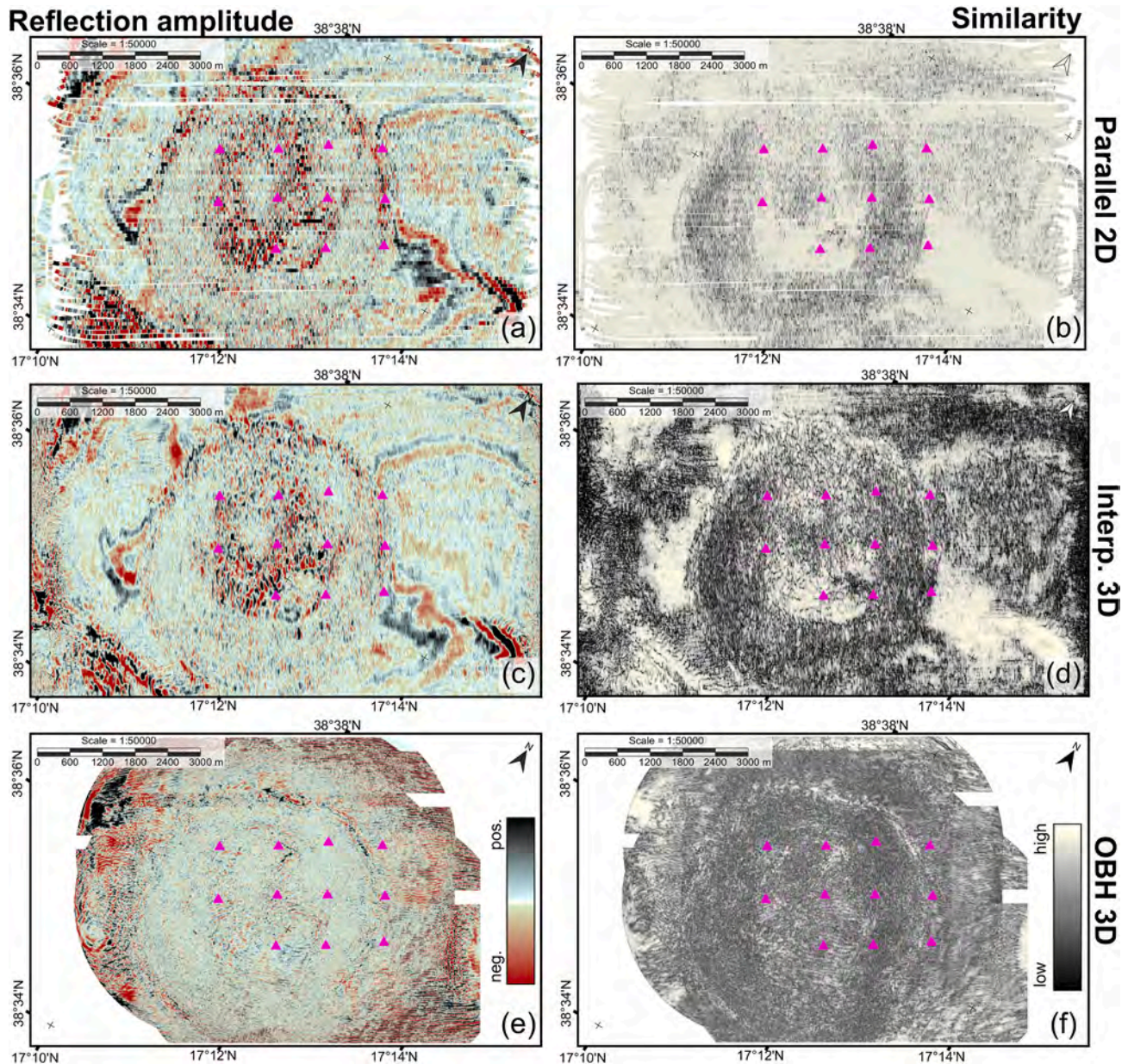


Fig. 6. Analyses of 3D seismic character at Venere MV using original parallel 2D and interpolated 2D MCS data and a full 3D cube obtained from OBH data. Comparison of time-slices of reflection amplitude (left column) and similarity attribute (right column) taken at 2.26 s two-way travel-time from (a), (b) the parallel 2D MCS data (c), (d) the interpolated pseudo-3D MCS data, and (e), (f) the 3D-migrated OBH cube (stack of stations 1, 3, 5, 6, 7, 8, 9, 11, 12). OBS locations are shown by pink triangles. Note, the data cubes are rotated $\sim 31^\circ$ clockwise from North. In all images a ring-like structure of reduced reflection amplitude with corresponding reduced similarity is evident. Sedimentary layers outside the ring are nearly flat with minimal dip. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

OBH data reveal two regions with bright-spots of opposite polarity to the seafloor at the summit of the west cone and a ring fault north of the east cone with gas flare F1 (Fig. 10d). No free gas was seen in any of the seismic data types available around the gas flares F3 – F5 tied to the ring faults south of the east cone.

4.3.3. Mud-flow deposits of Venere MV

As shown in the high-resolution seafloor bathymetry data by Loher et al. (2018a), several individual and clearly separable mud flows had been emitted from the east and west cones. Currently, only the west cone appears to emit mud and earlier mud-flow deposits from the east cone have been cut by the ring-fault system (see Fig. 10; Loher et al., 2018a, b). We mapped individual packages of mud flows in the subsurface using the 2D MCS data. The east and west cones are apparently not always

active at the same time. At least three alternating episodes of mud-deposition were identified based on the predominant dip of reflections (Fig. 11).

Along 2D MCS line 1027 three packages of mud flows for each of the cones are shown revealing that mud extrusion must have been switching between both edifices over longer periods in time. However, faster changes with minor flows below the resolution limit of the seismic data cannot be differentiated. The AUV bathymetric data show that mud flows do not seem to have long flow-paths and rather run down the slope and stop near the foot of the cones (Loher et al., 2018a). A question arises if that always had been the case and whether individual mud flows can be identified at greater depth below the seafloor. The pseudo-3D seismic data show no consistent pattern, likely due to a too coarse bin spacing (12.5 m). In contrast, the 3D OBH data allow a more detailed

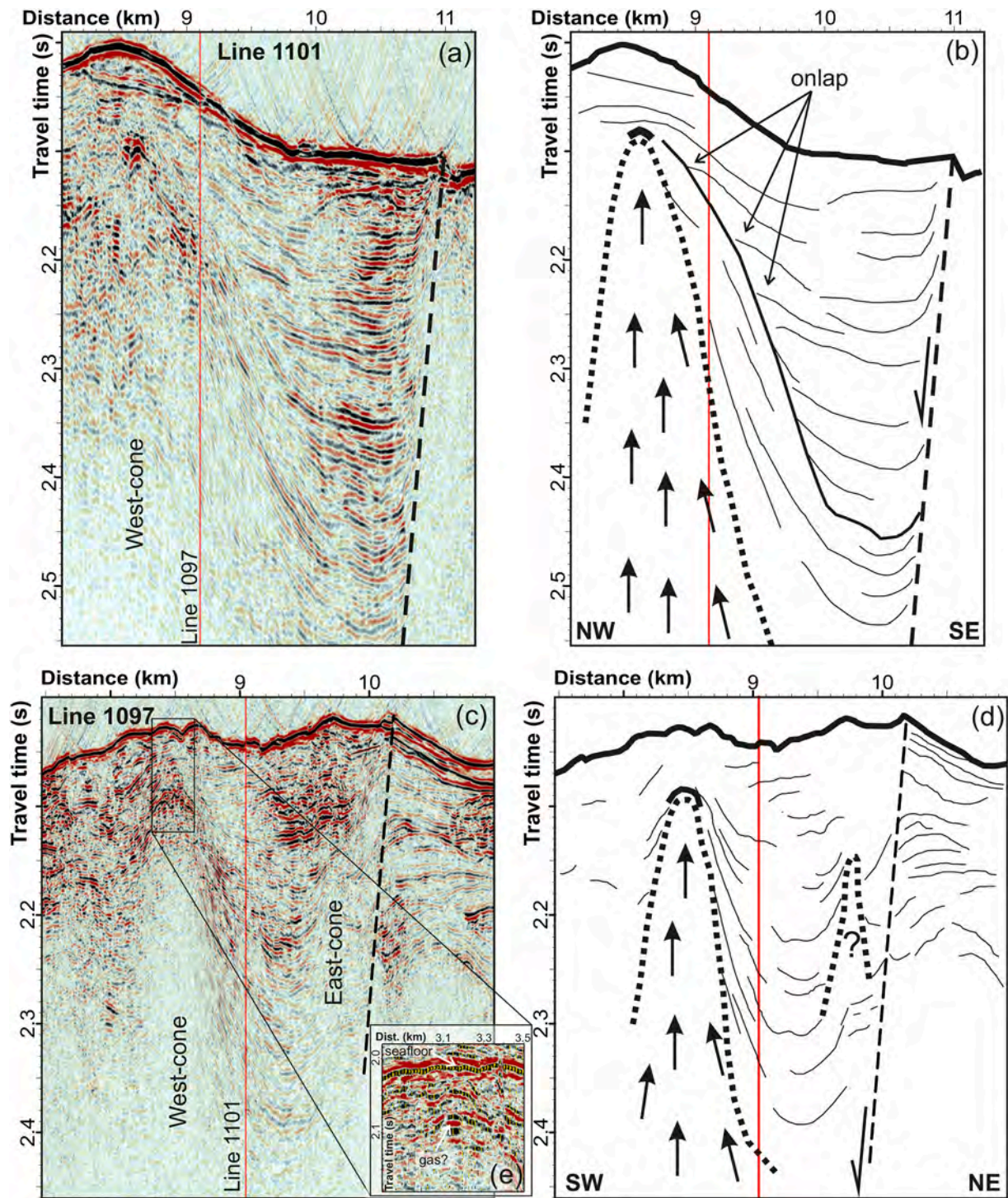


Fig. 7. (a) Section from MCS line 1101 (after 2D FK time migration) and (b) interpreted line-drawing showing feeder channel and developing onlap structures near the west cone of Venere MV. (c) Section from MCS line 1097 in perpendicular direction as in (a) through the west cone of Venere MV with (d) interpreted line-drawing. Crossing of the two lines is indicated by vertical red line. (e) Inset showing reflection polarity of the cap of the feeder channel being opposite to seafloor (from 3D OBH cube). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

investigation although data are of overall lower resolution and also suffer from a poorer signal-to-noise ratio than the MCS data. Yet, slicing the data cube parallel to the seafloor reveals unexpected intricate details of many minor flows emitted from each of the edifices (Fig. 12).

The shallowest slices taken at 6 ms twt bsf (ca. 5 m bsf) shows most of the flows seen on the AUV bathymetry as high-amplitude events. Especially regions labelled 'a' and 'b' in Fig. 12a are wide-spread zones of mud-flow deposits. Interestingly, zone 'a' was not identified from the

AUV data and probably is covered by sediments removing the original corrugated topography that is characteristically of the flows labelled 'b'. Strong amplitude mud flows are seen emitted from the east cone (label 'c') but are short-lived events with a maximum length of ~300 m. These flows are cut by the ring fault and seen to continue further out from the cone (label 'g'). At the west cone, the most recent mud flow is labelled 'e' and is seen as reflection event of opposite polarity relative to the surrounding seafloor (Fig. 12e) indicating a lower impedance than the

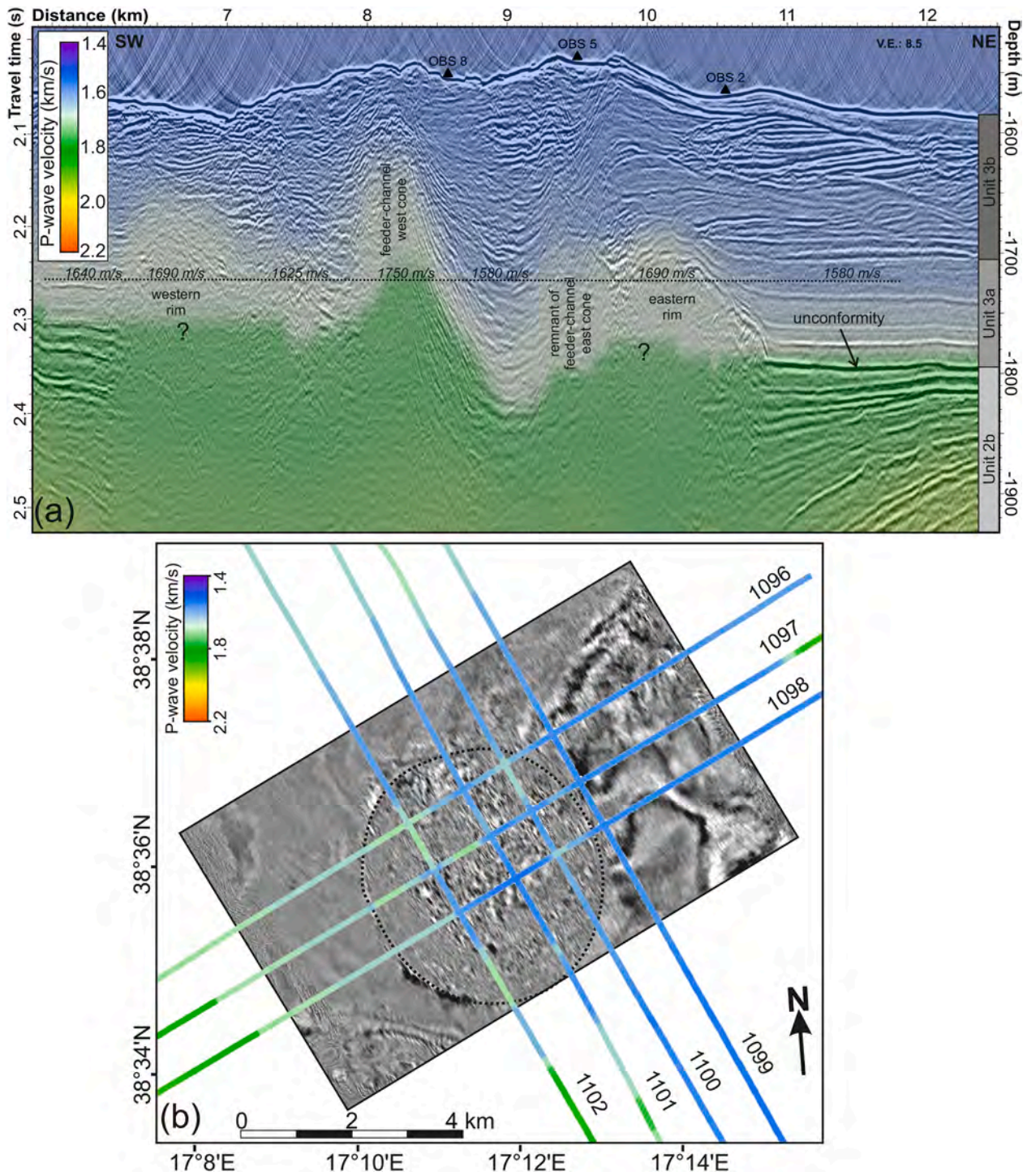


Fig. 8. (a) Combination of P-wave velocity and reflection image along seismic line 1097 (after 2D FK time migration) revealing high-velocity material in outer east- and west-rim, as well as within feeder-channels of east and west cones. A velocity jump is associated with the unconformity, which appears also within the feeder channel of the west cone. The unconformity was not picked underneath both rim-structures, thus the iso-velocity layer appears flat from extrapolation (denoted by a question mark). (b) Comparison of P-wave velocity along major lines at 2.25 s twt (~ 1720 m depth below sea surface) with a time slice of reflection amplitude taken from the pseudo-3D data set showing the ring-like zone of low-reflectivity.

overlying water body. Free gas is emitted at the edifice (flare F2), the origin of this most recent mud flow. As the flow hits flat seafloor at the foot of the cone, it spreads out and reflection polarity switches back to normal. At a depth of 20 ms twt bsf (ca. 15 m bsf, Fig. 12b) several detailed thin mud flows are seen emitted from the west cone (label 'h') and east cone (label 'i'). These flows are very narrow (~ 20 –40 m) and again have an outrunning distance of ~ 100 –500 m only. On the eastern

flank of the east cone, two patches of high amplitudes are seen (label 'j'), similar to the zones near the seafloor (label 'a' and 'b' in Fig. 12a), and thus likely being some wide-spread mud-flow deposits. However, none of these extends far from the centre of the MV edifices. At a depth of 30 ms twt bsf (ca. 25 m bsf, Fig. 12c) the same overall pattern is recognized but with fewer narrow mud flows being emitted from the two cones (labels 'k', 'm', and 'n'). Only a small-extended region of a mud-flow

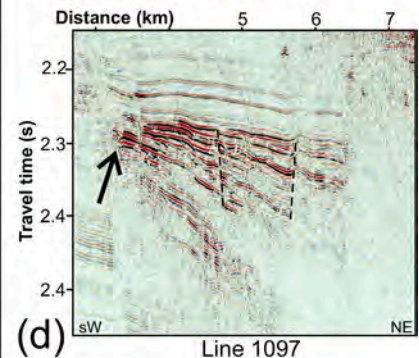
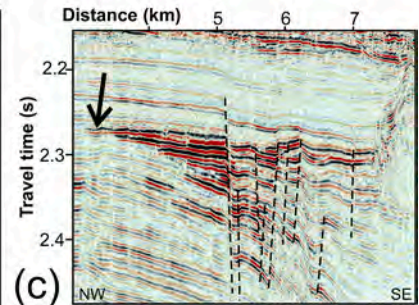
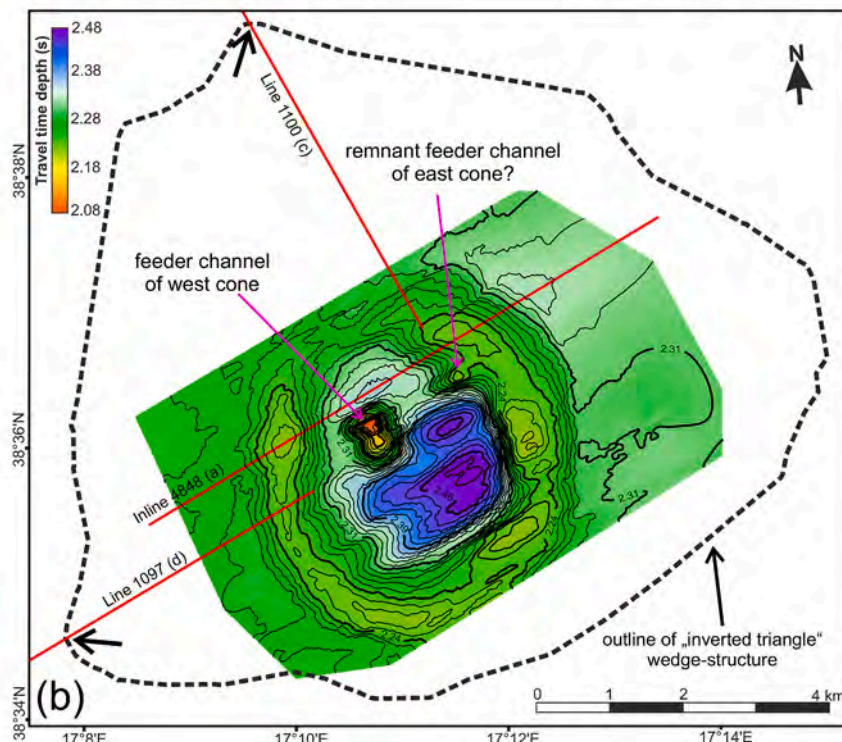
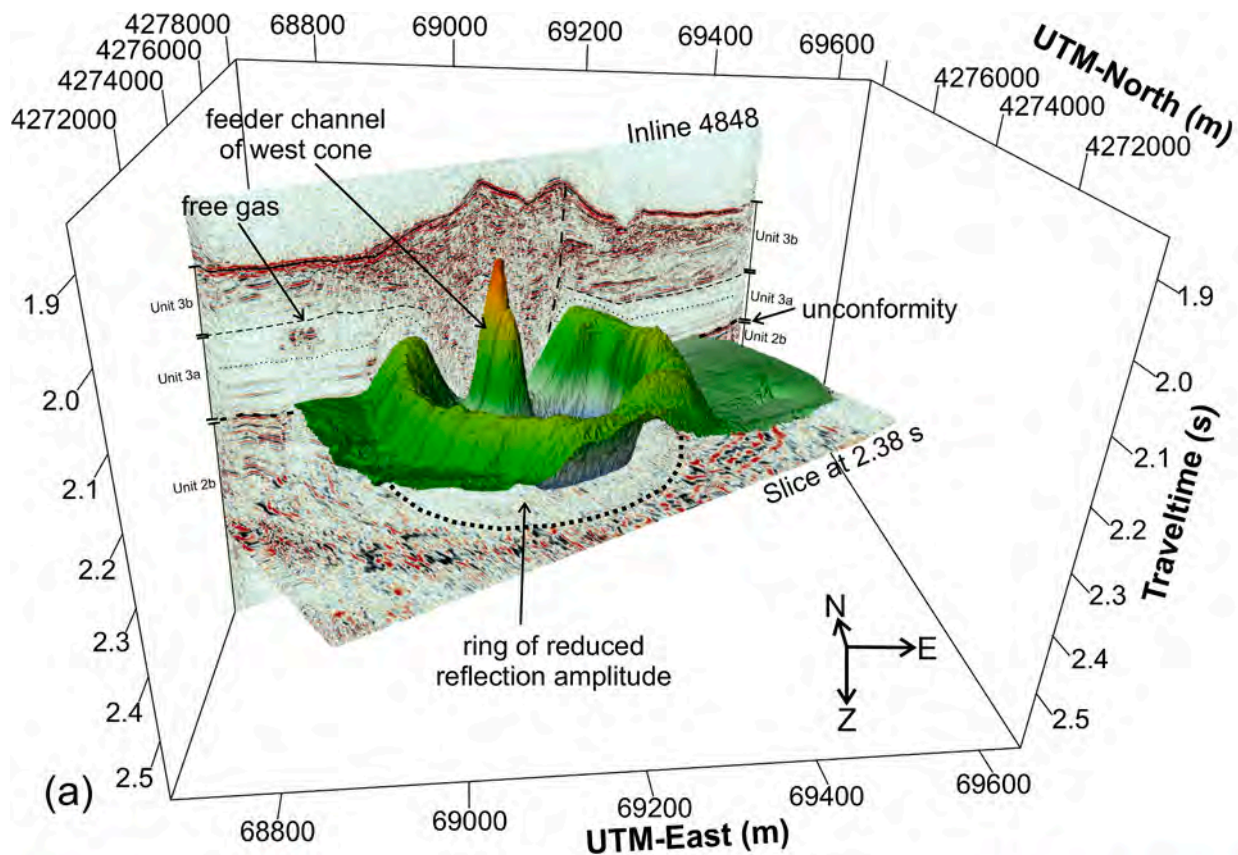


Fig. 9. (a) 3D view of the ring-like structure with inline 4848 and time slice at 2.38 s twt below sea surface highlighting low-amplitude reflection nature beneath the bulges protruding above the unconformity between stratigraphic units 3a and 2b. (b) Map-view of the ring-like structure with contour lines combined with outline of the extent of the wedge-like feature (“inverted triangle”) of dipping reflections towards center of the Venere MV (black dashed line). (c) Portion of MCS line 1100 and (d) of MCS line 1097 showing high-amplitude reflectors dipping towards the center of the Venere MV and dissected by faults, forming a wedge-like feature (“inverted triangle”). Thick black arrows mark the maximum extent of the high-amplitude reflectors. All seismic data are shown after 2D FK time migration.

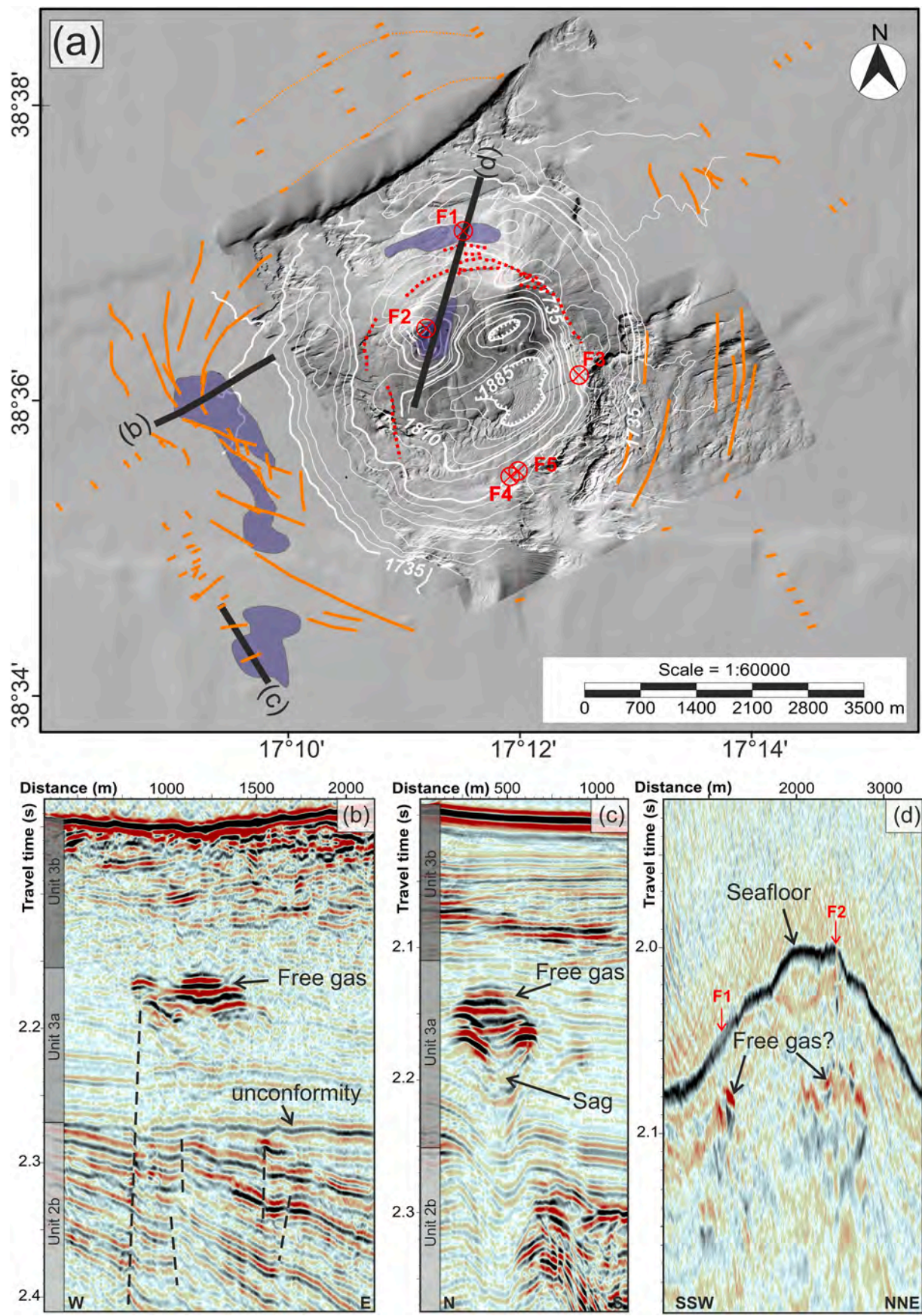


Fig. 10. Map showing the extent of inferred free gas from seismic imaging (blue polygons), location of the five previously detected gas flares (F1 – F5), and ring faults (dotted red lines) from [Loher et al. \(2018a, b\)](#). The seismically mapped fault system from this study is shown as orange lines. Larger faults identified on consecutive 2D MCS lines north of Venere MV are connected by dotted orange lines. The outline of the buried MV structure as shown in [Fig. 9](#) is drawn in white lines (depth-contours, values are meters below sea surface) on top of the hill-shaded seafloor bathymetry from AUV and regional data. (b) and (c) are examples of inferred free gas occurrences as imaged by MCS data to the west of Venere MV. (d) Example of an arbitrary line extracted from the 3D cube of OBS hydrophone data indicating potential free gas linked to flares F1 and F2. Note, potential free gas zone to the west are not imaged with the 3D OBH data. All MCS data are shown after 2D FK time migration. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

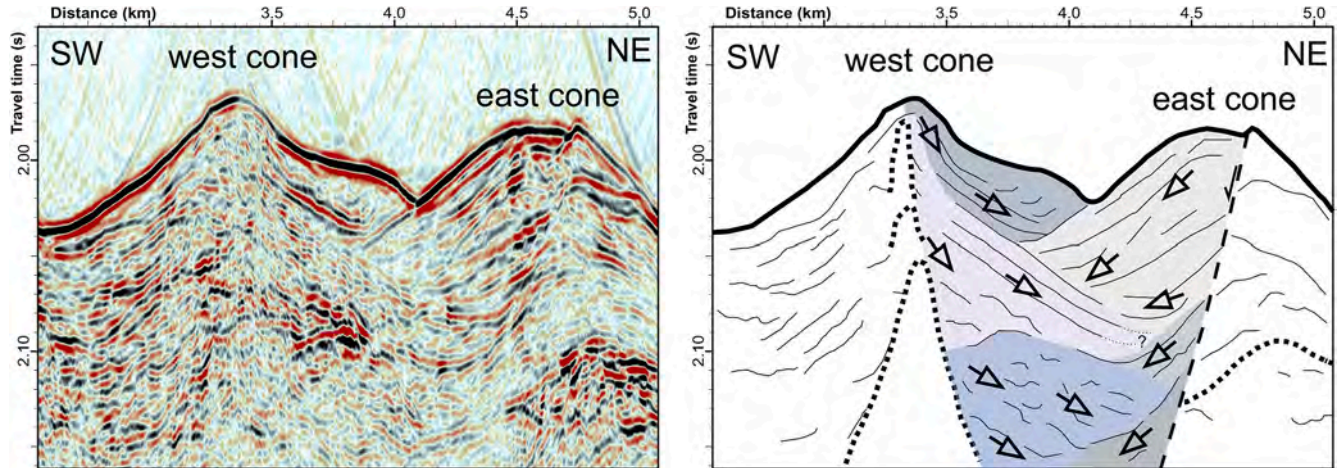


Fig. 11. (a) Example from 2D MCS line 1027 (after 2D FK time migration) between the two cones of Venere MV. (b) Interpretation of alternating packages of mud flows with predominant flow-directions emitted from the west and east cone. The youngest (latest) mud flows were emitted from the west cone. Note, only the region between the cones is interpreted in terms of stages in mud-flow episodes.

deposit (label 'o') at the eastern foot of the east cone can be recognized. At this depth, however, bright amplitude spots occur in the vicinity of gas flare F1. With increasing depth at 40 ms twt bsf (ca. 30 m bsf, [Fig. 12d](#)) imaging of individual mud flows is reduced in quality, but still several flows are being recognized (labels 'p' and 'q', [Fig. 12d](#)). At this depth, flow emitted from the east cone appear only south-ward flowing, whereas flows at the west cone still cover the entire circumference of the cone. The reduced image quality is potentially a result of flows no longer being parallel to the seafloor as paleo-topography was likely different than today. We thus also extracted time-slices at constant depth (time) through the 3D seismic cube and traced flows to a maximum depth below which no additional flows were recognized. That maximum depth was defined as base of the two cones ([Fig. 12f](#)) where sediments are predominantly, but not necessarily exclusively, made of mud flows. Integrating this thickness map yields a total volume of 0.385 km³ of extruded mud. However, this is under the assumption that all sediment within this region is extruded material without additional hemipelagic sediments, thus this volume is likely grossly overestimated.

4.4. OBH mirror-imaging vs. MCS migration

One of the main purposes of the mirror imaging and 3D migration was to identify reflections underneath the Venere MV cone structures that are potentially masked in the MCS reflection data (see [Fig. 4a](#), zones of reduced reflectivity). The loss of reflectivity could possibly be a result of either scattering, absorption (attenuation), or an acquisition artifact from the short offset (190 m) of the streamer in water depths >1800 m. Alternatively, the lack of reflectivity could be real as the sediments may lack layering with associated impedance contrasts and/or be physically disrupted and represent feeder conduits. The OBH mirror-imaging and 3D migration processing yields overall a lower-frequency response than the MCS data ([Fig. 13](#)) and have therefore smaller vertical resolution. Also, the 3D migration around the OBH reduces as expected the outer range (maximum footprint) of useful data for interpretation. Velocity uncertainties from extrapolation of the 2D results to the rim of the

migration space result in distortions of reflections when compared to the MCS data. However, these data sets do show that some sedimentary reflections are continuous underneath the MV structure and can be traced from East to West underneath the MV ([Fig. 13](#), black dashed lines), i.e. these layers exist as impedance contrast on wavelengths corresponding to the seismic frequencies used and velocities encountered, i.e. ~20 m) and are not disrupted. Therefore, we can exclude these broad zones of reduced reflectivity imaged by the MCS data to be related to large feeder conduits.

5. Interpretation and discussion

5.1. Regional sediment stratigraphy and age

The three sedimentary units imaged with our data can be compared to those introduced by [Praeg et al. \(2009\)](#) for other MV systems in the Calabrian Arc and the activity at Venere MV appears synchronous in timing to the other MVs in the Calabrian Arc ([Praeg et al., 2009](#)). Our uppermost sedimentary Unit 3 with the associated prominent basal unconformity is similar to that structure seen at the Madonna dello Ionio MV (ca. 45 km SW of Venere MV) and Pythagoras MV (ca. 90 km S of Venere MV). We assign Unit 3 therefore to Unit PQ2b of [Praeg et al. \(2009\)](#). This unit is tied to the uplift of Calabria (0.8 – 0.5 Ma ago). Our Unit 2b correlates to PQ2a by [Praeg et al. \(2009\)](#) that spans the period from 3.6 Ma to 0.8 Ma. Our underlying Unit 2a then correlates to PQ1 of [Praeg et al. \(2009\)](#), older than 3.6 Ma. The reflection of the acoustic basement (Unit 1) in our data is projected to correspond to the Miocene-Pliocene boundary (~5.3 Ma). From the limited amount of interfingering of mud flows within Unit 2b and the contrasting majority of mud flows deposited on top of the unconformity and interfingering with sediments of Unit 3a, we interpret that Venere MV has its strongest extrusive activity occurring in more recent geologic time, since ~0.8 Ma. However, the lack of deep coring and age control makes a more precise timing of mud flow activity at Venere MV presently difficult.

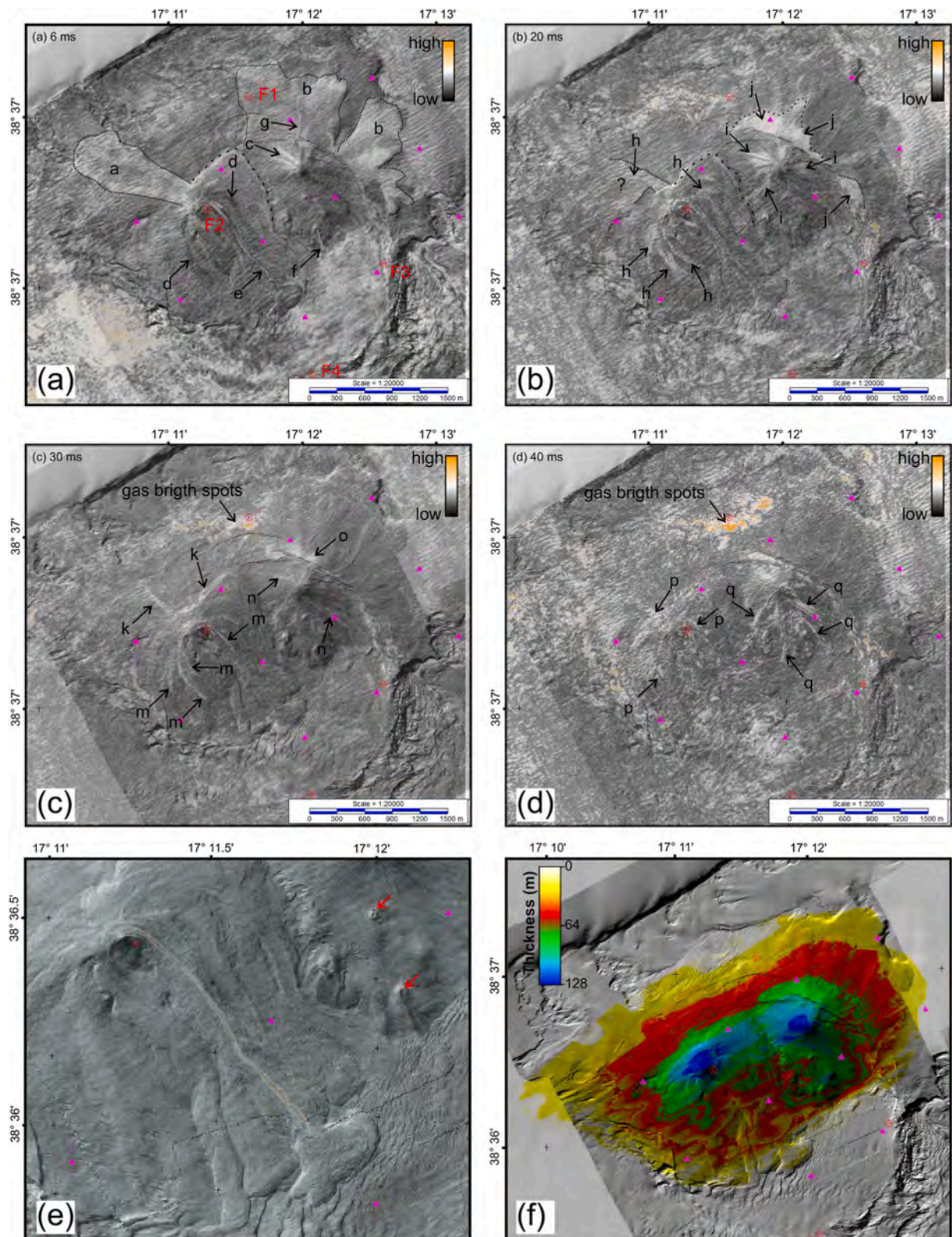


Fig. 12. Time slices of instantaneous amplitude (envelope) extracted from the 3D OBH cube parallel to the seafloor draped over the AUV hill-shaded bathymetry. Time slices were extracted parallel to the seafloor at (a) 6 ms, (b) 20 ms, (c) 30 ms, and (d) 40 ms twf bsf. (e) Amplitude of the seafloor reflection from the 3D OBH data, note two small gryphons (red arrows) with small high-amplitude patches indicating recent mud eruption. (f) thickness of mud-flow deposits beneath the two cones of Venere MV. Black arrows with labels a – q mark individual mud flows, discussion see text. Pink triangles show OBS locations. Red symbols F1–F4 indicate gas flare locations as mapped by [Loher et al. \(2018a\)](#). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

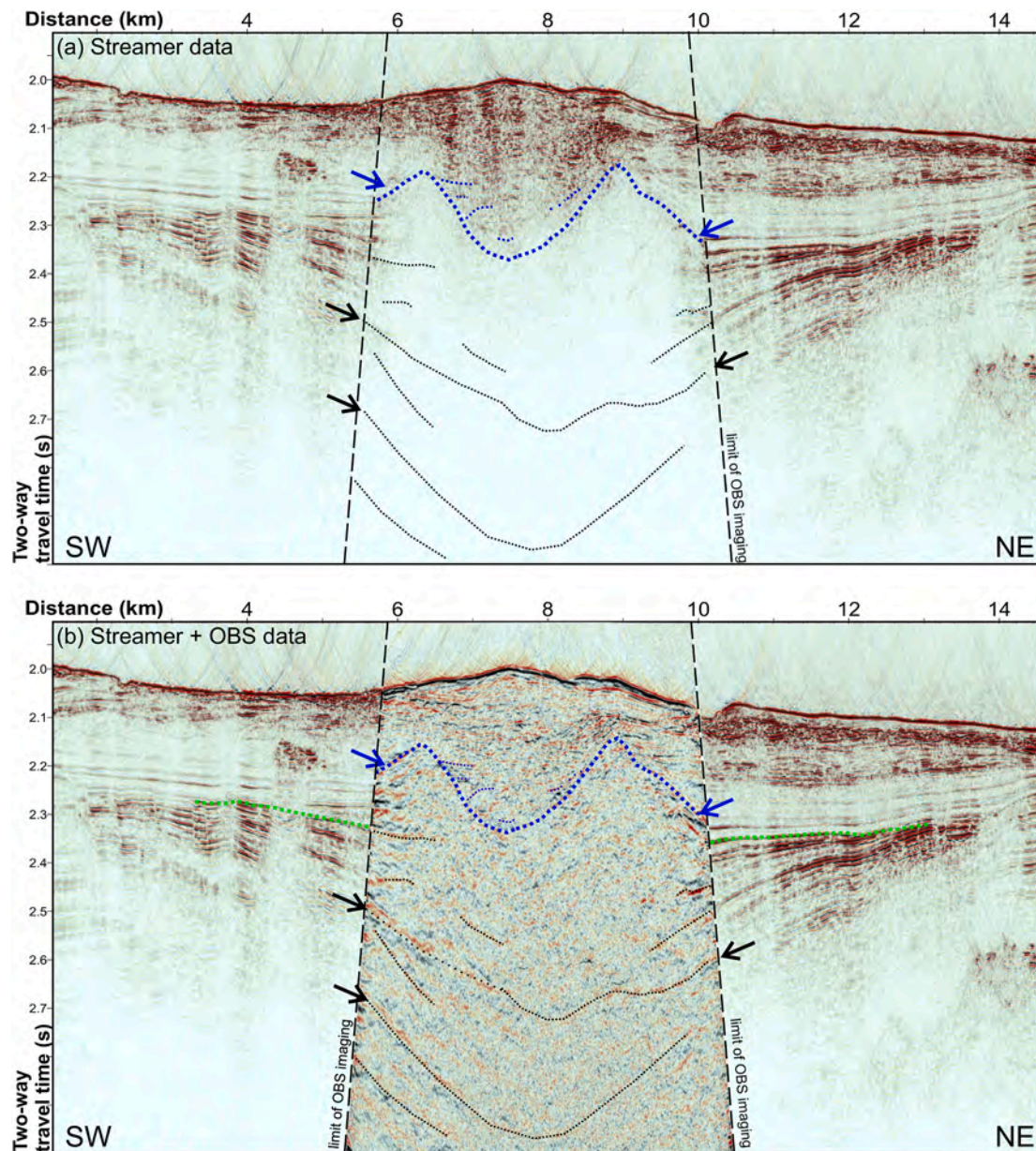


Fig. 13. Comparison of line 1096 between MCS and OBH data across Venere MV. (a) Profile imaged only with the streamer data (after 2D FK time migration) revealing prominent low-amplitude zones beneath the upper cone structure and (b) same profile imaged with the mirror imaging technique (OBS station 07). The illumination by the OBH is indicated by outward-slanted dashed lines. The OBH data image several reflections not seen by the MCS data (black dotted lines and arrows) within the upper cone structure (blue dotted line marks surface of initial MV structure, compare to Fig. 4) and beneath the main unconformity (green dotted line). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

5.2. V_p distribution

The velocity model obtained along the main seven profiles are overall robust (as seen from the achieved RMS misfit and χ^2 -values, Table 1) and consistent from line to line. The velocity model derived from first arrivals was tested on the multiple arrivals in the OBS records for the most prominent reflections and refractions seen and a misfit within the picking uncertainty was achieved, confirming the overall robustness of the model. Overall, V_p is increasing smoothly with depth outside the main MV structure reflecting regular sediment burial (i.e. age). No velocity inversions were identified. Only one major velocity step was identified at the unconformity between stratigraphic sub-units 2b and 3a. Here, velocity jumps by ~ 100 m/s from an average value of 1.7 km/s within the overlying sub-unit 3a to 1.8 km/s in underlying sub-unit 2b. Whether this velocity jump is a result of erosion or a hiatus of

sedimentation cannot finally be resolved from the data available, lacking core information across the interface. However, the increased reflection strength of Unit 2b in comparison to Unit 3a may suggest a different composition of the sediments underneath the unconformity. As the high reflection strength of layers within Unit 2b is forming a wedge-like feature reaching up to 6 km out from the central Venere MV, which gives the impression of an inverted triangle on the seismic reflection images, we interpret that increase in reflectivity as a result of interference of regular sediments with thin mud flows that were emitted at an early stage of the Venere MV formation. Similar amplitude variations around MVs were imaged in the Canadian Beaufort Sea slope (Paull et al., 2015), where the interlayering of mud flows with hemipelagic sediments creates interference patterns and enhances reflection coefficients between the individual layers.

Within Venere MV, some stronger velocity variations (laterally and

vertically) are closely associated to the bulges of the ring structure (Fig. 8). The two bulges of the ring structure with an increased velocity (+100 m/s) relative to an equivalent depth outside the ring structure indicate that the material within the bulge is either older or of different composition. Loher et al. (2018a, b, c) showed that the mud extruded on the seafloor around Venere MV contained a mixture of carbonates, sandstones, shales and marl with an estimated matrix density of 2600 kg/m³. The composite bulk density is reduced to 2150 kg/m³ at an average porosity of 0.5. In contrast, the surrounding clast-free pelagic/hemi-pelagic muds will have lower density of 1600–1800 kg/m³ over the depth range encountered (e.g. Tenzer and Gladkikh, 2014). Accordingly, P-wave velocity of the mud-breccia is higher than the clast-free pelagic/hemipelagic sediments. The imaged Christmas-tree structure of the ring-like bulges (Fig. 5) in combination with the observed higher velocity suggests that the ring is likely made of stacks of mud breccia. The highest lateral velocity contrast beneath the west cone (+200 m/s relative to layers outside the cone) within the up-warping structure with strongly deflected sediment packages (Figs. 7 and 8) is interpreted as evidence that this structure is the feeder-conduit for the west cone. The increase in velocity within the feeder-conduit is again a result of the different composition of the material within the conduit compared to the surrounding sediment. An increase in velocity from the mix in composition of the mud-breccia may be in part counter-balanced by higher fluid content and/or the presence of overpressure within the feeder conduit(s). However, without any in situ samples or logging it remains unresolved whether or not, the feeder channels are more enriched by fluids and/or over-pressured. As the higher velocity is not only seen inside the conduit, but also affects some of the deflected sediment package, we interpret this structure as a combination of sediment with mud flows from the gradual build-up of the west cone around the conduit. That process is also reflected in the overall thickness of mud flows (Fig. 12f) with the thickest deposit underneath the west cone. In contrast, no similarly clear velocity structure and sediment deformation is associated with the east cone (Fig. 7c and d). As the east cone appears currently dormant (as evidenced by the collapse along the ring-fault system imaged with AUV data by Loher et al., 2018a), the former feeder-conduit may have subsided and only a remnant of the conduit is still visible in the MCS data.

The Vp analyses did not yield any evidence for extensive free gas accumulations beneath or linked to the Venere MV structure, despite the observed gas flares in the multibeam water-column data (Loher et al., 2018a). The presence of free gas within the sediments was inferred at four locations, two outside the MV (Fig. 12a, b, c) and two bright-spots around the west cone (Fig. 12a–d). Yet, these deposits apparently do not represent sufficient free gas accumulations to perturb the velocity field in any significant way. The bright-spots can thus be a result of very minor concentrations of free gas not linked to any major reservoir in the near sub-surface imaged by the seismic data.

5.3. Fault systems

An outer set of normal faulting nearly exclusively tied to stratigraphic Unit 2 outside the observed ring structure defined by the MCS data adds to the inner ring-fault system seen on the high-resolution AUV bathymetry data (Figs. 10 and 12, see also Supplement Fig. S5–S10). The newly defined faults suggest that they may be generated in response to mud extrusion and associated subsidence of a much wider zone around Venere MV than inferred from the seafloor topography of the double-cone structure and inner ring faults alone. The fault-structures imaged around Venere MV show some similarity to concentric fault systems seen at a prominent MV in the Caspian Sea (Davies and Stewart, 2005). Adding the observation of the wedge-like feature (“inverted triangle”) defining the outer limits of subsidence and faulting, the footprint of Venere MV is roughly 12 km by 12 km, about three times larger than the surface expression of the cones seen on today's seafloor. Noteworthy is further that the wedge-like feature extends far beyond the current limits

of Squillace-canyon, especially towards the NW. The fact that the faults are terminated at the top of stratigraphic sub-unit 2b and that sediments of sub-unit 3a homogeneously drape the wedge-like feature suggest that these faults are linked to an early stage of Venere MV activity and related subsidence. These faults though have completely become dormant and further subsidence as well as related fault activity has likely ceased. Normal faults of the inner ring structure seen in the AUV bathymetry are in contrast linked to the double-cones and sediment build-up with associated latest collapse of the east cone. These faults – though seismically not imaged – may link to a set of fluid-conduits and faults tapping into deeper sources or mud-chambers (>3 km depth), which would explain the presence of the sampled thermogenic fluid components (Loher et al., 2018b).

5.4. Ring structure

The reduced reflection strength seen in the MCS data beneath the nearly symmetrical double-bulges and associated ring structure (Figs. 4, 6 and 9) could be the result of poor imaging with a short streamer (i.e. near vertical incidence) and amplitude loss at steep and rough topography. However, the same ring structure of reduced reflectivity clearly emerges from the OBH processing, where we utilize wide-angle reflection multiple imaging, which has the ability to undershoot these steep structures from the augmented aperture. The bulges of the ring structure are clearly imaged with the OBH data, in part enhancing the reflectivity of the upper boundary in the lower-frequency data. The structure shown in Fig. 9 is a combined surface from picks made on all available data, which were gridded and smoothed to overcome heterogeneities originating from the data footprint (data were acquired in a parallel nature, not true 3D). Taken by itself without the overburden, the ring structure at Venere MV looks very similar to the surface topography of Cetus MV (Fig. 14a), located ~80 km to the SE of Venere MV and close to the Calabrian escarpment (Fig. 1b). Cetus MV has a prominent near circular outer rim that appears in the MCS data as bulge with low reflection amplitude beneath (Fig. 14b and c). The inner portion of Cetus MV is filled with mud of layered reflectivity. At depth, sediment layers to both sides of the MV dip steeply towards the center, identical to observations made around Venere MV. Cetus MV thus forms an analogy for the ring structure at Venere MV and we proposed this ring structure to be the original morphology of Venere MV, prior to the formation of the shallower double-cone structure.

The bulges of the ring structure of Venere MV are progressively covered with sediments of stratigraphic Unit 3a. The bulges (likely comprised of mud breccia) were growing at the same time as sediments of Unit 3a are deposited, as seen by the Christmas-tree structure at the edges of the bulges reflecting periods of more intense mud-expulsion followed by higher hemipelagic sedimentation. At the same time, the inner basin formed between the outer rim as a result of intermittent collapses of the MV and formation of small calderas followed by periods of new mud supply refilling the inner basin. The 3D OBH data did not show any evidence of mud being emitted outside the ring structure and forming wider flows intermingling with sediments of stratigraphic Unit 3a. Thus, the mud breccia extruded must have been relatively viscous as otherwise, wide-spread mud-flow deposits would have been observed as e.g. demonstrated around Sartori MV by Doll et al. (2025) or seen on the modern seafloor around Venere MV (Fig. 12). Alternatively, mud-extrusion episodes may have been relatively moderate in volume so no breach in the outer rim structure occurred as seen today at Cetus MV (Fig. 14). The inner portion between the bulges probably was steadily filled with mud-pie in analogy to Cetus MV. However, at some time in the past, no new mud breccia was extruded as sediments of stratigraphic Unit 3a cover the bulges completely and smoothly. These sediments are also traced into the inner bowl-shaped mini-basin between the bulges, which we interpret as evidence of a cease in MV activity linked with a deflation (depression), possibly forming a small caldera.

The deepest root of Venere MV is beyond imaging of the MCS and

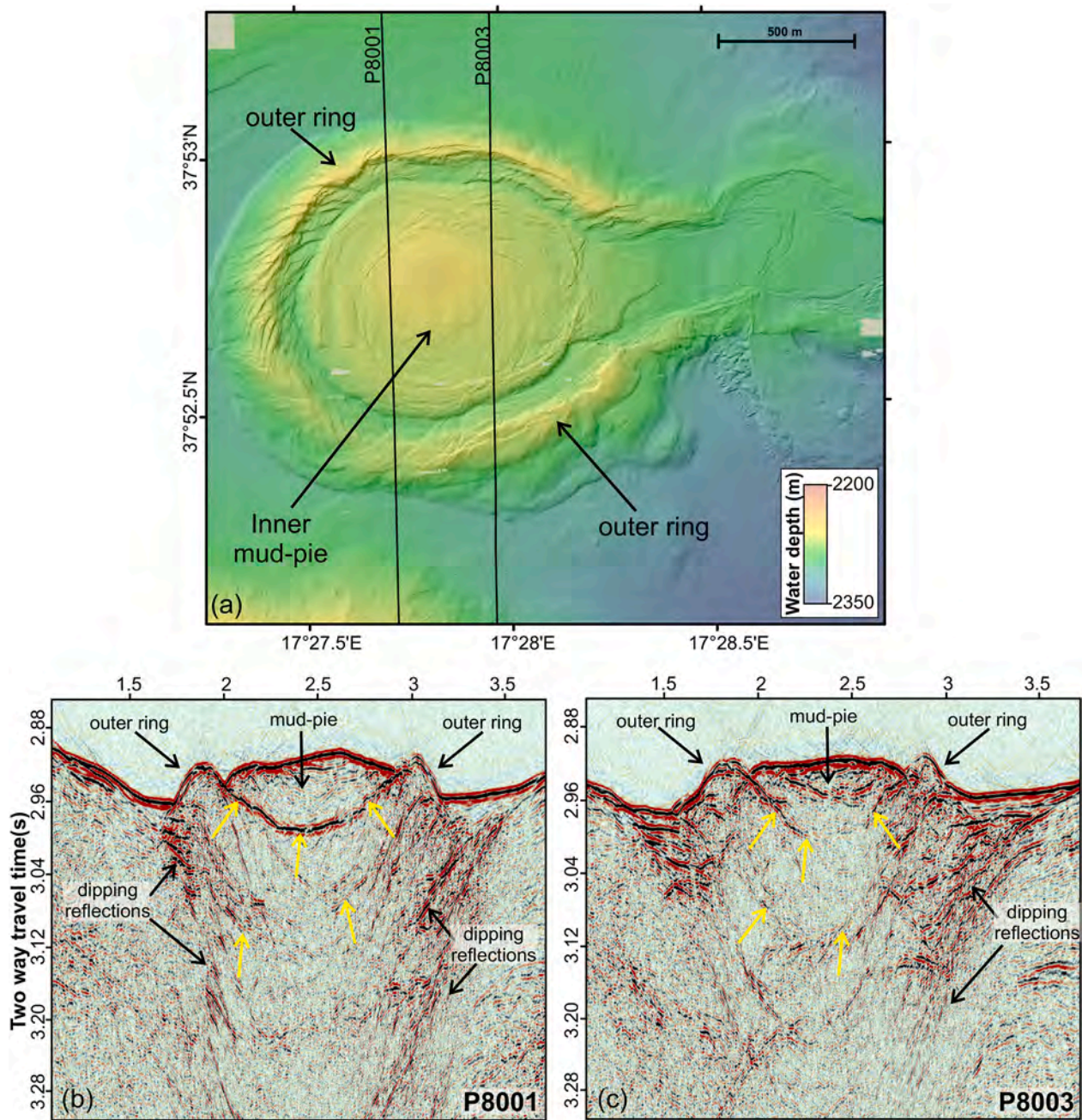


Fig. 14. (a) Seafloor bathymetry of Cetus MV (from cruise POS499, [Bohrmann et al., 2016](#)) and (b) and (c) two seismic sections (after 2D FK time migration with constant P-wave velocity of 1500 m/s) crossing the ring-like structure of the MV, showing formation of a rigid outer ring (bulges) and dipping reflections to the centre of the MV. Within the outer ring the MV is filled with extruded mud forming a pie-like structure. Surfaces within the mud-pie (yellow arrows) can be through-going or broken when lying at greater depth. We propose that this shape is similar to the original Venere MV prior to the formation of the double cone structure and activity by the Squillace Canyon. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

OBH data, which is a result of limited penetration power of the airgun used. However, especially the low-frequency OBH data show that several layers can be traced beneath Venere MV and the ring structure, especially at the outer limits of the ring. These layers are not seen with the MCS data. But on the wavelengths of the OBH data, the impedance contrast at these layers result in reflections, overall forming a deep bowl-shaped structure. However, reflection strength is low and the reflections are much broader than outside the MV, indicating a frequency loss from signal attenuation other than pure spherical divergence. The source of such attenuation is beyond the scope of this study though. A consequence of imaging layers beneath the central MV with the OBH data is that the conduits providing a pathway of upward migrating mud breccia

and associated fluids must be relatively localized and narrow. They may also shift laterally in time and disrupt the layers only locally. The deep layers indicate that Venere MV overall sits on top of a wider basin that progressively deepened as mud was extruded at depth and piled on top of the seafloor. Removal of sediment from depth and deposition onto the seafloor propels deepening (subsidence) of the basin. In response to the deepening, the two sets of ring faults are created. The maximum extent of the basin (and effect of removal of mud at depth) is imaged by the wedge-like feature (“inverted triangle”) described above.

The fact that we were able to image and trace layers continuously underneath Venere MV suggests that the mud flows and mud breccias incorporated into the modern double-cones could in part be mobilized

from relatively shallow depths. As shown by the analyses of the most modern mud flows deposited on today's seafloor around Venere MV by [Loher et al. \(2018a, b, c\)](#), the mud flows contained breccias with clasts of carbonates, sandstones, shale and marl. No dating of the clasts was conducted; thus, a source-depth cannot be defined. Sediment pore-fluid extracted point to a mix in origin with source-depths being >3 km below seafloor ([Loher et al., 2018b, 2018c](#)). This points to a complex interacting plumbing system and possible remobilization of sediment, breccia and pore fluid from a variety of depths.

5.5. The double-cone structure and mud-flow deposits

The newly conducted MCS and OBH seismic imaging corroborate observations previously made with the AUV that individual mud flows emitted from the edifices of the east cone are cut by a set of ring faults, whereas the flows emitted from the west cone are not disrupted. The 3D OBH data sharply image the seafloor flows ([Fig. 12](#)) and highlight the most recent flow as being acoustically opposite in reflection polarity than the surrounding seafloor ([Fig. 11e](#)). Such reduced acoustic impedance (lower than seawater) can only be explained by incorporation of some free gas into the mud flow. Although impedance is smaller than seawater, this mud flow is still of high backscatter intensity (see [Fig. 3b](#) in [Loher et al., 2018a](#)). Since free gas is emitted close to the edifice (flare location F2), which is near the origin of this mud flow, it is conceivable, that some of this free gas travels with the sediment down-slope. While the mud flow travels down-slope, the gas is emitted into the overlying water and finally becomes gas free at the foot of the MV cone, where the mud flow spreads laterally and reflection polarity switches back to normal. Such difference in reflection character of individual flows was also seen at a MV imaged by AUV data in the Canadian Beaufort Sea (see [Fig. 7d](#) in [Paull et al., 2015](#)). From the top of a cone-shaped MV more than 20 thin mud flows travers downslope, with the youngest being easily identifiable as showing much stronger seafloor backscatter intensity than all others.

Using the 3D OBH data, we image several small, in part <10 m wide, mud flows emitted from both cones in all directions at depths >10 m bsf. Some of these flows are very short (<300 m in length) and do not form wide-spread flow-features, such as those seen at and within the top 5 m bsf. Six individual packages of layers with internally consistent dip-direction interpreted from the MCS data (with higher vertical resolution) indicate that both cones had periods of stronger and weaker eruption activity, and that flows periodically overlap. The cause of such switch in activity between east and west cone remains enigmatic but likely points to a complex plumbing system that may seal itself at some portions within the subsurface, blocking some and creating new pathways for mud extrusion. The layers within the cones are seismically slightly different in character than sediments within stratigraphic Unit 3b, which exists at the same relative depth-range as the cones. Although some mixing between mud and hemipelagic sediments of Unit 3b cannot be excluded, especially at greater depth, we defined a maximum depth of mud flows emitted from the cones using the 3D OBH data. Mud flows predominantly flow down slope in any possible direction, whereas hemipelagic sediments of Unit 3b are deposited mostly horizontally and within the overall sedimentary system around Venere MV and Squillace Canyon in a West to East down-slope pattern. On time slices those two depositional settings are discernible as they would cross-cut each other. We used this as a guide to define a maximum depth of the mud flows, recognizing however, that at the very onset of cone-formation, such a distinction may not be very clear. The region between seafloor and this maximum depth of mud flows defines an approximate estimate of the total volume of mud extruded through the cone structures. Under the assumption that all material between seafloor and the horizon marking the depth of mud flows are mud flows, we calculated a total volume of 0.4 km³ of sediment, which is about twice as much as estimated by [Loher et al. \(2018a\)](#), who integrated the volume of sediment between an arbitrary flat horizon at the foot of the cones and the seafloor

bathymetry. Our newly estimated volume is similar to that of Touragay MV in Azerbaijan on land (0.343 km³, [Mazzini and Etiope, 2017](#)). However, the uncertainty in our calculations is substantial, not just from the definition of a maximum depth of the mud flows, but also the exclusion of any possible pelagic sediments intermingled with mud flows within the cone structures. Uncertainties related to the Vp structure are deemed comparably smaller given the careful velocity analyses carried out. We estimate a cumulative uncertainty in the total volume to be at most 10% (e.g. comparing results from using different definitions of the maximum depth of mudflows).

Estimating the volume incorporated into the ring structure of Venere MV is more challenging. While the top of the ring structure is well defined, the base is not clearly imaged with the MCS data, and the OBH data did yield evidence only of some reflections going through continuously beneath the ring structure. Strong interpolation was used between individual reflections seen to get a lower bound for mud within the ring structure and former mud-pie structure. The total volume is estimated to ~1.2 km³. Here, the combined uncertainty was estimated to be 25% by again comparing different interpretations of the base of the old MV structure.

5.6. A two-stage formation history of Venere MV

We propose a two-stage evolutionary history of Venere MV combining all the different observations from seismic data and previously made observations and linked analyses ([Loher et al., 2018a, 2018b, 2018c](#)) and incorporating the overall relation between CAP tectonics and MV formation as proposed by [Praeg et al. \(2009\)](#).

Stage 1 A mud-pie structure, similar in shape to Pythagoras MV or Cetus MV is slowly building over time ([Fig. 15a](#) and [b](#)). From correlation to the stratigraphy suggested by [Praeg et al. \(2009\)](#), formation of the MV may have started around 3.6 Ma ago. Once mud breccia is deposited episodically on the seafloor, subsidence from the added sediment load and flexure of sediments beneath develop progressively ([Fig. 15c](#)). A rigid outer ring structure is not broken allowing major mud flows to develop beyond the MV ([Fig. 15c](#)). The process of mud extrusion and intermittent collapse result in a progressive deepening and formation of an inner basin with build-up of the mud-pie structure ([Fig. 15d](#)). The early stage of Venere MV may have looked like Cetus MV today (compare to [Fig. 14](#)). A Christmas-tree structure is created with interfingering of mud extrusion phases and hemipelagic sedimentation. As a result of the build-up of the mud-pie structure, the wider region around the MV experiences some subsidence from extrusion of material at greater depth. This results the formation of an outer set of faults ([Fig. 15e](#); orange lines in [Fig. 10](#)). The maximum extent of the subsidence can seismically be seen by the “inverted triangle” structure (compare to [Fig. 9b–d](#)). In a later phase of Stage 1, hemipelagic sedimentation appears increasing and progressively covering the initial mud-pie structure ([Fig. 15d, e](#)) as seen by onlap-structures at the edges of the ring structure (sediments of Unit 3a). These sediments are not faulted and lie conformably above sub-unit 2b. Thus, no major new mud extrusion may have occurred with no further positive build-up of the main structure (quiescence, [Fig. 15e](#)). As sediments of sub-unit 3a ultimately covered the central portion of the entire ring structure and dip towards the centre (compare to [Fig. 5](#)), subsidence (deflation) of the initial mud-pie structure must have occurred. This formed caldera gets progressively deeper and filled with sediments.

Stage 2 A new phase of mud extrusion starts with a build-up of a feeder channel system through the former mud-pie structure and overlying sediments ([Fig. 15f](#)). Re-initiation of mud flow and new mud extrusion may be linked to the onset of Calabrian

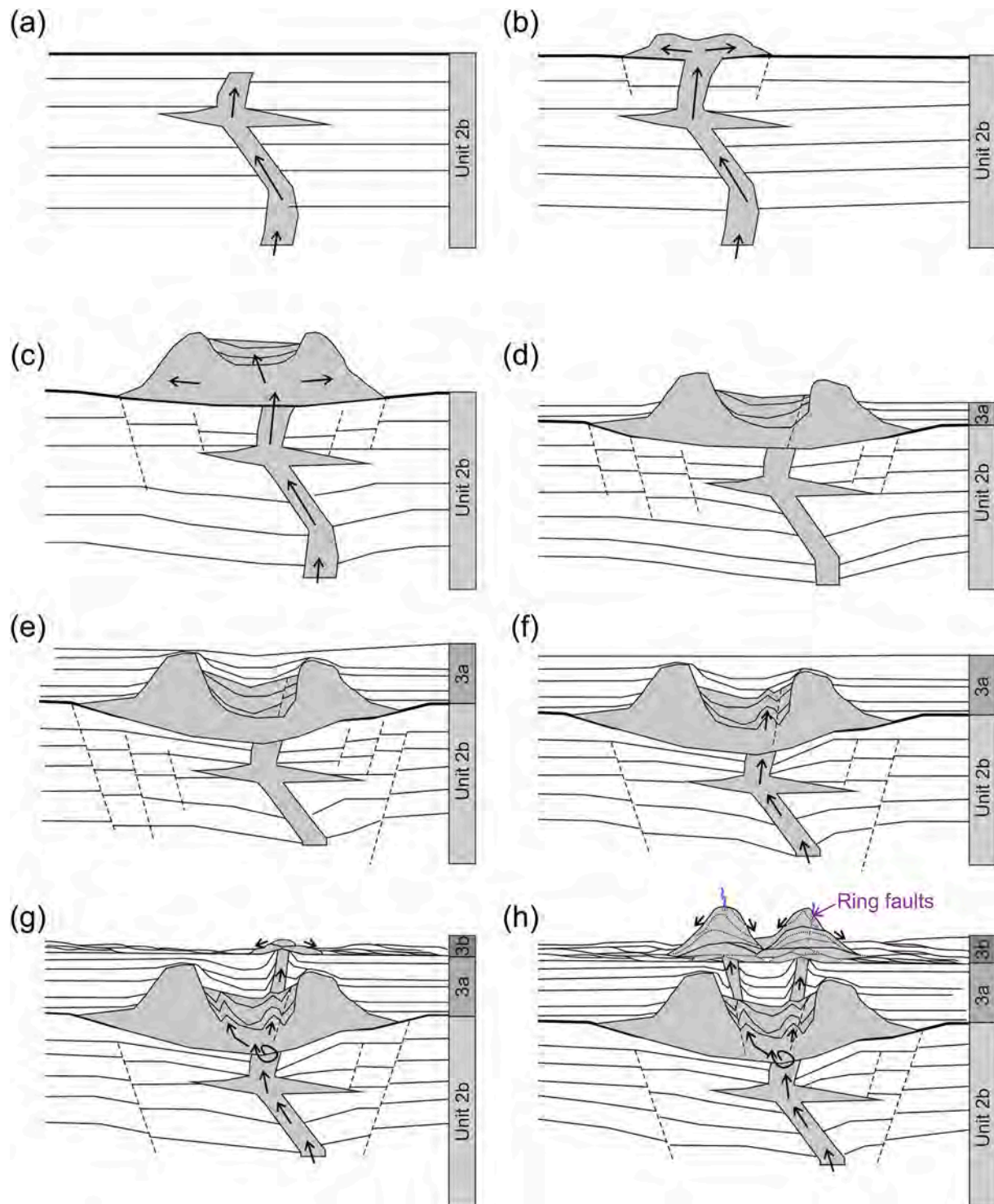


Fig. 15. Structural model of Venere MV and two-stage evolution. Mud flows and mud breccia are shown as grey-filled polygons surrounded by regular hemipelagic sediments layers. Main sedimentary units are indicated on the right-hand side in each panel. Stage 1 (a – c) is a formation of a mud-pie structure with a rigid outer ring and normal faulting with subsidence in response to build-up of the MV. This is followed by a quiet period with sedimentation covering the mud-pie structure which also partially collapsed (deflation) resulting in the characteristic faulting pattern (d – e). Stage 2 is marked by a re-initiation of mud flows from depth (possibly re-using the same conduit) and mud-breccia extrusion (f – h). Sediments of the older mud-pie structure and hemipelagic sediment cover are progressively deformed and partially incorporated in the new mud flows. Stage 2 is coincident with sedimentation down Squillace Canyon and formation of sediment waves. As the latest part of the evolution, ring faults occurred as the east cone slightly collapsed (h).

uplift (0.8 – 0.5 Ma) and associated compression as described in Praeg et al. (2009). This process of new mud-mobilization results in the upward-bending of sediments in the central portion of the MV and formation of prominent finger-like structures

(compare to Fig. 7). A switch in sedimentation style possibly coincident with the onset of activity of the Squillace Canyon results in a rapid build-up of sediments forming sub-unit 3b with characteristic sediment waves (Figs. 2e and 15g). While

the new feeder-channels develop and new mud flows erupt at the seafloor, sediments are also deposited around it creating the chaotic inner structure of MV (Fig. 15g). The feeder-channels of the east and west cones are active intermittently resulting in overlapping sequences of mud flows with a characteristic switch in predominant flow-direction (Fig. 15h). At current times, the west cone with its feeder-channel is still active as seen by (i) high Vp to shallow sub-seafloor depths (Figs. 7–9), (ii) a declined equivalent remnant of a small velocity anomaly associated with the east cone (Fig. 8a), (iii) ring faults at the east cone indicating recent deflation (Fig. 12), and (iv) the freshest mud flows at the seafloor emanating at the west cone edifice (Fig. 12e, Loher et al., 2018b). While the second eruption phase is ongoing, sediments of sub-unit 3b interfinger with the newly formed mud flows until mud flows take over and protrude above seafloor forming the current double-cone structure (Fig. 15h). Strong activity of the east cone must have faded at some point in the past resulting in a small collapse of the structure and forming of shallow ring faults (indicated by purple color in Fig. 15h). Subsidence of the east cone is around 5–10 m. Some activity (though not at the top but at the southern flank) is though still occurring at the east cone at current times as seen by two gryphons in the high-resolution bathymetry and small high-amplitude patches at the seafloor, indicating some recent mud extrusion (e.g. Fig. 11e). Gas venting at Venere MV was seen at five distinct vent locations. However, seismic data indicate that only two of those gas vents are linked to some gas accumulation at shallow subseafloor depths (<80 m bsf). The apparent largest gas accumulation seen in the study region is to the SW of Venere MV linked to a fault system. However, gas is not discharged at the seafloor and is apparently trapped within the sedimentary units at an average depth of ~120 m bsf. The MCS and OBH seismic data did not show any evidence for gas accumulations at greater depths below Venere MV. Thus, the observed gas flares may only tap into shallow reservoirs that act as intermediate trap of the fluid migration occurring from greater depth that was indicated by characteristic isotopic composition of the dissolved gases in pore-waters sampled around Venere MV (Loher et al., 2018b). Sedimentation within Squillace Canyon around Venere MV is at current state erosive as seen by the formation of seafloor scours at the southern rim of the MV (Loher et al., 2018a). The erosion has removed a significant portion of the initial cone structures (mostly at the east cone) which may have destabilized the overall architecture of the MV and lead to a further subsidence of the cones (e.g. by slumping). Thus, an asymmetric topography is created with the steepest flanks situated at the southern rim and no recent mud flows can emanate at the north-west or north-east side of Venere MV at current times.

5.7. Environmental impact

Through integrating different types of geophysical data sets this study allowed a better understanding of the evolutionary system of Venere MV and provides a step forward in our knowledge of sub-surface environments of MVs. Using 3D seismic imaging, the volume of extruded material was estimated to be ~1.2 km³ during stage 1 and 0.4 km³ during stage 2 (with an uncertainty of ~10%). Such detailed knowledge can help in assessing global inventories of discharged greenhouse gases from submarine MVs (e.g. Dimitrov, 2003; Etiope and Milkov, 2004; Wallmann et al., 2006; Mazzini and Etiope, 2017; Napoli et al., 2025a). Only few other studies have been conducted within the CAP or other mud volcano provinces that estimated the amount of material extruded directly from sub-surface geophysical data (e.g. Murton and Briggs, 2003; Kirkham et al., 2017; Loher et al., 2018a; Doll et al., 2025). Assessing volume from surface-data alone (e.g. Napoli et al., 2025b) may

be misleading and underestimate total volume as often a simplified assumption of the MV's base is used (e.g. Rabaut and Chamot-Rooke, 2007; Casalbore et al., 2020). Thus, our new analyses using 3D seismic imaging provide a more realistic estimate of total mud erupted at Venere MV compared to Loher et al. (2018a). Using the same assumptions as Loher et al. (2018b) on gas-sediment ratio of 3.68 and that 98.5% of the emitted gas is methane, the estimated total extruded volumes of mud at Venere MV amount to 5.8×10^9 m³ methane (4.35×10^9 m³ during stage 1; 1.45×10^9 m³ methane during stage 2), which is equivalent to 4.14×10^6 t of methane at standard pressure and temperature. If we further assume that stage 2 of Venere MV is linked to the Calabrian uplift, an average methane extrusion rate of ~1810 m³/yr (~1.3 t/yr) is estimated for the past ca. 800,000 years. These values are much smaller than methane emission rates from 5000 to 47,000 m³/yr (equivalent to 12–114 t/yr) estimated by Loher et al. (2018b) for the past ~880 years of the most recent eruption history only. However, this discrepancy is not surprising as mud eruption likely occurs in episodic cycles (e.g. Doll et al., 2025) with long quiescent periods between individual active phases. Although these values are quite uncertain (volume estimates, gas-sediment ratio, as well as assumed timing of Venere MVs activity during stage 2) this study provides an important step forward in understanding the role of MVs in the natural global methane budget not only today, but also during the more recent geologic history (the Pleistocene in case of Venere MV).

6. Summary and conclusion

Venere MV with its current prominent double-cone structure and ring-fault system has been imaged with multichannel seismic (MCS) and ocean bottom seismometer (OBS) data augmenting previous knowledge obtained from surface AUV seafloor mapping and 3.5 kHz sub-bottom profiler imaging. The wide-angle OBS data allowed recording of refracted arrivals constraining the P-wave velocity (Vp) structure up to a depth of 1.5 km below seafloor beneath the center of the MV. Arrivals from reflections recorded on all OBS stations were combined with refractions utilizing 2D travel time tomography for Vp modeling. With these velocities, the MCS data were depth-converted. Combining wide-angle OBS mirror imaging with near vertical incidence MCS data allowed imaging the complex structure of Venere MV. The observations suggest a two-stage evolutionary history of Venere MV: At the early stage (~3.6–0.8 Ma), the MV was forming a round mud-pie structure with a prominent rigid outer ring still identified in the seismic data today. During a time of quiescence and partial collapse, this mud-pie structure was covered by sediments. A second phase (younger than 0.8 Ma) of mud extrusion and ascent of mud breccia from depth is reworking the older structure, ultimately forming the modern prominent double-cone structure of Venere MV. The initial size of the mud-pie structure was at least twice in diameter as the current double-cones. The rigid outer ring standing above the paleo seafloor was approximately 80–100 m high. The effect of subsidence in result of mud extrusion at the initial MV structure extends as far as 5 km away from its current center. Utilizing the available seismic data and velocity information, we estimate a total of 0.4 km³ (±10%) of sediment contained within the inner double-cone structure, similar in volume to that of Touragay MV in Azerbaijan. The volume of mud contained within the initial mud-pie structure (and outer rigid ring) was estimated to ~1.2 km³ (±25%) of extruded mud. The two-stage evolution of Venere MV and switch from a mud-pie to a double-cone structure may also be associated with a change in supply-rate of mud breccia, different ratios of over-pressure at greater depth, and/or a change in viscosity (water content) of the extruded mud.

CRedit authorship contribution statement

Michael Riedel: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Project administration, Writing – original draft. **Cord Papenberg:** Investigation, Methodology, Writing –

review & editing. **Anne Krabbenhoft**: Data curation, Formal analysis, Investigation, Writing – review & editing. **Joerg Bialas**: Supervision, Validation, Writing – review & editing. **Gerhard Bohrmann**: Funding acquisition, Supervision, Validation, Writing – review & editing. **Miriam Römer**: Data curation, Formal analysis, Supervision, Writing – review & editing. **Silvia Ceramicola**: Supervision, Validation, Writing – review & editing.

Funding sources

This work is funded by the German Science Foundation (Deutsche Forschungsgemeinschaft DFG), grant number BO1049/22-1 and RI2107/2-1.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Michael Riedel reports financial support was provided by German Science Foundation (DFG). Gerhard Bohrmann reports financial support was provided by German Science Foundation (DFG). If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We thank the Captain and Crew of POS515 for their professional help with the data acquisition. We would like to thank Schlumberger for providing the VISTA Desktop Seismic Data Processing software (Version 2024), S&P Global for the Kingdom software (Version 2025) under Academic User License Agreements.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.marger.2026.207656>.

Data availability

All data used for this study are all available at the data repository PANGAEA (<https://www.pangaea.de/>).

Processed OBS data: <https://doi.pangaea.de/10.1594/PANGAEA.967503>;

Continuous OBS raw data: <https://doi.pangaea.de/10.1594/PANGAEA.967530>;

Processed MCS data: <https://doi.pangaea.de/10.1594/PANGAEA.967506>;

Raw and gridded AUV seafloor data: <https://doi.pangaea.de/10.1594/PANGAEA.884110>;

Raw EM122 seafloor data: <https://doi.pangaea.de/10.1594/PANGAEA.893103>;

Gridded EM122 seafloor data: <https://doi.pangaea.de/10.1594/PANGAEA.893205>, <https://doi.pangaea.de/10.1594/891656>

References

Aliyev, A.A., Gasanov, A., Bayramov, A., Belov, I., 2001. Earthquake and activation of mud volcano (causal link and interaction). *Proc. Geol. Inst* 29, 26–39.

Aslan, A., Warne, A.G., White, W.A., Guevara, E.H., Smyth, R.C., Raney, J.A., Gibeault, J. C., 2001. Mud volcanoes of the Orinoco Delta, Eastern Venezuela. *Geomorphology* 41 (4), 323–336. [https://doi.org/10.1016/S0169-555X\(01\)00065-4](https://doi.org/10.1016/S0169-555X(01)00065-4).

Bohrmann, G., cruise participants, 2015. Report and preliminary results of R/V METEOR cruise M112, Dynamic of Mud Volcanoes and Seeps in the Calabrian Accretionary Prism, Ionian Sea, Catania (Italy) – Catania (Italy), November 6 – December 15. *Berichte, MARUM – Zentrum für Marine Umweltwissenschaften, Fachbereich Geowissenschaften, Universität Bremen* 306, 217 urn:nbn:de:gbv:46-00104282-14.

Bohrmann, G., Bachmann, K., Buchheister, S., Candoni, O., Ceramicola, S., Loher, M., Meinecke, G., Renken, J., Spiesecke, U., von Wahl, T., Wintersteller, P., 2016. Report and Preliminary Results of R/V POSEIDON Cruise POS499, Calabrian Mud Volcanoes, Catania (Italy) – Catania (Italy), 04 May – 22 May, 2016. *Berichte, MARUM – Zentrum für Marine Umweltwissenschaften, Fachbereich Geowissenschaften, Universität Bremen*, No. 311, p. 76. Bremen, 2016. ISSN 2195-9633. <http://nbn-resolving.de/urn:nbn:de:gbv:46-MARUM9>.

Brown, K.M., 1990. The nature and hydrogeologic significance of mud diapirs and diatremes for accretionary systems. *J. Geophys. Res.* 95 (B6), 8969–8982. <https://doi.org/10.1029/JB095iB06p08969>.

Brown, K.M., Westbrook, G., 1988. Mud diapirism and subcretion in the Barbados ridge complex. *Tectonics* 7, 613–640. <https://doi.org/10.1029/TC007i003p00613>.

Camerlenghi, A., Cita, M.B., Hieke, W., Ricchiuto, T., 1992. Geological evidence of mud diapirism on the Mediterranean Ridge accretionary complex. *Earth Planet Sci. Lett.* 109, 493–506. [https://doi.org/10.1016/0012-821X\(92\)90109-9](https://doi.org/10.1016/0012-821X(92)90109-9).

Camerlenghi, A., Cita, M.B., Della Vedova, B., Fusi, N., Mirabile, L., Pellis, G., 1995. Geophysical evidence of mud diapirism on the Mediterranean Ridge accretionary complex. *Mar. Geophys. Res.* 17, 115–141. <https://doi.org/10.1007/BF01203423>.

Camerlenghi, A., Pini, G.A., 2009. Mud volcanoes, olistostromes and Argille scagliose in the 916 Mediterranean region. *Sedimentology* 56 (1), 319–365. <https://doi.org/10.1111/j.1365-9173091.2008.01016.x>.

Casalbore, D., Ingrassia, M., Pierdomenica, M., Beaubien, S.E., Martorelli, E., Bigi, S., Ivaldi, R., DeMarté, M., Chiocci, F.L., 2020. Morpho-acoustic characterization of a shallow-water mud volcano offshore Scoglio d'Affrica (Northern Tyrrhenian Sea) responsible for a violent gas outburst in 2017. *Mar. Geol.* 428, 1069277. <https://doi.org/10.1016/j.margeo.2020.106277>.

Capozzi, R., Artoni, A., Torelli, L., Lorenzini, S., Oppo, D., Mussoni, P., Polonia, A., 2012. Neogene to Quaternary tectonics and mud diapirism in the Gulf of Squillace (Crotona-Spartivento Basin, Calabrian Arc, Italy). *Mar. Petrol. Geol.* 35 (1), 219–234. <https://doi.org/10.1016/j.marpetgeo.2012.01.007>.

Ceramicola, S., Praeg, D., Cova, A., Accetella, D., Zecchin, M., 2014. Seafloor distribution and last glacial to postglacial activity of mud volcanoes on the Calabrian accretionary prism, Ionian Sea. *Geo Mar. Lett.* 34, 111–129. <https://doi.org/10.1007/s00367-013-0354-y>.

Chamot-Rooke, N., Rangin, C., Le Pichon, X., the DOTMED Working Group, 2005. Deep offshore tectonics of the Eastern Mediterranean: a Synthesis of deep Marine Data in the Eastern Mediterranean. *Mémoires de la Société géologique de France, nouv. ser.*, No. 177 64, 9 plates fl CD, ISBN 2853630919 9782853630917.

Coste, M., 2014. Les processus sédimentaires, depuis la pente continentale jusqu'au bassin, en contexte de tectonique active: analyse comparée entre la Marge Calabro-Ionienne et la Marge Ligure durant les derniers 5 Ma. [Doctoral dissertation, University of Nice Sophia Antipolis]. HAL archive. <https://te.archives-ouvertes.fr/tel-01062293>.

Davies, R.J., Stewart, S.A., 2005. Emplacement of giant mud volcanoes in the South Caspian Basin: 3D seismic reflection imaging of their root zones. *Journal of the Geological Society [London]* 162 (1–4). <https://doi.org/10.1144/0016-764904-082>.

Déville, E., Guerlais, S.H., Callec, Y., Griboulard, R., Huyghe, P., Lallemand, S., Mascle, A., Noble, M., Schmitz, J., the Caramba working group, 2006. Liquefied vs stratified sediment mobilization processes: insight from the South of the Barbados accretionary prism. *Tectonophysics* 428 (1–4), 33–47. <https://doi.org/10.1016/j.tecto.2006.08.011>.

Dimitrov, L.I., 2002. Mud volcanoes – the most important pathway for degassing deeply buried sediments. *Earth Sci. Rev.* 59, 49–76. [https://doi.org/10.1016/S0012-8252\(02\)00069-7](https://doi.org/10.1016/S0012-8252(02)00069-7).

Dimitrov, L.I., 2003. Mud volcanoes - a significant source of atmospheric methane. *Geo Mar. Lett.* 23, 155–161. [https://doi.org/10.1016/S0025-3227\(02\)00092-8](https://doi.org/10.1016/S0025-3227(02)00092-8).

Doll, M., Römer, M., Pape, T., Kölling, M., Kaul, N., dos Santos Ferreira, C., Bohrmann, G., 2023. Recent and episodic activity of decoupled mud/fluid discharge at Sartori mud volcano in the Calabrian Arc, Mediterranean Sea. *Front. Earth Sci.* 11. <https://doi.org/10.3389/feart.2023.1181380>.

Doll, M., Pape, T., Römer, M., Klügel, A., Bohrmann, G., 2025. A 56 ka eruptive history of Sartori mud volcano in the Calabrian accretionary prism, Mediterranean Sea. *Mar. Petrol. Geol.* 172, 107218. <https://doi.org/10.1016/j.marpetgeo.2024.107218>.

Dupré, S., Buffet, G., Mascle, J., Foucher, J.-P., Gauger, S., Boetius, A., Marfia, C., the AsterX AUV Team, the Quest ROV Team, the BIONIL Scientific Party, 2008. High-resolution mapping of large gas emitting mud volcanoes on the Egyptian continental margin (Nile Deep Sea Fan) by AUV surveys. *Mar. Geophys. Res.* 29 (4), 275–290. <https://doi.org/10.1007/s11001-009-9063-3>.

Etiopie, G., Milkov, A.V., 2004. A new estimate of global methane flux from onshore and shallow submarine mud volcanoes to the atmosphere. *Environ. Geol.* 46, 997–1002. <https://doi.org/10.1007/s00254-004-1085-1>.

Faccenna, C., Piromallo, C., Crespo-Blanc, A., Jolivet, L., Rossetti, F., 2004. Lateral slab deformation and the origin of the western Mediterranean arcs. *Tectonics* 23 (1), TC1012. <https://doi.org/10.1029/2002TC001488>.

Faccenna, C., Molin, P., Orecchio, B., Olivetti, V., Bellier, O., Funicello, F., Minelli, L., Piromallo, C., Billi, A., 2011. Topography of the Calabria subduction zone (southern Italy): clues for the origin of Mt. Etna. *Tectonics* 30 (1), TC1003. <https://doi.org/10.1029/2010TC002694>.

Feseker, T., Brown, K.R., Blanchet, C., Scholz, F., Nuzzo, M., Reitz, A., Schmidt, M., Hensen, C., 2010. Active mud volcanoes on the upper slope of the western Nile deep-sea fan—first results from the P362/2 cruise of R/V Poseidon. *Geo Mar. Lett.* 30 (3/4), 169–186. <https://doi.org/10.1007/s00367-010-0192-0>.

Fujie, G., Kasahara, J., Murase, K., Mochizuki, K., Kaneda, Y., 2008. Interactive analysis tools for the wide-angle seismic data for crustal structure study (Technical Report). *Explor. Geophys.* 39 (1), 26–33. <https://doi.org/10.1071/EG08006>.

- Goes, S., Giardini, D., Jenny, S., Hollenstein, C., Kahle, H.-G., Geiger, A., 2004. A recent tectonic reorganization in the south-central Mediterranean. *Earth Planet Sci. Lett.* 226, 335–345. <https://doi.org/10.1016/j.epsl.2004.07.038>.
- Grión, S., Exley, R., Manin, M., Miao, X., Pica, A., Wang, Y., Granger, P., Ronen, S., 2007. Mirror imaging of OBS data. *First Break* 25 (11). <https://doi.org/10.3997/1365-2397.2007028>.
- Guliyev, I.S., Yusubov, N.P., Huseynova, Sh.M., 2023. Hydrocarbon systems and mud volcanoes: paragenesis or associated development, ANAS Transactions. *Earth Sci.* (2023), 60–64. <https://doi.org/10.33677/ggiasconf20230300015>. Special Issue.
- Gutscher, M.-C., Kopp, H., Krastel, S., Bohrmann, G., Garlan, T., Zaragosi, S., Klauke, I., Wintersteller, P., Loubrieu, B., Le Faou, Y., San Pedro, L., Dominguez, S., Rovere, M., Mercier de Lepinay, B., Ranero, C., Sallares, V., 2017. Active tectonics of the Calabrian subduction revealed by new multi-beam bathymetric data and high-resolution seismic profiles in the Ionian Sea (Central Mediterranean). *Earth Planet Sci. Lett.* 461, 61–72. <https://doi.org/10.1016/j.epsl.2016.1s2.020>.
- Huguen, C., Mascle, J., Woodside, J., Zitter, T., Foucher, J.P., 2005. Mud volcanoes and mud domes of the Central Mediterranean Ridge: Near-bottom and in situ observations. *Deep Sea Res. Oceanogr. Res. Pap.* 52 (10), 1911–1931. <https://doi.org/10.1016/j.dsr.2005.05.006>.
- Kirkham, C., Cartwright, J., Hermanrud, C., Jebens, C., 2017. The spatial, temporal and volumetric analysis of a large mud volcano province within the Eastern Mediterranean. *J. Marine and Petroleum Geology* 81, 1–16. <https://doi.org/10.1016/j.marpetgeo.2016.12.026>.
- Kirkham, C., Cartwright, J., 2022. Mud volcanoes and dissolution structures as kinematic markers during salt tectonic deformation. *Basin Res.* 34, 99–120. <https://doi.org/10.1111/bre.12612>.
- Kopf, A., 2002. Significance of mud volcanism. *Rev. Geophys.* 40 (2), 1005. <https://doi.org/10.1029/2000RG000093>.
- Krabbenhoef, A., Papenberg, C., Klaeschen, D., Bialas, J., 2016. Distribution of free gas and image structures beneath Sevastopol mud volcano, Black sea, from a 3D study of a high resolution wide-angle seismic dataset. In: *CIESM 2016*, vol. 12. Kiel, Germany. (Accessed 16 September 2016).
- Loher, M., Ceramicola, S., Wintersteller, P., Meinecke, G., Sahling, H., Bohrmann, G., 2018a. Mud volcanism in a canyon: morphodynamic evolution of the active Venere mud volcano and its interplay with Squillace Canyon, Central Mediterranean. *G-cubed* 19, 356–378. <https://doi.org/10.1002/2017GC007166>.
- Loher, M., Pape, T., Marcon, Y., Römer, M., Wintersteller, P., Praeg, D., Torres, M., Sahling, H., Bohrmann, G., 2018b. Mud extrusion and ring-fault gas seepage – upward branching fluid discharge at a deep-sea mud volcano. *Sci. Rep.* 8, 6275. <https://doi.org/10.1038/s41598-018-24689-1>.
- Loher, M., Marcon, Y., Pape, T., Römer, M., Wintersteller, P., dos Santos Ferreira, C., Praeg, D., Torres, M., Sahling, H., Bohrmann, G., 2018c. Seafloor sealing, doming, and collapse associated with gas seeps and authigenic carbonate structures at Venere mud volcano, Central Mediterranean. *Deep Sea Res. Oceanogr. Res. Pap.* 137, 76–96. <https://doi.org/10.1016/j.dsr.2018.04.006>.
- Loncke, L., Mascle, J., Parties, Fanil Scientific, 2004. Mud volcanoes, gas chimneys, pockmarks and mounds in the Nile deep-sea fan (Eastern Mediterranean): geophysical evidences. *J. of Marine and Petroleum Geology* 21 (6), 669–689. <https://doi.org/10.1016/j.marpetgeo.2004.02.004>.
- Lykousis, V., Alexandri, S., Woodside, J., de Lange, G., Dählmann, A., Perissoratis, C., Heeschen, K., Ioakim, C., Sakellariou, D., Nomikou, P., Rousakis, G., Casas, D., Ballas, D., Erçilla, G., 2009. Mud volcanoes and gas hydrates in the Anaximander mountains (Eastern Mediterranean Sea). *Mar. Petrol. Geol.* 26, 854–872. <https://doi.org/10.1016/j.marpetgeo.2008.05.002>.
- Maesano, F.E., Tiberti, M.M., Basili, R., 2017. The Calabrian Arc: three-dimensional modelling of the subduction interface. *Sci. Rep.* 7, 8887. <https://doi.org/10.1038/s41598-017-09074-8>.
- Malinverno, A., Ryan, W.B.F., 1986. Extension in the Tyrrhenian Sea and shortening in the Apennines as result of arc migration driven by sinking of the lithosphere. *Tectonics* 5 (2), 227–245. <https://doi.org/10.1029/TC005i002p00227>.
- Mascle, J., Mary, F., Praeg, D., Brosolo, L., Camera, L., Ceramicola, S., Dupré, S., 2014. Distribution and geological control of mud volcanoes and other fluid/free gas seepage features in the Mediterranean Sea and nearby Gulf of Cadiz. *Geo Mar. Lett.* 34 (2–3), 89–110. <https://doi.org/10.1007/s00367-014-0356-4>.
- Mazzini, A., Etiope, G., 2017. Mud volcanism: an updated review. *Earth Sci. Rev.* 168, 81–112. <https://doi.org/10.1016/j.earscirev.2017.03.001>.
- Mellors, R., Kilb, D., Aliyev, A., Gasanov, A., Yetirmishli, G., 2007. Correlations between earthquakes and large mud volcano eruptions. *J. Geophys. Res.* 112, B04304. <https://doi.org/10.1029/2006JB004489>.
- Menapace, W., Völker, D., Sahling, H., Zoellner, C., dos Santos Ferreira, C., Bohrmann, G., Kopf, A., 2017. Long-term in situ observations at the Athina mud volcano, Eastern Mediterranean: taking the pulse of mud volcanism. *Tectonophysics* 721, 12–27. <https://doi.org/10.1016/j.tecto.2017.09.010>.
- Murton, B.J., Briggs, J., 2003. Numerical modelling of mud volcanoes and their flows using constraints from the Gulf of Cadiz. *Mar. Geol.* 195 (1–4), 223–226. [https://doi.org/10.1016/S0025-3227\(02\)00690-4](https://doi.org/10.1016/S0025-3227(02)00690-4).
- Napoli, S., Spatola, D., Casalbore, D., Lombardo, L., Tanyas, H., Chiocci, F.L., 2025a. Comprehensive global inventory of submarine mud volcanoes. *Sci. Data* 12 (1), 382. <https://doi.org/10.1038/s41597-025-04726-1>.
- Napoli, S., Spatola, D., Casalbore, D., Chiocci, F.L., 2025b. Geomorphometric analysis of submarine mud volcanoes: variability, evolutionary trends, and geohazard implications. *Mar. Sci. Eng.* 13 (3), 622. <https://doi.org/10.3390/jmse13030622>.
- Pape, T., Kasten, S., Zabel, M., Bahr, A., Abegg, F., Hohnberg, H.J., Bohrmann, G., 2010. Gas hydrates in shallow deposits of the Amsterdam mud volcano, Anaximander Mountains, Northeastern Mediterranean Sea. *Geo Mar. Lett.* 30 (3–4), 187–206. <https://doi.org/10.1007/s00367-010-0197-8>.
- Papenberg, C., Krabbenhoef, A., Klaeschen, D., Bialas, J., 2016. Distribution of free gas and 3D mirror image structures beneath Sevastopol mud volcano, Black sea, from 3D high resolution wide-angle seismic data. In: *AGU Fall Meeting 2016*, vol. 12. San Francisco, USA. (Accessed 16 December 2016).
- Paull, C.K., Dallimore, S.R., Caress, D.W., Gwiazda, R., Melling, H., Riedel, M., Jin, Y.K., Hong, J.K., Kim, Y.G., Graves, D., Sherman, A., Lundsten, E., Anderson, K., Lundsten, L., Villinger, H., Kopf, A., Johnson, S.B., Hughes Clarke, J., Blasco, S., Conway, K., Neelands, P., Thomas, H., Côté, M., 2015. Active mud volcanoes on the continental slope of the Canadian Beaufort Sea. *G-cubed* 16 (9), 3160–3181. <https://doi.org/10.1002/2015GC005928>.
- Planke, S., Svensen, H., Hovland, M., Banks, D.A., Jamtveit, B., 2003. Mud and fluid migration in active mud volcanoes in Azerbaijan. *Geo Mar. Lett.* 23, 258–268. <https://doi.org/10.1007/s00367-003-0152-z>.
- Polonia, A., Torelli, L., Mussoni, P., Gasperini, L., Artoni, A., Klaeschen, D., 2011. The Calabrian Arc subduction complex in the Ionian Sea: regional architecture, active deformation and seismic hazard. *Tectonics* 30, TC5018. <https://doi.org/10.1029/2010TC002821>.
- Polonia A., Melis R., Galli P., Colizza E., Insinga D.D., Gasperini L., 2023. Large earthquakes along slow converging plate margins: Calabrian Arc paleoseismicity based on the submarine turbidite record, *Geosci. Front.* 14 (5), art. no. 101612 DOI: 10.1016/j.gsf.2023.101612.
- Praeg, D., Ceramicola, S., Barbieri, R., Unnithan, V., Wardell, N., 2009. Tectonically-driven mud volcanism since the late Pliocene on the Calabrian accretionary prism, central Mediterranean Sea. *Mar. Petrol. Geol.* 26, 1849–1865. <https://doi.org/10.1016/j.marpetgeo.2009.03.008>.
- Rabaute, A., Chamot-Rooke, N., 2007. Quantitative mapping of active mud volcanism at the western Mediterranean Ridge-backstop contact. *Mar. Geophys. Res.* 28, 271–293. <https://doi.org/10.1007/s11001-007-9031-8>.
- Riedel, M., Bialas, J., Krabbenhoef, A., Bähre, V., Beeck, F., Candoni, O., Kühn, M., Muff, S., Rindfleisch, J., Stange, N.U., 2017. Report of Cruise POSS15, 18.06.2017 – 13.07.2017 Dubrovnik – Catania, Berichte Aus Dem GEOMAR Helmholtz-Zentrum Für Ozeanforschung Kiel, Nr. 36. https://doi.org/10.3289/GEOMAR_REP_NS_36. 2017. August 2017, 73 pp, ISSN Nr. 2193-8113.
- Rossi, S., Sartori, R., 1981. A seismic reflection study of the external Calabrian Arc in the northern Ionian Sea (eastern Mediterranean). *Mar. Geophys. Res.* 4, 403–426. <https://doi.org/10.1007/BF00286036>.
- Tenzer, R., Gladkikh, V., 2014. Assessment of density variations of marine sediment with ocean and sediment depths. *Sci. World J.* 2014, 823296. <https://doi.org/10.1155/2014/823296>. Article ID.
- Wallmann, K., Drews, M., Aloisi, G., Bohrmann, G., 2006. Methane discharge into the Black Sea and the global ocean via fluid flow through submarine mud volcanoes. *Earth Planet Sci. Lett.* 248 (1–2), 545–560. <https://doi.org/10.1016/j.epsl.2006.06.026>.
- Xu, S., Menapace, W., Hüpers, A., Kopf, A., 2021. Mud volcanoes in the Gulf of Cadiz as a manifestation of tectonic processes and deep-seated fluid mobilization. *J. of Marine and Petroleum Geology* 132. <https://doi.org/10.1016/j.marpetgeo.2021.105188>.
- Yusubov, N.P., Guliyev, I.S., Soto, J.I., 2024. Structure and formation of mud volcanoes in the South Caspian Basin according to seismic data. *Interpretation* 12 (4), 105–118. <https://doi.org/10.1190/INT-2023-0134.1>.
- Zecchin, M., Caffau, M., Civile, D., Critelli, S., Di Stefano, A., Maniscalco, R., Muto, F., Sturiale, G., Roda, C., 2012. The Plio-Pleistocene evolution of the Crotona Basin (southern Italy): interplay between sedimentation, tectonics and eustasy in the frame of Calabrian Arc migration. *Earth Sci. Rev.* 115, 273–303. <https://doi.org/10.1016/j.earscirev.2012.10.005>.
- Zelt, C.A., Smith, R.B., 1992. Seismic traveltime inversion for 2-D crustal velocity structure. *Geophys. J. Int.* 108, 16–34. <https://doi.org/10.1111/j.1365-246X.1992.tb00836.x>.