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Modeling the interaction between pre-salt seamounts and gravitational failure in salt-bearing passive margins: The Messinian case in the Northwestern Mediterranean Basin

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MODELING THE INTERACTION BETWEEN PRE-SALT SEAMOUNTS AND
GRAVITATIONAL FAILURE IN SALT-BEARING PASSIVE MARGINS: THE MESSINIAN
CASE IN THE NORTHWESTERN MEDITERRANEAN BASIN

Oriol Ferrer[1], Oscar Gratacós[1], Eduard Roca[1] and Josep Anton Muñoz[1]

[1] Geomodels Research Institute. Grup de Geodinàmica i Anàlisi de Conques. Departament de

Dinàmica de la Terra i de l'Oceà, Facultat de Ciències de la Terra, Universitat de Barcelona, C/

Martí i Franquès s/n, 08028 Barcelona, Spain

E-mails: joferrer@ub.edu, ogratacos@ub.edu, eduardroca@ub.edu, jamunoz@ub.edu

ABSTRACT

The Northwest Mediterranean Basin includes a thick Messinian salt sequence composed

of three evaporitic units. From these the intermediate unit, which is dominantly composed of

halite, acts as a gravitational detachment favoring the downslope failure of the overlying

sediments in a thin-skinned deformation regime. As a result, the structure of the margin is

characterized by an upper extensional domain with basinward-dipping listric normal faults and a

lower contractional domain that accommodates upslope extension by folding, salt inflation or

diapir squeezing. Lower to middle Miocene volcanic seamounts (pre-salt reliefs) located at the

upper extensional domain locally disrupted the evaporitic units and produced salt flow

perturbations. They acted as passive buttresses during the gravitational failure modifying the

structural zonation of the margin.

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Using an experimental approach (sandbox models) this study analyses the role played by seamounts during the kinematic evolution of passive margins and how they alter salt flow and suprasalt deformation during gravitational gliding. The experiments show that seamounts locally interrupt the structural zonation of the margin as they hindered downdip salt flow during early deformation. Seamounts initially compartmentalize the margin architecture, resulting in the development of two gravitational sub-systems with two extensional/contractional pairs that are subsequently re-connected when the accumulation of salt analogue upslope of the relief is enough to overthrust it. From this moment, the cover is passively translated downslope as a regional system. The changes in the viscous layer flow velocity related to the dip differences between the flanks and edges of the seamount determine the kinematic evolution of this system. The experiments also provide geometrical constraints to consider during interpretation of these structures, which are commonly poorly imaged in seismic data.

INTRODUCTION

The downslope failure of salt-bearing passive margins by gravitational gliding or spreading generates broad zones affected by thin-skinned deformation and produces a well-studied structural zonation (Fig. 1). A typical gravity-driven margin is characterized by wide deformation belts dominated by extensional processes in the upper part linked with a contractional domain in the lower part where the salt pinches-out (e.g., Marton et al., 2000; Brun and Fort, 2004 and 2011; Fort et al., 2004; Hudec and Jackson, 2004 and 2011; Rowan et al., 2004 and 2012, Quirk et al., 2012; Peel, 2014) (Fig. 1). Upslope extension is accommodated by an extensional fault system characterized by basinward-dipping listric faults soling into the salt

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producing salt rollers and rafts (e.g., Duval et al., 1992; Gaullier et al., 1993; Mauduit et al., 1997; Mauduit and Brun, 1998; Brun and Maudit, 2009). In contrast, folds, thrusts, and salt structures (salt-cored anticlines, diapirs or extruding salt sheets) accommodate downslope contraction (e.g., Fort et al., 2004; Hudec and Jackson, 2004; Rowan et al., 2004. Dooley et al., 2007). Depending on the margin scale, a third domain may also develop where the overburden is passively translated basinwards above the salt detachment (Rowan et al., 2004) (Fig. 1).

Pre-salt reliefs that act as flow barriers hindering salt drainage can locally disrupt this classic structural zonation. The reliefs may also act as a nucleation point for secondary structures. These inherited topographic anomalies may be related to pre-salt folds and faults (e.g., Adam and Krézsek, 2012) or to a pre-existing topography related to irregularly eroded surfaces (e.g., Gaullier et al., 1993 and 1996; Maillard et al., 2003) and/or volcanic edifices (e.g., Loncke et al., 2006 and 2010; Guennoc et al., 2011; Granado et al., 2016). The continuity of these reliefs (isolated or linear bodies) and their orientation with respect to the margin slope are key factors during gravitational failure and suprasalt deformation (Cobbold and Szatmari, 1991; Gaullier et al., 1993; Gaullier and Bellaiche, 1996; Loncke et al., 2006 and 2010; Augustin et al., 2014; Feldens and Mitchell, 2015; Dooley and Hudec, this issue; Dooley et al., this issue).

All these observations prompt key questions regarding the kinematic evolution of a salt-bearing passive margin with pre-salt reliefs (specifically seamounts):

- How does deformation evolve around pre-salt seamounts during gravitational failure of the margin?
- What are the main factors intrinsic to the geometry of volcanic edifices that control the resulting structural style?

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Using sandbox models and new analysis techniques, this article characterizes salt and suprasalt deformation in response to a pre-salt seamount during gravitational failure of a passive margin. To do so, our experimental programme includes elliptical seamounts with different heights oriented perpendicular to the main salt flow direction. The comparison between experimental results and seismic examples of the North Western Mediterranean Basin depicts that pre-salt seamounts can modify the classical structural zonation of salt-bearing passive margins, hindering salt flow and favoring the development of secondary structures around the relief.

THE LIGURO-PROVENÇAL BASIN (NORTHWESTERN MEDITERRANEAN)

Geological setting

The Northwestern Mediterranean Basin developed between the Iberian-European continental margin and its Corsica-Sardinia conjugate (Fig. 2). It is an Oligocene-Miocene back-arc basin that formed during the roll-back of the Maghrebian-Tethys oceanic slab below the Iberia-Europe continental lithosphere (Doglioni et al., 1997; Roca et al., 1999; Cavazza et al., 2004; Schettino and Turco, 2010 among others). In this regional setting, the northwestern margin of the basin was affected by a system of NE-trending extensional faults and shear zones that thinned the Iberian-European continental crust to exhume the lower crust/mantle in the abyssal part of the basin (Chamot-Rooke et al., 1997; Bache et al., 2009; Jolivet et al., 2015) (Fig. 2). The formation of this basin was synchronous with late Oligocene-middle Miocene calc-alkaline magmatism that formed volcanic edifices distributed in the intermediate part of the margin as well as in the surrounding areas (Martí et al., 1992; Maillard and Mauffret, 1993; Beccaluva et al., 1994; Roca, 2001; Guennoc et al., 2011).

The study area is located in the central part of the northwestern margin of this basin between the Gulf of Lions and the Liguro-Provençal Basin (Fig. 2). A regional cross-section

across this area (Fig. 3) shows the margin architecture with a pre-rift basement that, affected by latest Eocene (?) to early Miocene (Aquitanian) extensional faults, is overlain by a thick succession of uppermost Eocene (?) to present-day deposits (Gorini et al., 1993; Roca, 2001; Jolivet et al., 2015). In this essentially terrigenous succession outlines a major erosive surface (Margin Erosion Surface or MES in Fig. 3) that basinwards is onlapped by Messinian deposits (Lofi et al., 2011a and b). This rugged surface exhibiting subaerial erosion features (Stamplfli and Höcker, 1989) is seismically evidenced by an angular unconformity in the upper part of the margin (Bache et al., 2009). The Messinian deposits include four seismic units ascribed to different lithological compositions: the Clastic Unit (CU) and the "Messinian evaporitic trilogy" formed by the Lower Unit (LU), the Mobile Unit (MU) and the Upper Unit (UU) (Lofi et al., 2011b and Bache et al., 2015).

The Lower Unit (LU) is characterized by a set of continuous reflectors with high amplitude (Lofi et al., 2005 and 2011a; Obone Zue Obame et al., 2011) (Fig. 4). The nature of this unit is still speculative because it has never been sampled. It has been interpreted as clastic turbidites (Lofi et al., 2005 and 2011a) that, according to Roveri et al. (2001 and 2008), may include resedimented gypsum. The LU grades towards the base of the slope to a chaotic and poorly imaged sedimentary body that, integrated by the Clastic Unit (CU), belongs to alluvial fan deposits deriving from margin erosion (Gorini et al., 2015; Cameselle and Urgelés, 2016). Overlying the LU, the intermediate Mobile Unit has transparent seismic facies (Lofi et al., 2005 and 2011a; Obone Zue Obame et al., 2011) (Fig. 4) and has been classically interpreted as consisting dominantly of halite (Nelly, 1994). Finally, the Upper Unit (UU) corresponds to a tabular body made up by high amplitude parallel and continuous reflectors (Lofi et al., 2005 and 2011a; Obone Zue Obame et al., 2011) (Fig. 4). It has been correlated to a layered evaporitic

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sequence and may include dolomitic marls, marls, anhydrites and clastics close to the main canyons (Lofi *et al*., 2011a).

The deposition of these post-rift Messinian units and the formation of the linked Margin Erosion Surface (MES) have been related to the huge sea-level drop that took place in the Mediterranean during the Messinian Salinity Crisis (Hsü et al., 1973). This sea-level drop was followed by a very fast reflooding in Zanclean (Pliocene) times, which led to the deposition of clastic deposits in a prograding shelf to a deep-sea fan environment that quickly onlapped both the Messinian units and the related unconformity (Fig. 3) (Garcia-Castellanos et al., 2009). These Pliocene to Quaternary deposits derive from the Iberian and European mainland and in the abyssal plain belong to turbidites deposited in the Rhône and Valencia deep sea fan systems (Maldonado et al., 1985; Droz et al., 2006).

The Messinian dips basinwards (Figs. 3 and 4) as a result of the Plio-Quaternary differential thermal subsidence between the Northwestern Mediterranean Basin margins and the basin depocenter (Bessis and Burrus, 1986). This tilting, together with the wedge geometry of the prograding Plio-Quaternary deposits on the upper margin slope, led to the gravitational failure of the sediments deposited above the Messinian salt (MU). Thus, the Messinian Upper Unit (UU) and the Plio-Quaternary deposits were deformed by a combination of gravitational sliding and spreading processes (Cobbold and Szatmari, 1991; Gaullier, 1993; Gaullier and Bellaiche, 1996; Dos Reis *et al*., 2008). The structural style of these materials is characterized by 1) listric normal growth faults dipping basinwards that sole into the upper part of the MU, 2) contractional detachment folds and squeezed diapirs accommodating upslope extension at the toe of the margin and 3) a passively translated cover without significant deformation between these

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two domains (Gaullier, 1993; Maillard et al., 2003; Gaullier et al., 2006; Dos Reis *et al.*, 2005

and 2008; Loncke et al., 2006; Obone Zue Obame et al., 2011) (Fig. 4a).

The margin architecture of the Liguro-Provençal Basin is similar to other gravitationally

failed passive margins with post-rift salt deposits (e.g the South-Atlantic passive margins of

Brazil and Angola) (e.g., Marton et al., 2000; Fort et al., 2004; Hudec and Jackson, 2004; Rowan

et al., 2004; Quirk et al., 2012). Furthermore, as seen in these margins, pre-salt seamounts are

rather common in the entire Northwestern Mediterranean Basin (Sans and Sàbat, 1993; Guennoc

et al., 2011; Granado et al., 2016). They are mainly formed by upper Oligocene - middle

Miocene calc-alkaline volcanic edifices (Martí *et al.*, 1992; Beccaluva et al., 1994; Roca, 2001;

Maillard et al., 2003). Many of these volcanic edifices remained as islands during the whole

Messinian Salinity Crisis episode inducing local changes in salt thickness or even disrupting salt

continuity (see Fig. 4 for examples of different levels of salt disruption). Such unhomogeneities

had a noticeable influence on the structural evolution of the Liguro-Provençal margins during the

gravitational failure (Fig. 4).

EXPERIMENTAL METHODOLOGY

Set-up and procedure

The experimental program presented in this article includes eight analogue models to

analyze how the height of a pre-salt seamount modifies the downslope failure of a salt-bearing

passive margin (Table 1). Different models with the same setup have been used to examine the

temporal evolution of the system (Table 1). According to the case study these seamounts are

located between the extensional and contractional domains, where suprasalt deposits are

transported basinwards by translation. These models were carried out in a glass-sided deformation rig that was 110 cm-long, 50 cm-wide and 15 cm-deep (Fig. 5). Seamounts were built manually with light blue plasticine in order to facilitate the slicing of the models at the end of the experiment. They were glued to a basal mylar sheet that remained fixed throughout the experiment. The shape and size of the basal seamount section was the same in all the experiments, consisting of a rectangle with a semicircle on each short side (Fig. 5a). All of them had a triangular section in the slope direction with the same height along the rectangular area (Figs. 5a and 5b). The main difference between the seamounts of the different experiments was their height, and consequently the average slope angle of their flanks (Table 1).

Twelve 2.5 mm-thick layers of alternating white and blue dry sand were deposited above the basal mylar sheet simulating uppermost Eocene (?) to upper Miocene (Tortonian) clastic infill of the Liguro-Provençal Basin (Figs. 5b and 5c). Salt equivalent units onlapped the plasticine seamount. They also pinched out upslope against a 3°-downslope dipping erosional surface and terminated downslope against a vertical boundary that acted as a frontal buttress during gravitational failure (Figs. 5a and b).

The mechanical stratigraphy of the experimental evaporitic units was designed according the stratigraphy of the Messinian trilogy in the study area (Fig. 5c). Thus, taking into account that the LU has been never drilled and may contain resedimented gypsum (Roveri et al., 2001 and 2008) we used a 5 mm-thick layer of a 50% volumetric mixture of sand and a pink polydimethylsiloxane polymer (Rhodosil GUM FB; Dell'Ertole & Schellart, 2013). This mixture has a higher effective viscosity than pure polymer (the halite analogue) due to the sandy impurities (see Callot et al., 2012 and Cartwright et al., 2012). The halite-rich MU, was simulated using a 10 mm-thick layer of the same polymer but pure and transparent in this case

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(Fig. 5c). Following the methodology proposed by Dooley et al. (2009), different vertical colored polymer plugs located around the plasticine seamount were used as passive markers to trace the flow of the pure polymer during gravitational gliding (Fig. 5a). The mechanical properties of these markers were the same as those of the transparent polymer. Two 2.5 mm-thick layers of white and green silica sand were used as the UU analogue (Fig. 5c). The pre-kinematic package was completed with a 2.5 mm-thick layer of white silica sand covering the entire model and reaching a total thickness of 3 cm (Fig. 5b).

Gravitational gliding was triggered by tilting the baseboard of the rig to 4.5º (Fig. 5b). From that moment, additional syn-kinematic layers of dry white and brown silica sand were added at regular two-hours intervals. Both syn- and pre-kinematic sand was poured into the experimental apparatus and then leveled using a mechanical scraper (Krantz, 1991; Lohrmann et al., 2003). Prior to the deposition of each syn-kinematic sand layer, the baseboard was tilted back to horizontal. This slowed the gravitational flow of the polymer and variations in topography during scanning of the modeland deposition of syn-kinematic sand. The regional datum was raised 1.8 mm by each syn-kinematic layer. After the deposition of each syn-kinematic layer the baseboard was tilted again 4.5º in the same direction to re-start the gravitational gliding. At the end, the experiments were covered by post-kinematic sand, preserved and serially sectioned into 3 mm-thick vertical slices.

Scaling and mechanical properties of the analogue materials

The fine-grained (199 µm grain size) silica sand used in the experiments deforms according to Navier-Coulomb failure at moderate-high values of normal stress (Horsfield, 1977). The mechanical properties of the poured sand were determined by a shear box test, resulting in

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an internal friction of 34.6º, a bulk density of 1500 kg m^{-3}, a coefficient of internal friction of 0.69 and a low apparent cohesive strength of 55 Pa. In contrast, the pure polymer is a near-Newtonian viscous fluid with a density of 972 kg m^{-3} at room temperature and a viscosity of 1.6 x 10^{-4} Pa s when deformed at a laboratory strain rate of 1.83 x 10^{-4} cm s^{-1} (Dell'Ertole and Schellart, 2013). The 50% by volume mixture of sand and polymer has a density of 1550 kg m^{-3} at room temperature and a higher effective viscosity than pure polymer (3.35 x 10^{-4} Pa s) when deformed at the same laboratory strain rate (see Callot et al., 2012 for more information). A summary of these properties and other experimental scaling parameters are shown in Table 2.

Analogue models analysis procedure

Model's kinematic was documented and subsequently analyzed by means of oblique and overhead time-lapse photographs taken every 30 seconds, in combination with model surface topography recorded before and after the deposition of each syn-kinematic layer using a sub-millimeter resolution white light scanner (SidioPro from Nub3D).

The vertical serial sections carried out at the end of the experiments were also recorded using high-resolution digital cameras to analyze the variation in the structures along strike. A 4-cm wide section along each side of the experiments was omitted in the analysis to avoid border effects related to the friction between glass sidewalls and the sandpack. High-resolution photographs of the model cross sections were used to reconstruct a 3D voxel model in image-processing software allowing the generation of virtual strike and depth slices (see Dooley et al., 2009 for further details).

EXPERIMENTAL RESULTS

Baseline model (without seamount)

We performed a baseline experiment without a seamount (Table 1) to illustrate the main structural features resulting from the tilting of the modeled passive margin. The experimental results illustrate a structural zonation similar to other salt-bearing passive margins, characterized by upslope extension, downslope contraction and an intermediate translational domain (e.g., Marton et al., 2000; Brun and Fort, 2004 and 2011; Fort et al., 2004; Hudec and Jackson, 2004 and 2011; Rowan et al., 2004 and 2012; Quirk et al., 2012; Peel, 2014) (Fig. 6a). As occurs in natural cases, deformation of the sand layers (sedimentary overburden) during tilting is driven by gravitational failure above the pure polymer (regional detachment) as it flows downslope. As a result, the thickness of the polymer decreases upslope in the extensional domain and increases downslope in the contractional domain (Fig. 6a). In contrast, the more viscous LU modeled by the sand and polymer mixture maintained a constant thickness throughout the experiment (Fig. 6a).

A set of basinward dipping listric normal growth faults rooted in the transparent polymer developed in the upslope extensional domain (Duval et al., 1992; Gaullier et al., 1993; Mauduit et al., 1997; Mauduit and Brun, 1998; Brun and Fort, 2004 and 2011; Brun and Mauduit, 2009; Carthwright et al., 2012) (Fig. 6a). While different rollovers grew in the hanging walls of these listric faults, polymer trapped in the footwalls as salt rollers (Duval et al., 1992; Gaullier, 1993; Mauduit and Brun, 1998; Brun and Mauduit, 2009). The strike of these faults was parallel to the upslope polymer pinch-out that constrains the location of the peripheral faults (Fig. 6a). Extensional faults propagated basinward becoming younger downslope. Upslope regional

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extension was accommodated by downslope contraction developing incipient detachment folds

at the beginning of gravitational gliding. The growth of these folds was usually aborted by syn-

kinematic sedimentation that strengthens their roofs by thickening during early gravitational

gliding. After 3 hours, the outermost fold belt evolved to a simple thrust verging basinwards

above the downslope edge of the polymer layer that experience inflation by buttressing (Fig. 6a).

In contrast, the overburden of the intermediate translational domain was passively transported

downslope above the transparent polymer with no obvious visible deformation (Fig. 6a).

Models with seamounts

The structural style of the upslope extensional and downslope contractional domains of

models with seamounts is very similar to the baseline model (comparison of Figs. 6a and 6c).

Whereas different listric normal faults dipping basinwards formed upslope after 6 hours of

gravitational gliding, a detached fold belt evolving into a simple thrust developed downslope ~~in~~ at

the salt pinch-out (Fig. 6c). If gravitational gliding continues (e.g., models with 18 hours of

gravitational gliding, Fig. 6b), the extensional domain widens, with younger faults progressively

developing downslope. The increase of extensional deformation is balanced downslope by a

second thrust developed in a break-back sequence and by polymer inflation (Fig. 6b).

However, the main difference between models with and without a seamount is the

interruption of polymer flow by pre-salt reliefs. The kinematic evolution of the overburden in

models with a seamount clearly depends on the position of their summit lying below or above the

top salt at the beginning of the experiment. Thus, the seamount partially blocks salt flow when

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their summit lies below the top salt (Fig. 6b). In contrast, the salt flow is totally blocked when

the summit lies above the top salt (Fig. 6c). This entails the development of secondary structures

around the seamount that in the second case disrupts the continuity of the translational domain

(Fig. 6c). The following sections of the manuscript introduce the main structural elements as well

as the kinematic evolution of both cases.

Seamount does not fully block salt flow – summit lies below top salt

In the case whereby the seamount lies below top salt cover deformation is characterized by a

regional extensional-contractional system that continually glides basinwards throughout the

experiment (Fig. 6b). At the beginning of the gravitational failure, the seamount partially

opposed to polymer flow and hampered its drainage. Buttressing favored polymer inflation

upslope of the seamount slightly raising the top of the initial regional datum (Fig. 7a). Coeval

with polymer inflation, the development of a syncline downslope of the seamount occurred in

conjunction with the consequent thinning of the pure polymer layer (Fig. 7a). An incipient

collapse graben may develop during the early deformation at the crest of the anticline (Fig. 7b).

Syn-kinematic layers onlapped the pre-kinematic unit above the syncline and progressively

offlapped upslope of the seamount due to polymer inflation (Fig. 7a).

As the model evolved downdip polymer flow fed the anticline that was gradually translated

downdip (Fig. 7b). The interaction between the syn-kinematic sedimentation and the anticline

growth produced an erosive unconformity that climbed through younger syn-kinematic units.

Basinwards this unconformity evolved into a paracomformity (Fig. 7b). Taking into account that

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the seamount is fixed during the experiments, the upslope migration of syn-kinematic depocenters and onlaps (Fig. 7) indicates that the basin depocenter maintain a relatively fixed position during gravitational gliding. Thus, for the last stages of deformation, the syn-kinematic sand layers filling the syncline were deposited above uplifted areas previously located upslope of the seamount. This is noticed because older syn-kinematic layers where absent or pinched-out downslope against the unconformity (Fig. 7b).

Seamount fully blocks salt flow – summit lies above top salt

In this situation, the height of the seamount lying above top salt plays a key role in the regional structural style and the kinematic evolution of the model. In order to understand how is the temporal evolution when seamounts fully blocks salt flow, we used different models with the same initial setup but with different lengths (Table 1 and Fig. 8). The variation in the ratio between seamount height and top salt throughout the experiment highlights two distinct evolutionary stages.

During the first stage, the seamount locally interrupts the lateral continuity of the pure polymer layer and compartmentalizes the three-domain gravitational system into two extensional-contractional sub-systems (Figs. 6c, 8a and 9b to d). Updip extension was accommodated upslope of the seamount by polymer thickening and the development of a downdip-verging thrust (structure 1 in Fig. 8a). A "hanging-wall terrace" formed by the UU was preserved in the footwall of this thrust attached to the seamount. Thrust propagation uplifted the regional controlling the offlap terminations of the syn-kinematic layers in the backlimb of the hanging

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wall anticline (Fig. 8a). In contrast, a major listric normal fault rooted in the pure polymer flank (structure 2 in Fig. 8a) controlled the development of the basin. Thin-skinned extension triggered the rise of reactive ridges along the extensional faults of the basin (Vendeville and Jackson, 1992; Hudec and Jackson, 2011) (Figs. 8a, 9b to 9d and 10b). These ridges converged towards the central part of the basin leading to an active diapir (Fig. 9c). At the last stages of this first episode the pure polymer layer was continuous below the basin, being practically depleted below the hanging wall of the main extensional fault (structure 2 in Fig. 8a). This prevented the downdip flow of the pink layer (sand-polymer mixture). The forelimb of the hanging wall anticline above the seamount collapsed when the overburden reached the summit of the seamount at the end of this first stage. As a consequence debrites deposits were incorporated to the third syn-kinematic layer of the basin (greenish sand on Fig. 8a).

The second stage begins when top salt ride above the seamount and it was overthrusted by the upslope cover using the pure polymer as a detachment (Figs. 8b, 8c and 9e to 9h). At this point, the kinematics of the model dramatically changes and the two gravitational sub-systems are re-connected. The time sequence evolution of figures 8b and 8c shows how after re-connection the entire margin is translated downslope as a unique extensional-contractional system. As the model evolved, the structure around the seamount becomes much more complex with progressive overlap of the contractional and extensional zones downslope of the relief (Fig. 8b and 8c). Downslope of the seamount, the structural style dramatically changed after polymer depletion (Figs. 8b, 10b and 10f). This is the beginning of a gradual attenuation of the pre-existing structures (Fig. 9d to 9h). After welding, the basin was passively transported downslope above the main normal fault that initially developed attached to the downslope flank of the seamount (structure 2 in Fig. 8). Although the pink layer has a higher effective viscosity than pure

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polymer, the total depletion of the pure polymer triggered the flow of the sand-polymer mixture that   acted as a less efficient detachment (Figs. 8b, 8c, 10f and 10g).

The combined effect of cover overthrusting and welding also forced the development of a gravitationally linked contractional zone downslope of the seamount (Figs. 8b, 10b and 11). The structural style of this contractional zone results from the interaction between the height difference between the crest of the anticline above the seamount and the basin as well as from the syn-kinematic sedimentation rate. The most important height difference occurred during the early overthrusting and was coeval to the development of the first thrust and the maximum development of debrites (layers 3 and 4 of Fig. 11). The gradual height attenuation between the crest of the anticline and the adjacent basin during overthrusting resulted in a progressive reduction of the debrites volume (layers 5 and 6 of Fig. 11). The syn-kinematic sedimentation rate applied to our models aborted the growth of these folds and thrusts. A prominent angular unconformity developed as a result of the interaction between the growth of the gravitational linked contractional structures and the sedimentation rate (dashed lines in Figs. 8 and 11). The syn-kinematic layers of the basin onlapped against the partly eroded overthrusted syn-kinematic layers and the offlaps developed upslope of the seamount (Fig. 11).

DISCUSSION

What is the impact of a pre-salt seamount on the regional structure of a salt-bearing passive margin?

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The presence of linear pre-salt seamounts in a salt-bearing passive margin can modify the regional structure because seamounts interrupt the continuity of the evaporitic unit. Depending on the height differences between the seamount summit and the top of the viscous layer, this disruption can lead to significant changes in the classical structural zonation of such margins. Seamounts initially hinder salt drainage during early gravitational failure by acting as a passive buttress to flow. Our physical models show that when the summit of the seamount lies below top salt (experiments 1 and 1a, Table 1), the cover glides downslope as a unique extensional-contractional system encompassing an intermediate translational zone. The syn-kinematic units of the translational domain show significant thickness variations related to the development of a basin downslope of the seamount (Figs. 6b and 7). In contrast, two well-differentiated gravitational sub-systems with upslope extension and downslope contraction develop when the summit of the seamount is located near or above the top of the polymer layer (experiments 2 to 5, Table 1) (Fig. 6c). Here, the structural style of both pairs is slightly different. Although listric faults develop in the extensional domain of both sub-systems, these differ on number, spacing and slip (Fig. 6c). These differences are basically induced by the thickness of the pure polymer prior to the gravitational deformation (Fig. 6c) and the slope angle of the seamount flank (Figs. 8 and 12b, Table 1). Similarly, the dip of the thrusts developed upslope of the seamount is steeper that the thrusts related to the pure polymer downslope pinch-out (Fig. 6c). Here the main control factor is the relative height of the seamount summit above the top of the pure polymer at the beginning of the gravitational gliding. Both contractional sub-systems are extremely different for model 6 (Table 1, Fig. 12) in which the distance between the summit of the seamount and the top of the polymer does not allow cover overthrusting. As a result, buttressing produced by the

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upslope seamount flank enhanced the development of a backthrust with an associated piggy-back basin (Fig. 12).

How do seamounts affect the salt flow pattern during gravitational failure of the margin?

The experimental programme presented in this article depicts how a pre-salt relief hinders drainage of a viscous polymer induced by tilting. A contour map of the top of the pure polymer illustrates the zones where polymer was depleted or accumulated during gravitational gliding (Fig. 13a). It clearly shows how the polymer thickened upslope of the seamount before being able to flow over the summit and carries the roof with it as an overthrust (white blue colors above the black dashed line). This map also shows how a passive diapir developed downslope of the seamount (Fig. 13a). This diapir is surrounded by four welded basins separated by arcuate polymer ridges. The colored polymer plugs introduced in the pure polymer around the seamounts (Fig. 5a) allowed us to track the effect of the seamounts on polymer flow during gravitational gliding (Fig. 13). Depending on their location, these cylindrical markers were deformed in different ways. The outermost, located symmetrically at both ends of the seamount (blue and red markers with numbers 1, 5, 6 and 10 in Fig. 13b or blue polymer in Fig. 10a), were essentially deformed following straight trajectories parallel or slightly oblique to the regional dip direction. The top of these markers is the most seaward part of them, depicting a strong component of Couette flow related to the shearing of the pure polymer by downslope translation of the overburden (Fig. 10a).

In contrast, the polymer plugs around the seamount reveal a complex streamlines patterns and related flow velocities as suggested by areas of plug inflation and deflation (Fig. 13b). The deformation of the central blue marker located updip of the seamount is controlled by the

seamount height and the initial thickness of pure polymer. So, when the seamount summit lies above the top polymer (e.g., experiment 6, Fig. 12) the polymer cannot flow over it and the central marker deforms with a divergent flow pattern. Two horns with opposite streamline directions developed parallel to the seamount trend. These morphological variations imply significant variations in flow velocity that progressively decrease until the polymer reaches the summit of the seamount. An increase in flow velocity took place during overthrusting as a consequence of the progressive polymer thickening above the seamount. The yellow markers located upslope of the seamount (numbers 2 and 4 in Fig. 13b), show how the streamlines avoid the seamount using a curved trajectory or bypass. This divergent pattern considerably reduces the distance between streamlines, indicating an increase in flow velocity. Streamlines show a convergent pattern once the yellow markers surpass the seamount (Fig. 13). This is probably constrained by the development of the basin downslope of the seamount (Fig. 13b). On a different way, the sinking of the basin and the gravitational gliding stretched the three markers downslope of the seamount (numbers 6, 7 and 8 in Fig. 13). At the begining of gravitational gliding they show a marked Couette flow component (e.g., red marker on Fig. 7b). As gravitational gliding progressed, the polymer initially below the basin was expulsed downdip. The pressurized polymer moved towards the passive diapir – pressure release – showing a convergent streamlines trajectory. Figure 13b shows how the red markers followed the ridges between the welded areas to feed the central passive diapir. In the cross-section of figure 13c these red markers show a plume shape that reaches the surface of the diapir. The development of this plume was forced by the inward injection of the transparent polymer during the rise of the passive diapir (Dooley et al., 2009). Downslope of the diapir, the red markers show a divergent flow pattern following the ridges between the welded areas (Fig. 13b).

COMPARISON WITH THE LIGURO-PROVENÇAL BASIN

The gravitational system documented in our baseline model (Fig. 6a) is broadly similar to the geometries of the study area when seamounts are absent or their summit do not reaches the Messinian salt (Fig. 4a). In both cases, the salt unit is continuous and flows downdip. A set of listric normal faults dipping basinwards developed in the upper part of the margin (Gaullier, 1993; Gaullier et al., 1993; Reis et al., 2008) (Fig. 4a). Upslope extension is accommodated downslope by detachment folds and squeezed diapirs (Gaullier, 1993; Gaullier and Bellaiche, 1996; Reis et al., 2005 and 2008) (Fig. 4a). In between the practically undeformed overburden is gravitationally translated using the MU as a detachment (Gaullier, 1993; Reis et al., 2008) (Fig. 4a). Although the structural style of the extensional system is similar (Figs. 10b and 13a), the contractional system differs greatly between nature and the experiments (compare Figs. 4a and 6a). While detachment folds and squeezed diapirs are common in the Liguro-Provençal Basin (Fig. 4a), buckle folds were quickly aborted in our physical models evolving into different thrusts emplaced in a break-back sequence (Fig. 6b). The early detachment folds were buried due to the high sedimentation rate applied to our models developing a thick and strong overburden that inhibited folding. In contrast, thrust development is basically constrained by the downslope vertical edge of the salt basin, which acts as a nucleation point for the first thrust. However, in the Liguro-Provençal Basin, there is no downdip salt pinch-out, except towards the Balearic Islands and Corsica (Lofi et al., 2011a). Elsewhere, the salt layer is continuous from Marseille to Algiers (e.g., Gaullier and Bellaiche, 1996; Dos Reis et al., 2005; Lofi et al., 2011a).

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Our physical models predict that the presence of seamounts in the translational domain of the Liguro-Provençal Basin could significantly impact the margin architecture (Figs. 4b and 4c). The effect of seamounts on the margin deformation occurs at two different scales. At a regional scale, they could interrupt the continuity of the translational domain, resulting in the development of two gravitational sub-systems (Figs. 4b and 4c). In addition, they locally control the development of contractional and extensional structures upslope and downslope of the seamount respectively (Figs. 4b and c). The structural style of the upslope structures clearly differs between experiments and seismic data. Salt inflated areas (Fig. 4b) or asymmetric buckle folds (Fig. 4c) have been interpreted upslope seamounts in seismic profiles. In our experiments polymer inflates until it can flow over the seamount (Figs. 8a and 8b). Downdip-verging thrusts form in the overburden as the roof is carried over the pre-salt high. On the other hand, a backthrust develops when the salt inflated area upslope the seamount cannot reach the summit of the relief (experiment 6, Table 1, Fig. 12). Despite this, no thrust has been interpreted upslope of the seamounts in the studied dataset. Taking into account the limitations of 2D seismic for the characterization of complex tridimensional structures, the lack of thrusts may be related to several factors: 1) the amount of shortening (less than in our experiments); 2) the shape of the seamount (the buttressing for isolated circular seamounts may be small or non-existent); 3) the volume of salt available upslope of the seamounts; 4) the composition of the halite of the MU that could become less pure at the basin margin; or 5) the deformation rate of evaporites (slower for the Liguro-Provençal Basin due to progressive tilting but constant throughout our experiments).

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Additionally, the LU has been never sampled in the Liguro-Provençal Basin and its composition is speculative (clastic turbidites and resedimented gypsum, according to Roveri et al. 2001 and 2008). The approximation we have used as analogue of this unit is a material with a higher effective viscosity than pure polymer based on a mixture of sand and polymer (Callot et al., 2012). However, the experiments with a greater gravitational gliding clearly show that after pure polymer depletion, the weight of the basin triggered the deformation of this material (Figs. 8b and 8c). The seismic profiles studied in this project clearly show that the LU remains undeformed in the Liguro-Provençal Basin. This could be related to the mechanical properties of this unit, which are likely closer to a brittle behavior.

CONCLUSIONS

The presence of pre-salt relief in the form of a seamount can modify the three domain structural zonation of salt-bearing passive margins developing two gravitational sub-systems separated by the seamount. These are characterized by upslope extension and downslope contraction

The structural style and kinematics of both margin-wide and local structures may change during gravitational gliding if the amount of salt upslope of the seamount is sufficient to overtake the relief. Thus, depending on the seamount height with respect the top of the evaporitic unit, seamounts can act as temporary barriers during margin evolution, resulting in two different stages. During the first stage, the seamount initially hinders salt flow, forcing salt migration around the relief. As a consequence of the buttress upslope of the seamount, a thrust develops

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and gradually uplifts the cover. When the cover reaches the height of the relief, the seamount is

overthrusted, and falls rapidly downslope along the seamount flank. A significant increase in salt

flow velocity occurs coeval with overthrusting. The development of a primary weld below the

basin downslope of the seamount and the flow velocity decrease that occurs at the edge of the

seamount favors the formation of an fold and thrust system.

The seamounts hinder salt flow, forcing the development of a divergent pattern in the

polymer streamlines surrounding the relief during gravitational gliding. Streamlines deviation

also occur where there are diapirs allowing salt to escape vertically from beneath the basins. In

contrast, streamlines in areas without seamounts or diapirs describe dominantly linear traces

parallel to the dip direction of the passive margin.

The experimental results included in this manuscript provide a set of geometrical

constraints that can be used in seismic interpretation of similar structures in margins with pre-salt

seamounts (e.g., Eastern Mediterranean, Red Sea, offshore Morocco). Because the seismic

dataset available for the study area is 2D, analogue models also allow us to infer the three-

dimensional geometry of the supra-salt structures.

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Figure 1. Idealized sketch of a salt-bearing passive margin with a basinward-dipping salt detachment (purple polygon) (modified from Rowan *et al*., 2004). Gravity gliding and spreading of the salt layer trigger the failure of the cover, which is accommodated by upslope extension (listric faults) and downslope contraction (buckle folds) with a translational domain in between. The factors controlling the tilting of the detachment are the differential loading, the thermal subsidence and the tectonic uplift.

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Figure 2. Simplified structural map of the Northwestern Mediterranean Basin and surrounding Mediterranean areas (modified from Roca, 2001). Yellow lines indicate the location of the geoseismic sections shown in Figures 3 and 4.

Figure 3. Line-drawing across the central part of the northwestern margin of the Liguro-Provençal Basin (southeast of the Gulf of Lions) showing the structure and the sedimentary architecture of the basin infill (modified from Lofi *et al*., 2011b after Bache *et al*., 2009). See location in Figure 2.

Figure 4. Geoseismic sections across the toe of the northwestern part of the Liguro-Provençal Basin highlighting the gravitational failure structure around three pre-Messinian seamounts (vertical scale in TWTT, see location in Figure 2). They clearly illustrate how the structure of supra-salt units changes depending on the height and the slope of the flanks of pre-salt seamounts. a) Geoseismic section across a seamount with the summit located below the top of the Messinian salt that consequently did not affect the gravitational failure of the margin; b) Geoseismic section across a seamount with the summit located slightly above the top of the Messinian salt, and c) Geoseismic section across a much taller seamount with the summit that crops out on the seafloor. Note that the geometry of the reflectors in figures 4a, 4b and 4c is congruent with that of the structures depicted in our analogue models 3 (Fig. 8b) and 6 (Fig. 13b) respectively.

Figure 5. Experimental setup with the terminology used in the description of the models. a) Top-view sketch of the experimental setup with the location of the seamount and the different upslope pinch-out and downslope edge of the analogue evaporitic units; b) Longitudinal cross-section sketch of the setup before deformation (the height of the plasticine seamount "h" changes in our

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experimental programme; see Table 1); and c) Experimental stratigraphy with the strength curve

and equivalence with the sedimentary ifill in the deep Liguro-Provençal Basin.

Figure 6. Comparison between the main structural elements developed by gravitational gliding

at the end of the deformation in a cross-section of the experiment without a seamount

(experiment 0, Table 1) (a); in a cross-section of the experiment 1a cutting a seamount with the

summit located inside the pure polymer layer (b); and (c) in a cross-section of experiment 4

(Table 1) that cuts a seamount with the summit located above the top of the pure polymer layer.

LU: Mixed pink polymer and sand (50% by volume) representing the Messinian Lower Unit;

MU: pure transparent polymer that simulates de Messinian Mobile Unit.

Figure 7. Detailed cross-sections showing the main structures developed around the seamount

during gravitational gliding when the summit is initially located inside the pure polymer layer. a)

Cross-section of experiment 1 (Table 1) after 6 hours of gravitational gliding, b) cross-section of

experiment 1a (Table 1) after 18 hours of gravitational gliding. Note that the pure polymer layer

shows thickness variations, whereas the pink layer (mixture of sand and polymer) does not show

any deformation.

Figure 8. Detailed cross-sections showing the main structures developed around the seamount

during gravitational gliding before (a) and after (b and c) polymer overthrusting. a) Cross-section

of experiment 4 after 6 hours of gravitational gliding, b) Cross-section of experiment 3 after 18

hours of gravitational gliding, and c) Cross-section of experiment 7 after 34 hours of

gravitational gliding. Note that in Figures 7b and 7c, the pink layer (mixture of sand and

polymer) appears deformed downslope of the seamount, where it is thinner beneath the welded

areas and thicker in the adjacent inflated areas.

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Figure 9. a to h) Top view pictures draped over the colored relief surfaces created from the corresponding topography point cloud from the beginning (t_0) to the end (t_{16}) of experiment 3; i) Evolution of the topography along the cross-section a-a' during experiment 3 between t_0 to t_{16}. The figures show two evolutionary stages: the first one between t_0 and t_4, characterized by the progressive rising of the polymer and overlying cover above the upslope flank of the seamount and the presence of two extensional-contractional pairs separated by the seamount; and the second one between t_6 and t_{16} in which the previously rising polymer overthrusts the seamount and begins to slide down on the downslope seamount flank forming a gravitationally linked fold and thrust system. During this second stage the two extensional-contractional pairs are reconnected.

Figure 10. Slices of experiment 3 made from a 3D voxel that used the final serial sections as a seed to interpolate sections in every direction (see Dooley *et al.*, 2009). a and b) Inlines that correspond to real end sections; c) Interpolated depth slice; and d, e, f and g) Interpolated crosslines. The location of each section is shown in different colors in each image (inlines in blue; crosslines in purple; and depth slice in yellow). Blue, red and green colors inside the pure polymer correspond to the deformed polymer color plugs.

Figure 11. Detail of a cross-section of experiment 3 showing the structure of the downslope flank of the seamount after 18 hours of gravitational gliding and its correlation with the proposed evolutionary stagesThe development of debrites is highlighted during the progressive rising of the polymer at the upslope flank of the seamount and during the overthrusting coeval with the development of the erosive unconformity. Debrite deposits decrease progressively through time, disappearing with the deposition of layer 6.

Figure 12. Top-view photograph (a) and longitudinal cross-section (b) showing the main structural elements related to the highest seamount (experiment 6, Table 1). The overhead photograph was taken after 4 hours of gravitational gliding and prior to the deposition of the upper red layer in Fig. 12b.

Figure 13. a) Contour map of the top of the pure polymer at the end of experiment 3. The reference datum of this map (0 value) is the top of the last syn-kinematic sand layer (see Fig. 8b). b) The top view of the pure polymer layer in model 3 at the end of the experiment shows the effect of the seamount on the pure polymer flow and on the deformation of the colored polymer plugs. Welds, diapirs and the final shape of the polymer plugs were reconstructed by digitizing their position and edges on different depth slices (i.e., in the depth slice represented in Figure 10c). c) Interpreted cross-section through the seamount showing the shape of two polymer plugs (purple and yellow) at the end of model 3.

Table 1. Main experimental parameters for the physical models described in this article. [*] The slope angle corresponds to the value of the average angle of the seamount flanks.

Table 2. Scaling parameters used in the experimental program presented in this study.

Table 1. Experimental program

Experiment	Seamount height (mm)	Slope angle*	Time (hours)
Exp._0	no seamount	-	6
Exp._1	21	23º	6
Exp._1a	21	23º	18
Exp._2	28	29º	18
Exp._3	35	35º	18
Exp._4	35	35º	6
Exp._5	45	42º	6
Exp._6	55	48º	6
Exp._7	35	35º	34

* Average slope angle of seamount flanks

Table 2. Scaling parameters used in the experimental program

Quantity	Experiment	Nature	Ratio
Thickness			
Overburden	5-30 mm	300 m - 2 km	1.6×10^{-5}-1.5×10^{-5}
Upper Messinian Unit	6 mm	500 - 600 m	1.09×10^{-5}
Mobile Messinian Unit	10 mm	0 - 3 km	1.8×10^{-5}
Lower Messinian Unit	5 mm	400 - 500 m	1.1×10^{-5}
Density			
Overburden	1500 kg m^{-3}	2.300 kg m^{-3}	0.65
Upper Messinian Unit	1500 kg m^{-3}	2.600 kg m^{-3}	0.57
Mobile Messinian Unit	972 kg m^{-3}	2.200 kg m^{-3}	0.46
Lower Messinian Unit	1550 kg m^{-3}	2.600 kg m^{-3}	0.59
Density contrast			
UU / MU	528	500	1.05
MU / LU	578	500	1.56
Ductile layer viscosity			
Mobile Messinian Unit	1.6×10^{-4} Pa s *	10^{-18}-10^{-19} Pa s	1.6×10^{-14}-1.6×10^{-15} Pa s
Lower Messinian Unit	3.34×10^{-4} Pa s *	unkown	--
Overburden coefficient of internal friction	0.69	0.8	0.86
Gravity acceleration	9.81 m.s^{-2}	9.81 m.s^{-2}	1

* Viscosity measured when deformed at a laboratory strain rate of 1.83×10^{-4} cm s^{-1}

Figure 1

Figure 2

Interpretation

Figure 3

Figure 4

a) Experimental setup plan view without Messinian analogues
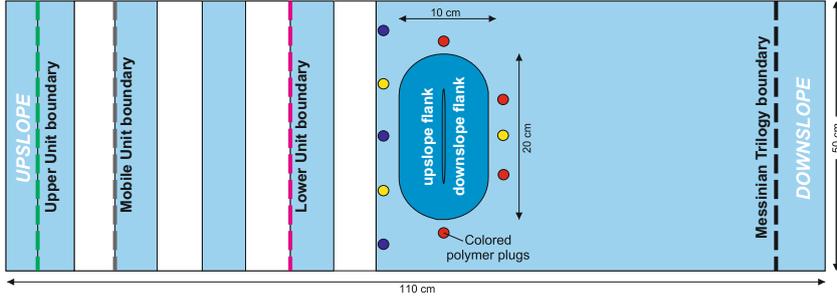
b) Experimental setup section view
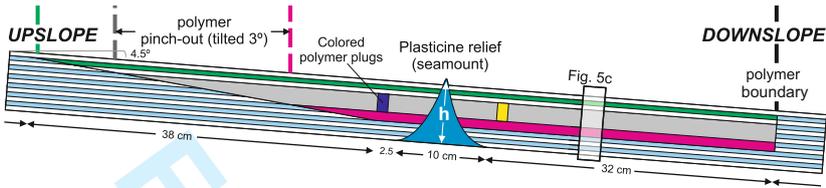
c) Seismic and experimental stratigraphy
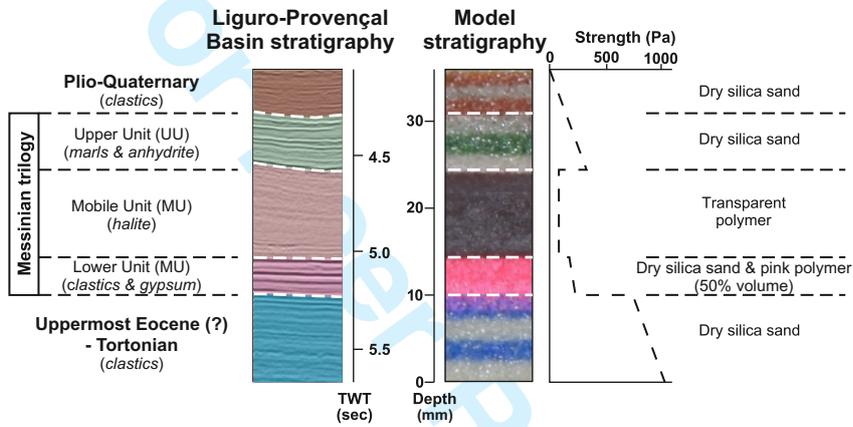
Figure 5

a) Gravitational failure geometry without seamount (baseline model - Exp. 0)
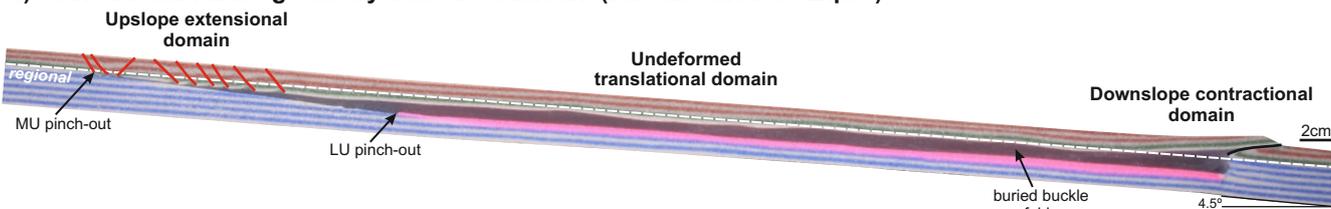
b) Gravitational failure geometry with seamount summit inside the pure polymer layer (Exp. 1a)
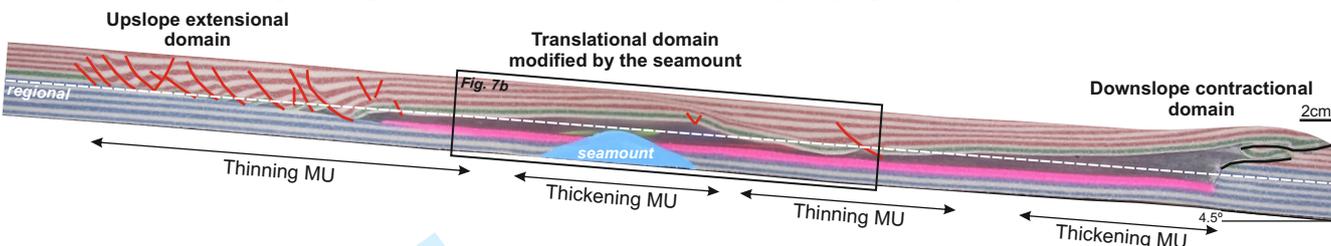
c) Gravitational failure geometry with seamount summit above the pure polymer layer (Exp. 4)
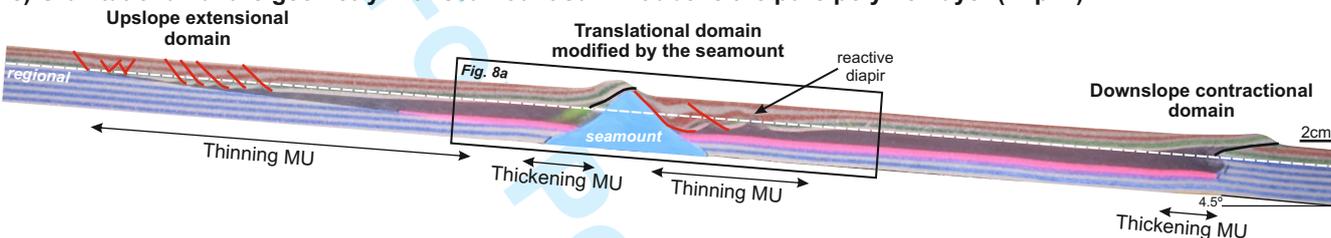
Figure 6

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a) Seamount detail after 6 hours of gravitational failure (Exp. 1)

UPSLOPE

Contractional deformation

offlap

Extensional deformation

DOWNSLOPE

Regional

onlap

①

seamount

2cm

4.5°

17
18
19
20
21
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b) Seamount detail after 18 hours of gravitational failure (Exp. 1a)

UPSLOPE

Contractional deformation

offlap

Extensional deformation

DOWNSLOPE

Regional

aborted crestal-
collapse graben

onlap

①

seamount

2cm

4.5°

Extensional faults   Syn-kinematic unconformity

①   Equivalent structures in both cross-sections

Figure 7

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a) Seamount detail after 6 hours of gravitational failure (Exp. 4)
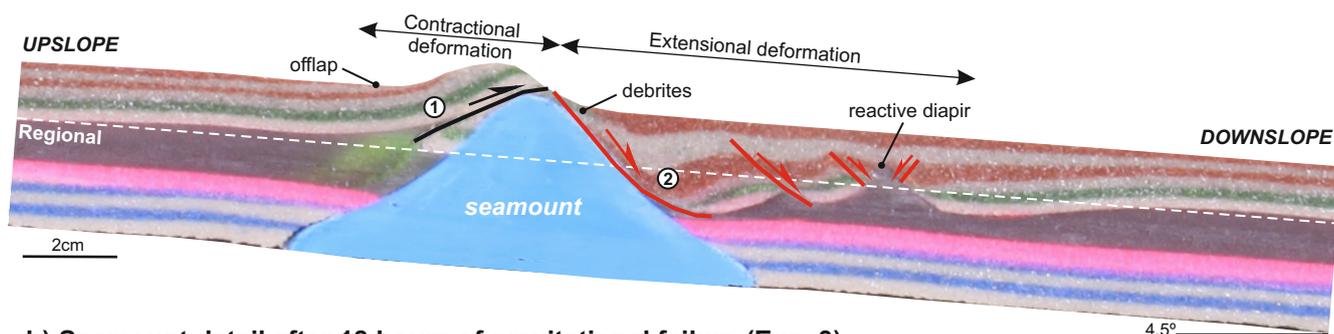
b) Seamount detail after 18 hours of gravitational failure (Exp. 3)
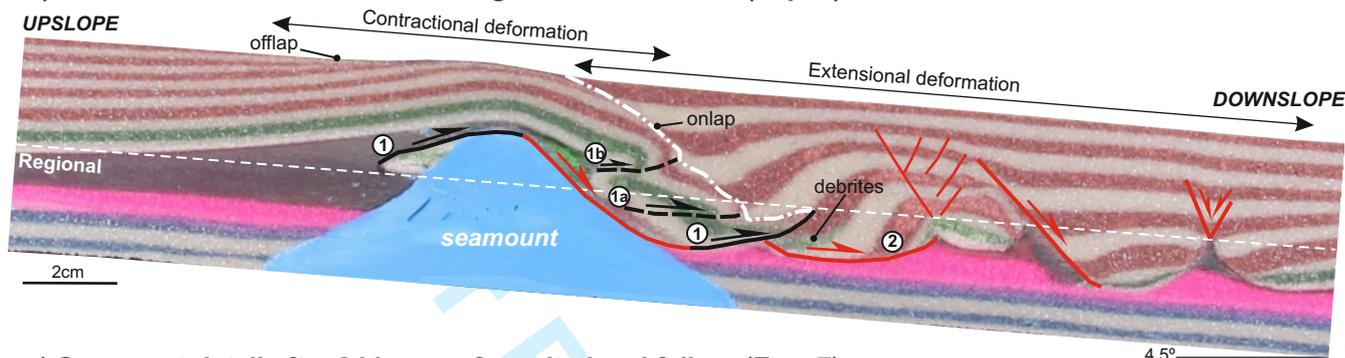
c) Seamount detail after 34 hours of gravitational failure (Exp. 7)
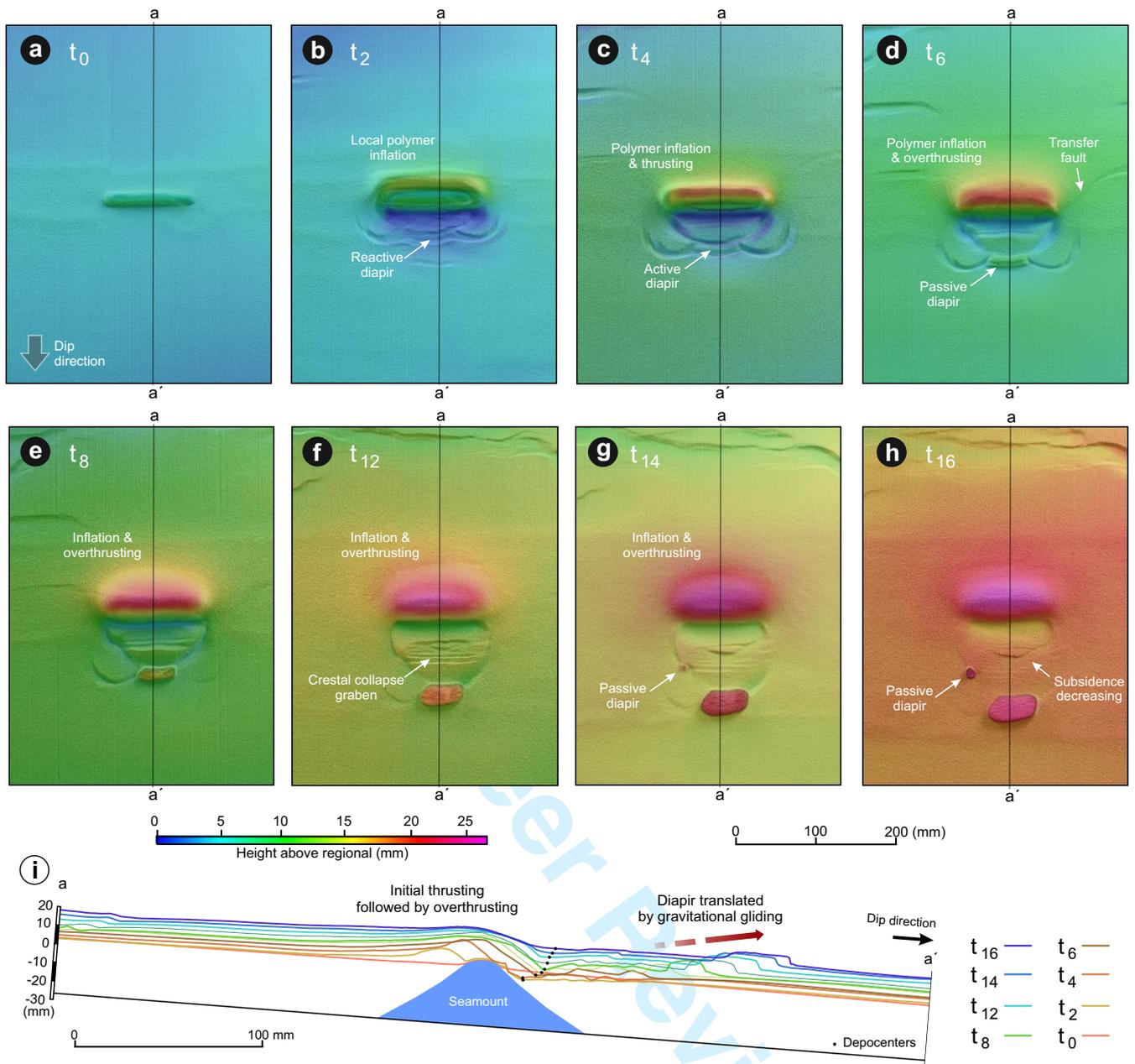
Figure 8

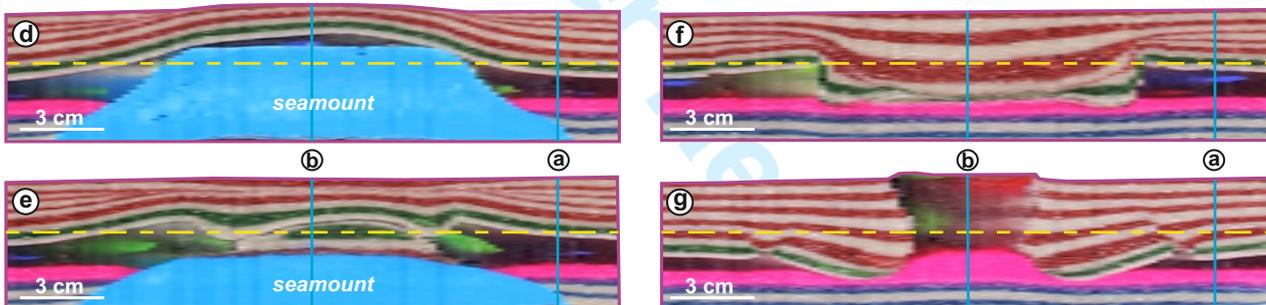Figure 9

Inlines
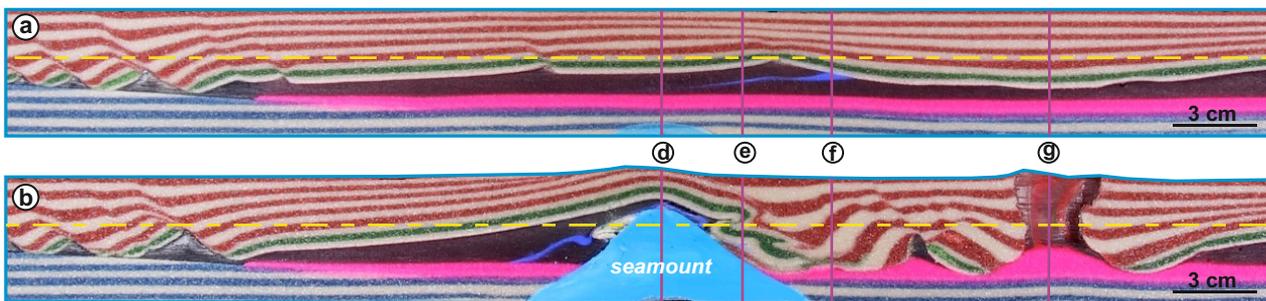
Depth slice
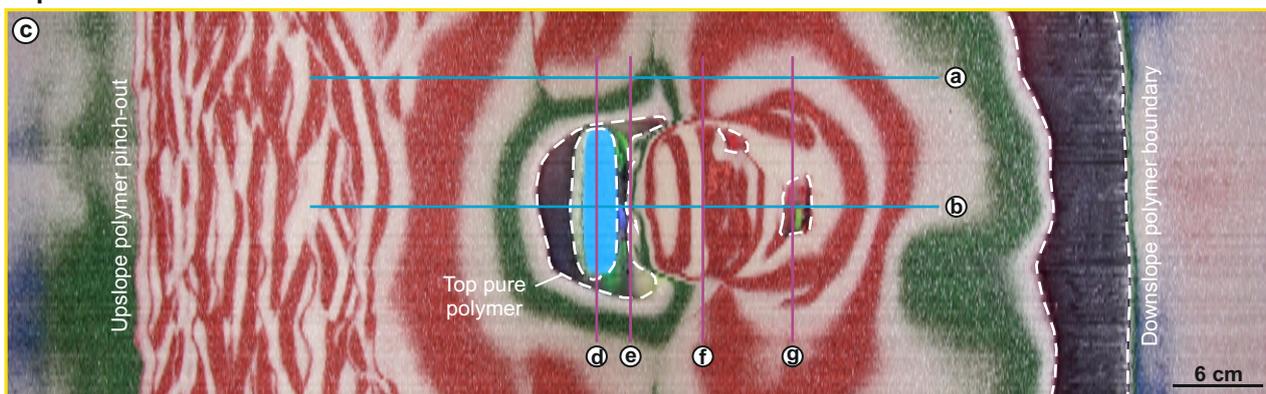
Crosslines

Figure 10

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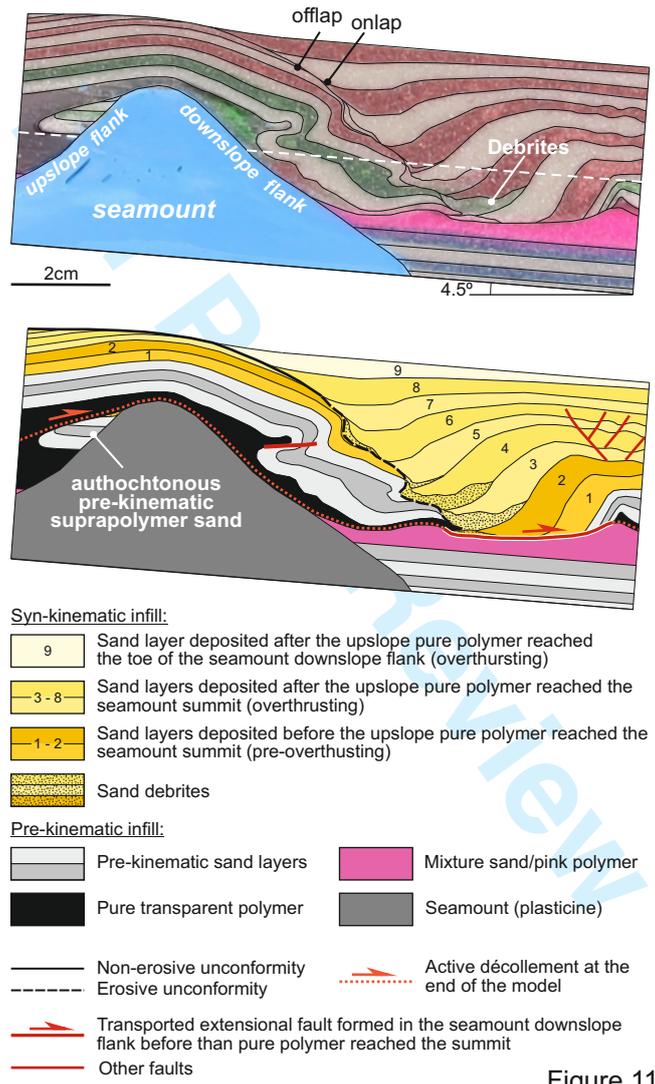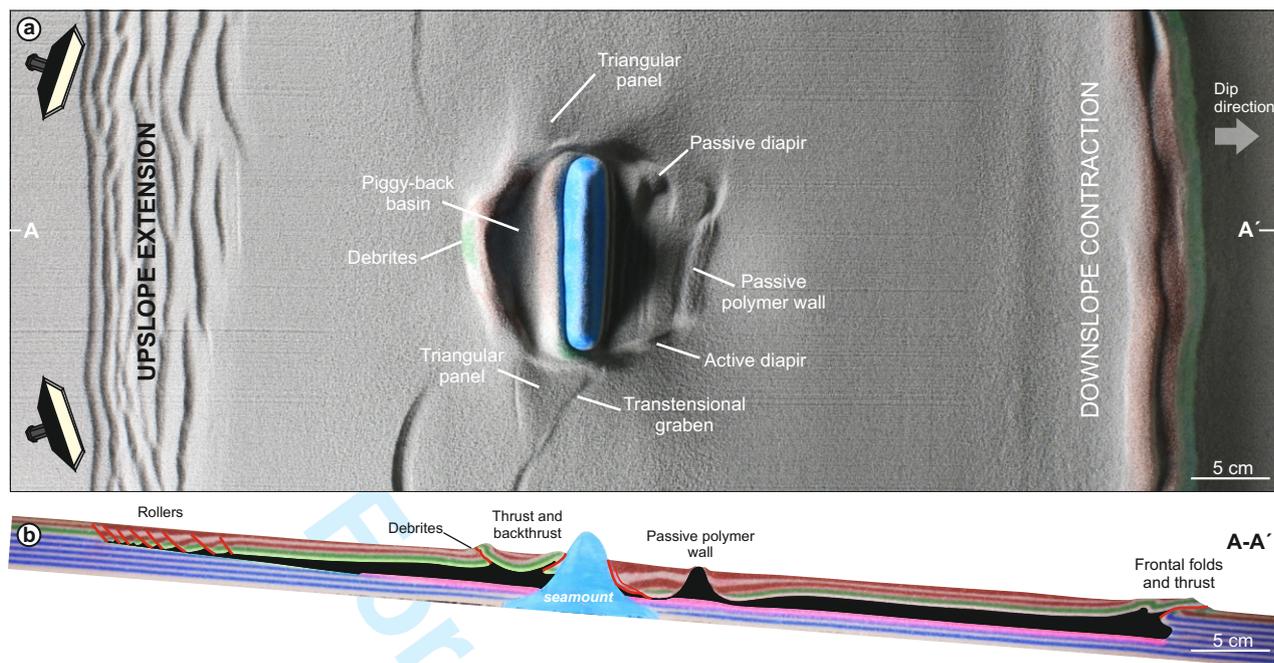39
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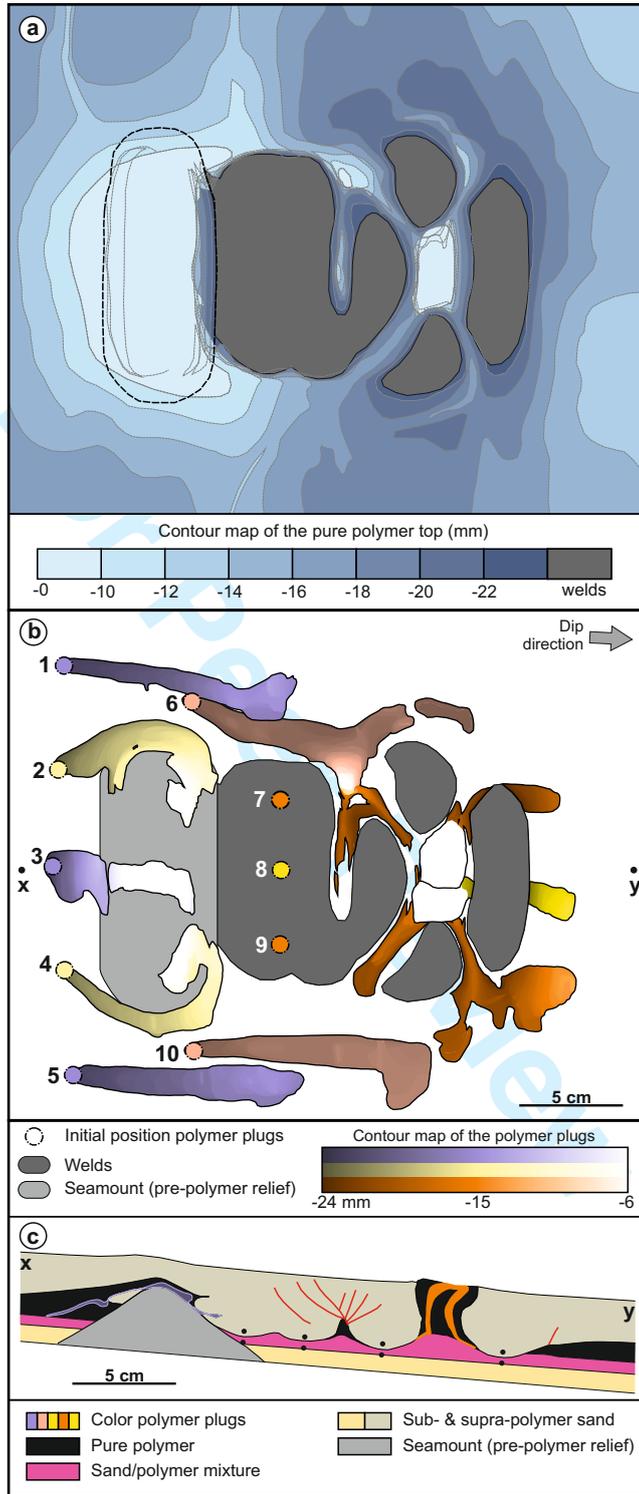41
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Figure 11

Figure 12

Figure 13