Geophysical Research Letters®

RESEARCH LETTER
10.1029/2021GL094922

Key Points:

- A shallow-sourced, early-burial mud diapir is documented in a deformed foredeep slope
- Required overpressure formed via lateral pressure transfer within shallow low-permeable units, a modality previously undocumented
- The overpressure favored both slope instability and mud intrusion in a mutually related process

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:
D. Oppo,
davide.oppo@louisiana.edu

Citation:
Oppo, D., Capozzi, R., Tingay, M., & Marabini, S. (2021). Early burial mud diapirism: Lateral overpressure transfer and slope failure in a deformed foredeep. *Geophysical Research Letters*, *48*, e2021GL094922. https://doi.org/10.1029/2021GL094922

Received 24 JUN 2021
Accepted 8 SEP 2021

Early Burial Mud Diapirism: Lateral Overpressure Transfer and Slope Failure in a Deformed Foredeep

Davide Oppo[1], Rossella Capozzi[2], Mark Tingay[3], and Stefano Marabini[2]

[1]Sedimentary Basins Research Group, The University of Louisiana at Lafayette, Lafayette, LA, USA, [2]BiGEA, University of Bologna, Bologna, Italy, [3]The University of Adelaide, Adelaide, SA, Australia

Abstract

Understanding triggers and evolution of post-depositional sediment intrusion is of major importance to decrease the risk associated with hazards to infrastructure and environment from events such as submarine landslides and fluid escape. Whereas deep-sourced intrusions (>1 km) are widely documented, early burial examples are poorly recognized and have been described only in large deltas. Their formation had not yet been documented in deformed foredeeps. Here, we show an exceptionally well-exposed, early burial mud diapir in the Northern Apennines fold and thrust belt. Disequilibrium compaction and tectonic basin tilt led to lateral pressure migration within shallow (<200 m) sediments. As a result, near-lithostatic overpressure developed at the basin margin causing sediment intrusion and destabilization of the slope. This work shows that early burial mud diapirs can develop in deformed foredeeps with similar characteristics to their deep-rooted counterparts, with important implications for hazard assessment in areas non-traditionally prone to shallow overpressure buildup.

Plain Language Summary

Unconsolidated mud can pierce the overlying sediments in a mechanism called mud diapirism. This process is associated with elevated pressure in the subsurface, which can be a relevant hazard for infrastructures and human society. The mud is most commonly sourced at great depth and shallow sourced mud diapirs, defined "early burial," were undocumented outside large river deltas. Here, we describe the first example of early burial mud diapirism in a different geological setting. The overpressure necessary for the mud diapir formation was generated by the lateral transfer of pressure along sedimentary strata. The lateral pressure transfer usually occurs in permeable sandstones, but we infer that here it occurred within low-permeability sediments. This modality of lateral transfer has not been described before and has potential implications for predicting overpressure in areas not commonly affected by this phenomenon.

1. Introduction

Post-depositional sediment intrusion is a significant hazard associated with subsurface overpressure, methane release, hydrodynamic perturbations, and slope failure (Mazzini & Etiope, 2017). Sediment intrusion and its extrusion at the surface may have a profound impact on nearby ecosystems (Judd & Hovland, 2007), depositional environment (Blanchard et al., 2018), anthropic activities, and human society (Davies et al., 2011). The large-scale intrusion of deeply buried sediments is commonly imaged in reflection seismic data (e.g., Capozzi et al., 2012), and it is documented in a few outcrops (e.g., Barreca, 2014; Oppo & Capozzi, 2016). The high-magnitude overpressure responsible for the intrusion commonly generates at depth (i.e., >1 km) and may move updip for tens of kilometers via highly permeable units (i.e., sandstones) or faults/fractures by processes such as lateral or vertical pressure transfer (Oppo et al., 2021; Reilly & Flemings, 2010; Tingay et al., 2007; Traugott & Heppard, 1994). These transfers create shallower areas of high overpressure, potentially leading to early burial mud diapirs when conditions suitable for hydrofracturing are met (Morley et al., 2008).

Our knowledge of early burial mud diapirism (i.e., with source <200 m deep) and its implications is limited by the sparsity of records. Early burial mud diapirs have been documented only within deltaic sediments (Blanchard et al., 2018; Morgan et al., 1968), where they form by reactive rise (i.e., along faults) and downbuilding (i.e., passive growth), thus excluding any active diapirism driven by near-lithostatic overpressure. Therefore, the exact nature of early burial mud diapirs and the factors governing the associated shallow overpressure are poorly constrained, particularly in compressive geodynamic settings.

Here, we document the unprecedented outcrop of an early burial mud diapir formed within foredeep units deformed in the Northern Apennines (Italy) fold and thrust belt. We then reconstruct the lateral transfer of overpressure within low-permeability, shallowly buried (<200 m) mudstones. The exceptional exposure of the entire sedimentary succession, from the diapir source to its complete overburden, provides precise temporal and stratigraphic constraints for these processes. This example offers essential, high-resolution information on pressure-driven sediment intrusion. It also links shallow fluid and sediment dynamics to the equivalent deep-rooted (>1 km) processes occurring in analogous tectonic settings, which are, instead, widely studied but less directly constrained (Huuse et al., 2010 and references therein).

2. Regional Setting

From the Messinian to the Pliocene, NE-verging compressive tectonics associated with the collision between Europe and Africa plates controlled the Northern Apennines architecture (Barchi et al., 2001). The resulting deformation generated a complex morphology, with ramp anticlines and intervening troughs (Ghielmi et al., 2010). These troughs developed as satellite basins, one of which, the Samoggia, hosts the Rio Albonello mud diapir (Figure 1). The Samoggia is confined to the South by a late Miocene blind thrust which creates a large wavelength structural flexure in the Miocene foredeep deposits (Figure S1). To the NE, the basin is limited by the Marzeno high, deformed from the Messinian through the Pliocene (Figure 1). The Marzeno high plunges to the NW and is buried under upper Pliocene to Pleistocene sedimentary units. The Samoggia basin experienced a phase of structural rearrangement since the late Zanclean due to the shortening at the Marzeno ramp (Capozzi & Picotti, 2003). This structural rearrangement was associated with the regional shortening of deeper Mesozoic units, which ultimately caused the northward tilting and steepening of the Samoggia basin (Picotti & Pazzaglia, 2008).

3. Stratigraphic Record

By using standard techniques for field survey and foraminifera biostratigraphy, integrated with the interpretation of reflection seismic and well logs (Supplemental Material), we reconstructed the stratigraphic setting of the Samoggia basin. Five stratigraphic sections show the basin stratigraphy of the units involved in and deformed by the mud diapir (Figure S3).

We identified seven units (U1-U7) involved in the intrusion (Figure 2). The basin hosts up to 1 km of prevailing mudstones belonging to the Argille Azzurre (AA) Fm., deposited in a tectonic slope setting during the Plio-Pleistocene. Their Zanclean interval (U1) deposited relatively fast (c. 604 m/My). The topmost 100 m of U1 host bulbous carbonate concretions up to 2 m in diameter (Figure 2d). The δ^{13}C of the carbonate cement (high-Mg calcite and dolomite) ranges from c. −27‰ to −15‰ and is characteristic of methane-derived authigenic carbonates, analogously to similar concretions along the Northern Apennines (Capozzi et al., 2017; Oppo et al., 2017; Viola et al., 2015). The AA Fm. sedimentation is interrupted in the early Piacenzian by sand sheets and interbedded mud (U2), and by two well-bedded, up to c. 200 m thick, dominantly calcarenite intervals locally named Spungone Mb. (U3-5, lower and upper, respectively; Figure 1c). The Spungone Mb. filled the Samoggia basin at a rate of c. 415 m/My following the onset of a carbonate factory on top of the Marzeno structural high (Figure 1c; Capozzi & Picotti, 2003). After the Spungone Mb., the AA Fm. resumed deposition in the basin with sandy mudstones (Figure 2). A more recent (2.87 Ma) AA Fm. interval (U6) overlies undeformed U1 to U5 stratigraphy and hosts allochthonous olistoliths of U5 (up to 10 m in diameter) downslope to the mud intrusion (U7; Figure 2c).

4. Evidence of Sediment Intrusion and Destabilization

The exposed, present-day mud diapir originates from U1 mudstones (top 40 m cropping out) and pierces 10 m thick U2 sandstones and 28 m of U3 Spungone Mb. It thus extends vertically for 78 m. Whereas U1 cropping out nearby the mud diapir is massive and chaotic, it shows bedding away from the intrusion. The overlying U2 sandstones display tensional features and partial remobilization recorded by boudinage and dispersed strata blocks (Figure 3c). The mud intrusion (U7) folded upwards U3, which is also displaced by small reverse faults (up to 5 m throw) caused by the vertical and lateral mud intrusion at the U2-U3 contact

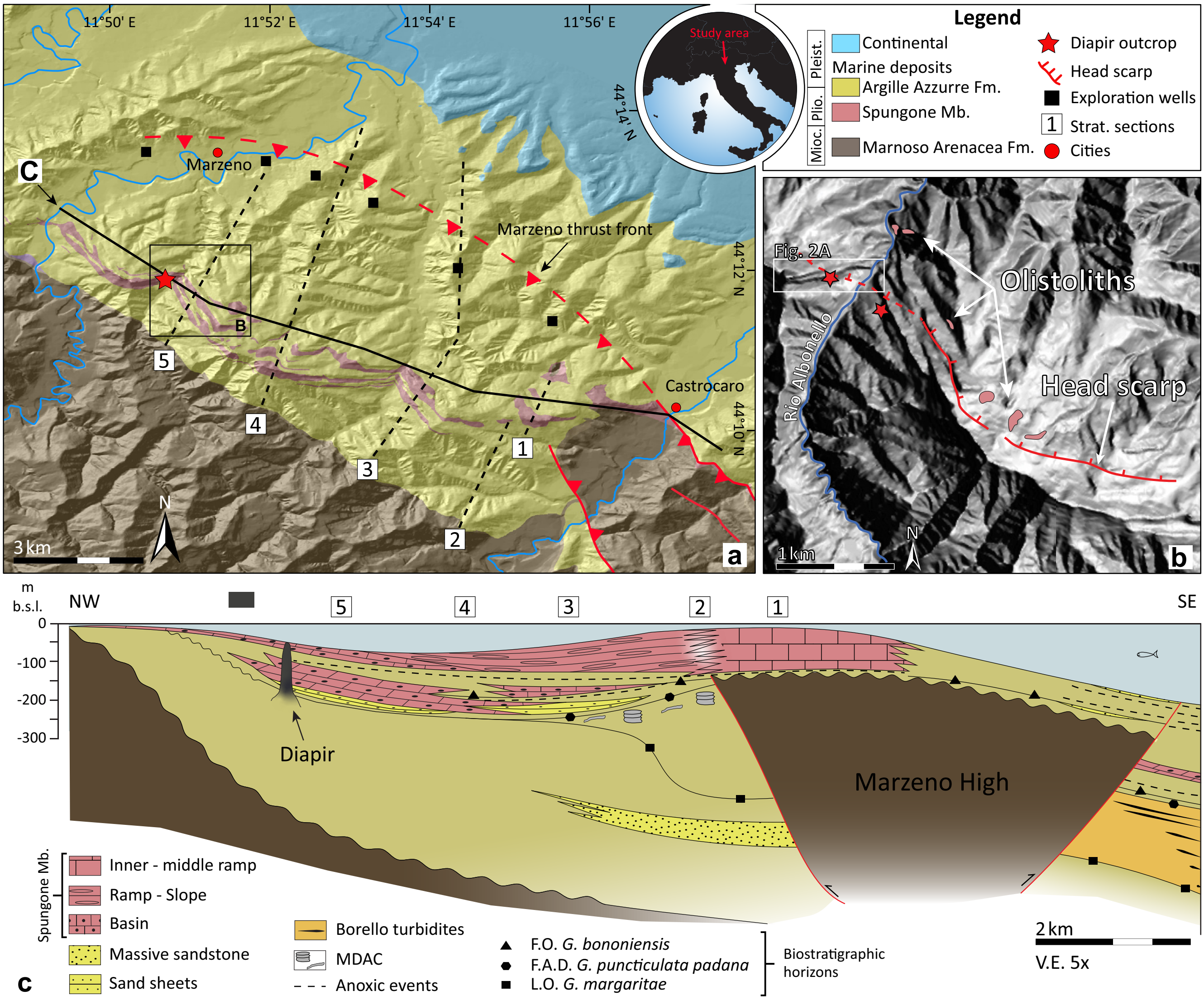

Figure 1. (a) Geological map of the Samoggia basin showing the mud diapir's location. The sampled stratigraphic sections (Figure S3) are indicated. Geology and topography are modified from Regione Emilia-Romagna maps (https://geo.regione.emilia-romagna.it/). (b) Closeup view of the Rio Albonello area showing the mud diapir (red stars), head scarp (barbed line) outcrops, and largest Spungone Mb. olistoliths. (c) Section across strike the Samoggia basin depicting its setting at 2.87 Ma, time of the mud diapir intrusion, along with the location of stratigraphic sections and main biostratigraphic events. Diapir not to scale.

(Figure 3a). The eroded top of the mud diapir is cropping out where U4-5, which are unaltered updip, abruptly end (Figure 3). This end coincides with a scarp (Figure 1b), suggesting the post-depositional removal of U4-5. Because of regional uplift, no units younger than U5 were deposited in the mud diapir area. The complete U2-5 succession, cropping out immediately updip to the mud diapir, shows that the intrusion formed when U1 was buried by up to c. 100 m of overburden (Figure 1c).

The scarp borders the up-slope side of an area extending a few hundred meters downslope the diapir, where the top part of U3 and the overlying units are missing (Figure 2b). In this area, slumped mudstones overlie U3 and contain *G Bononiensis* (Piacenzian) and reworked *G. Puncticulata*, the biostratigraphic marker of the late Zanclean U1 (Figure S3). Older markers of Zanclean age are absent. Despite the true base of the mud diapir is not exposed, this evidence suggests that only the top c. 100 m of U1 remobilized vertically in the intrusion.

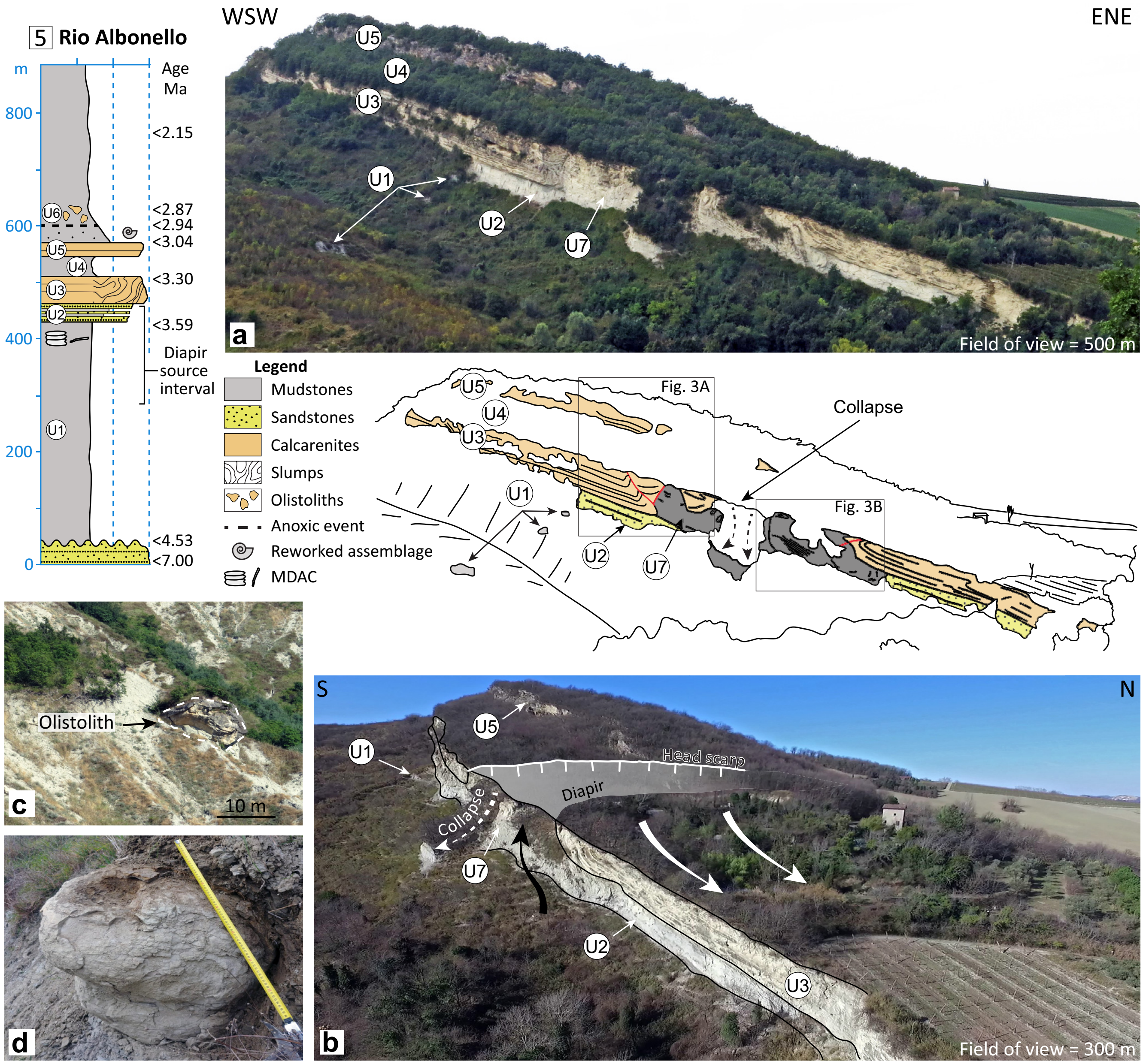

Figure 2. Stratigraphic log, aerial images, and interpretation of the outcrop on the western side of Rio Albonello valley (WGS84, 44.197466°N, 11.841907°E). (a) Gray mudstones (U1) at the outcrop base are the mud diapir (U7) source unit. View from SE. (b) A head scarp marks the abrupt truncation of U4-5 above and downslope of the mud diapir. View from the East. (c) Upper Spungone Mb. (U5) olistolith within U6. (d) Carbonate concretion within the uppermost U1 (tape is 1 m).

The mud diapir crops out on both sides of the Rio Albonello valley, with unchanged characteristics (Figure S5). This similarity suggests that the intrusion develops as a dike-like structure with an E-W strike, for a length of at least c. 400 m (the valley width).

5. Overpressure Build Up

Sediment intrusion is often caused by the build up of near-lithostatic overpressure and resultant hydrofracturing. At Rio Albonello, we exclude the vertical transfer of overpressure from fluid migration via faults as none occurs in the mud diapir area (Figures 1 and S1). Additionally, regional compression (i.e., horizontal loading) is not regarded as a significant cause of overpressure in the basin because it is improbable to occur

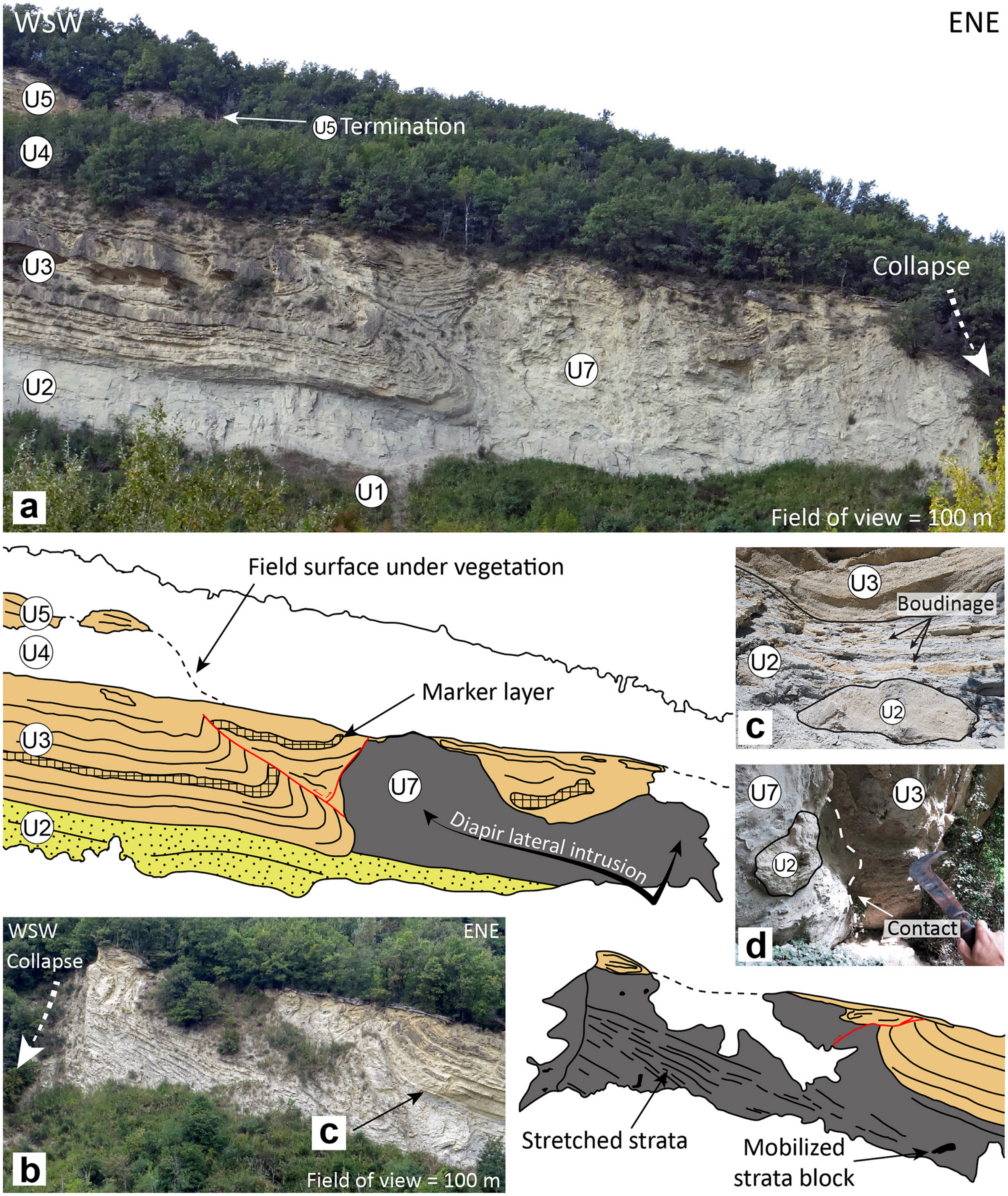

Figure 3. (a, b) Details of the deformation associated with the mud diapir intrusion in the western Rio Albonello valley. Locations in Figure 2. (c) Boudinage of sandstone beds and mobilized block within U2 mudstones. (d) Vertical contact between intruded mud (U7) and the pierced calcarenites (U3). A block of remobilized U2 is shown.

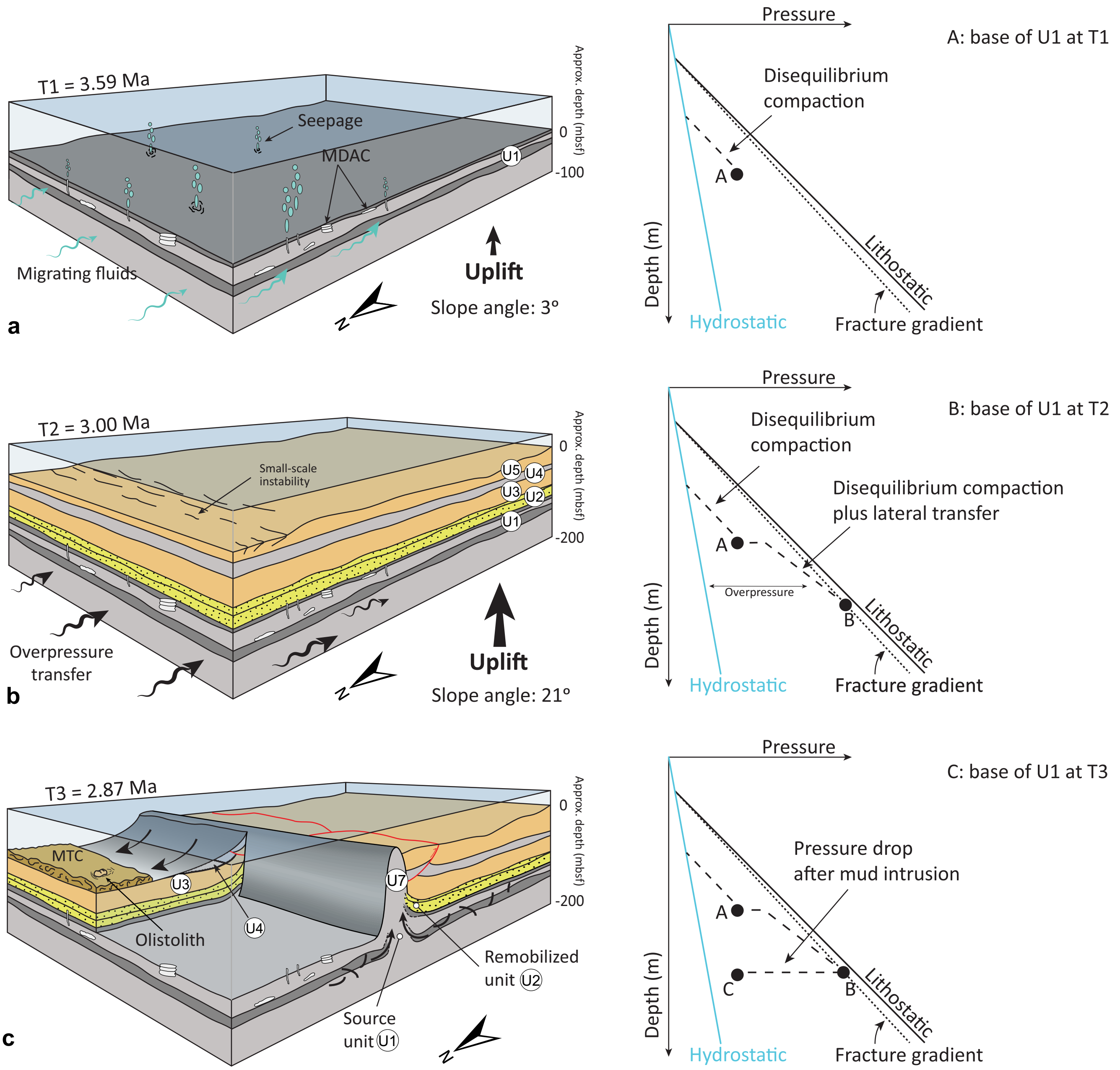

Figure 4. History of fluid migration in the Samoggia basin with schematic pressure-depth plots. (a) 3.59 Ma: methane migration resulted in diffuse seafloor seepage with the formation of methane-derived carbonates; (b) 3.00 Ma: methane seepage ceased with the deposition of U2 sandstones and the overlying U3-5 units. Increased basin tilt led to small-scale slope destabilization, while lateral migration focused overpressure toward the basin margin; (c) 2.87 Ma: overpressure reached near-lithostatic values, leading to the mud diapir formation and the collapse of the already unstable slope.

in shallow and underconsolidated sequences, such as those involved in the intrusion. Instead, the carbonate concretions within U1 provide firm evidence for an active, along strata fluid migration system and associated lateral transfer of overpressure in the Samoggia basin (Figure 4a).

Since the late Zanclean, basin tilt favored pressure buildup and fluid escape from the forming, and still poorly sealed, Marzeno ramp anticline. The basin asymmetry promoted updip fluid migration from the NE, according to the maximum tilt of the deformation front, and laterally from the SE sector of the Marzeno ramp. During this period, recently generated microbial methane possibly mixed with minor amounts of thermogenic hydrocarbons sourced from deeper foredeep units (Figure 1c; Oppo et al., 2017). However, the low content of organic matter and its dilution within the thick AA Fm. (Capozzi & Picotti, 2003) account for reduced methane volume and, thus, reduced potential to generate the overpressure. A different, more impactful, overpressure generating mechanism is necessary.

Disequilibrium compaction is the most common cause of elevated fluid overpressure within rapidly deposited mudstones (Osborne & Swarbrick, 1997). Disequilibrium compaction is mainly documented in deltas, where it causes early burial mud diapirism (Blanchard et al., 2018; Morgan et al., 1968). Less frequently, it occurs within syntectonic sediments of foreland basins, such as the Northern Apennines (Obradors-Prats et al., 2017). In the Samoggia basin, the rapid deposition of U1 mudstones led to disequilibrium compaction and overpressure. However, the mud diapir's location near the edge of the basin where U1 thins and is less buried limited the overpressure magnitude. Thus, an additional mechanism was responsible for increasing the overpressure to the near-lithostatic levels needed for the intrusion.

5.1. Transfer of Shallow Overpressure

Inclined units can be responsible for the local enhancement of pore pressure at structural crests or at basin margins, where they impose overpressure conditions and promote hydrofracture and fluid escape in passive margins (Reilly & Flemings, 2010). Lateral overpressure transfer has been implied in basins where low-permeability sediments confine permeable (i.e., sandstone) inclined units, which laterally transfer overpressure from deeper to shallower areas (Davies, 2003; Reilly & Flemings, 2010). The overpressure can either develop within the permeable layers or transfer into them from the surrounding units. Because the mud diapir formed in a zone with reduced potential for creating near-lithostatic pressure, the only possible mechanism to increase overpressure is its convergence toward the uplifted southern margin of the basin via inclined carrier beds. Here, it exceeded the least principal stress, inducing overburden hydrofracture and the mud diapir formation.

The Samoggia pressure system differs from any other documented example of lateral transfer for one key aspect: the overpressure built up and propagated through shallow, unconsolidated mudstone units and not along deeply buried, confined permeable sandstone layers. Although lateral transfer is most commonly observed along permeable beds such as sandstones (Davies, 2003; Reilly & Flemings, 2010), this condition is not theoretically required. In fact, lateral transfer could occur via any intra-layer permeability, and our data suggests that in the Samoggia basin it happened along layer-parallel permeability inside the mudstone sequence. This interpretation is supported by the lack of laterally continuous sandstone units underneath and within the AA Fm. (Figure 1) and by the MDAC occurrence along well-defined strata. Accordingly, the topmost U1 sediments acted as an overpressure carrier bed and not the U2 sand sheet and U3-5 calcarenites, the only more permeable units occurring in the area (Figure 2). U2 and U3-5 experienced early diagenesis, preserving part of their primary porosity. This early diagenesis may have created a weak seal and contributed to overpressure. Field and theoretical observations support this hypothesis. It is implausible that near-lithostatic overpressure diffused downwards from U2-5 into the uppermost c. 100 m of U1 mudstones because overpressure would have propagated in the direction with the largest pressure gradient. Indeed, at the time of intrusion (2.87 Ma), U2-5 were close or exposed at the seafloor, thus creating a net pressure gradient directed upward. An upward-directed pressure gradient would have favored overpressure dispersion into the water column. Additionally, U2-3 show tensional deformation such as boudinage and dispersed strata blocks, together with folding and fractures. This suggests a passive involvement in the intrusion rather than a driving role.

Detailed time calibration of the sedimentary sequence allows reconstructing the chronology of fluid migration and escape, started with fluid seepage and MDAC formation at 3.59 Ma (Figure 4). The mud diapir formation at 2.87 Ma indicates that overpressure build up occurred relatively fast in the Samoggia basin, over a time interval of only ca. 700 kyr. Most likely, the diapir intrusion was the principal and final pressure release event as no evidence of later fluid emission is documented.

6. Slope Failure

The synsedimentary deformation within U3-5 points to minor slope instability along the margin since 3.0 Ma (Figure S5). This minor instability was mainly promoted by the contemporaneous tilt of the margin. Because overpressure can precondition for slope failure (Dugan & Flemings, 2000), we hypothesize that the early stages of pressure build up contributed to the initial instability. It is reasonable that this instability weakened the overburden by locally thinning the shallowest sedimentary units and, likely, generating a network of fractures. As a result, the reduced shear strength favored the mud diapir formation at 2.87 Ma. The mud intrusion triggered a major slope failure, as testified by the 5 km long scarp above the diapir and the lack of U4-5 downslope to the diapir. The U5 olistoliths hosted within U6 (Vid. S1) are only downslope to the scarp (i.e., outrunner blocks) and provide further evidence of gravitative collapse. Therefore, the spatial association between the mud diapir and the evidence of slope instability suggests a mutually causal relationship. On this basis, we also hypothesize that the mud diapir extends laterally in the subsurface for c. 5 km to the East of Rio Albonello, along the area marked by the scarp at the surface (Figure 1b).

7. Conclusions

The evidence presented here shows that sediment intrusion can develop with similar characteristics at shallow and at elevated depths in deformed foredeep settings. This has profound implications for linking fluid hydrodynamics at different burial depths to the increased potential for seafloor hazards.

This study provides evidence of lateral transfer of near-lithostatic overpressure along shallow, low-permeability sediments. The evidence documented in the Samoggia basin shows that near-lithostatic overpressure can focus at the edge of deforming satellite basins, resulting in early burial mud diapirism and slope instability. In this setting, overpressure can generate and transfer laterally within shallow, low-permeability sediments. Because lateral transfer can move high-risk overpressure across significant distances from their source, it may undermine the seafloor's long-term stability in areas not usually affected by this process.

Rio Albonello is the first description of early burial mud diapirism, an elusive and poorly recognized phenomenon, in a deformed foredeep setting. Further occurrences should be identified in other basins, particularly in areas non-traditionally prone to its occurrence.

Data Availability Statement

All data used for this study is available on Figshare at https://doi.org/10.6084/m9.figshare.16567395. Well data can be retrieved on ViDEPI https://www.videpi.com/videpi/pozzi/consultabili.asp.

Acknowledgments
Funding was provided by PRIN 2009 (Italian MIUR) and RFO (U. of Bologna) to R.C. The authors are indebted to Dr. F. Gamberi for the helpful suggestions and Dr. L. Cantelli for drone imagery.

References

Barchi, M., Landuzzi, A., Minelli, G., & Pialli, G. (2001). Outer Northern Apennines. In G. B. Vai, & I. P. Martini (Eds.), *Anatomy of an orogen: The Apennines and adjacent Mediterranean Basins* (pp. 215–253). Dordrecht: Springer Netherlands. https://doi.org/10.1007/978-94-015-9829-3_15

Barreca, G. (2014). Geological and geophysical evidences for mud diapirism in south-eastern Sicily (Italy) and geodynamic implications. *Journal of Geodynamics*, *82*, 168–177. https://doi.org/10.1016/j.jog.2014.02.003

Blanchard, S., Matheson, E. J., Fielding, C. R., Best, J. L., Bryk, A. B., Howell, K. J., et al. (2018). Early burial mud diapirism and its impact on stratigraphic architecture in the Carboniferous of the Shannon Basin, County Clare, Ireland. *Sedimentology*, *66*(1), 329–361. https://doi.org/10.1111/sed.12492

Capozzi, R., Oppo, D., & Taviani, M. (2017). Cold seepages: An economic tool for hydrocarbon appraisal. *AAPG Bulletin*, *101*(4), 617–623. https://doi.org/10.1306/011817DIG17041

Capozzi, R., & Picotti, V. (2003). Pliocene sequence stratigraphy, climatic trends, and sapropel formation in the Northern Apennines (Italy). *Palaeogeography, Palaeoclimatology, Palaeoecology*, *190*, 349–371. https://doi.org/10.1016/S0031-0182(02)00614-4

Capozzi, R., Torelli, L., Lorenzini, S., Oppo, D., Mussoni, P., Polonia, A., & Polonia, A. (2012). Neogene to quaternary tectonics and mud diapirism in the Gulf of Squillace (Crotone-Spartivento Basin, Calabrian Arc, Italy). *Marine and Petroleum Geology*, *35*(1), 219–234. https://doi.org/10.1016/j.marpetgeo.2012.01.007

Davies, R. J. (2003). Kilometer-scale fluidization structures formed during early burial of a deep-water slope channel on the Niger Delta. *Geology*, *31*(11), 949–952. https://doi.org/10.1130/G19835.1

Davies, R. J., Mathias, S. A., Swarbrick, R. E., & Tingay, M. J. (2011). Probabilistic longevity estimate for the LUSI mud volcano, East Java. *Journal of the Geological Society*, *168*(2), 517–523. https://doi.org/10.1144/0016-76492010-129

Dugan, B., & Flemings, P. B. (2000). Overpressure and fluid flow in the New Jersey continental slope: Implications for slope failure and cold seeps. *Science*, *289*(5477), 288–291. https://doi.org/10.1126/science.289.5477.288

Ghielmi, M., Minervini, M., Nini, C., Rogledi, S., Rossi, M., & Vignolo, A. (2010). Sedimentary and tectonic evolution in the eastern Po-Plain and northern Adriatic Sea area from Messinian to Middle Pleistocene (Italy). *RENDICONTI LINCEI*, *21*(S1), 131–166. https://doi.org/10.1007/s12210-010-0101-5

Huuse, M., Jackson, C. A.-L., Van Rensbergen, P., Davies, R. J., Flemings, P. B., & Dixon, R. J. (2010). Subsurface sediment remobilization and fluid flow in sedimentary basins: An overview: Subsurface sediment remobilization and fluid flow. *Basin Research*, *22*(4), 342–360. https://doi.org/10.1111/j.1365-2117.2010.00488.x

Judd, A., & Hovland, M. (2007). *Seabed fluid flow: The impact on Geology, Biology, and the Marine Environment*. Cambridge: Cambridge University Press. https://doi.org/10.1017/CBO9780511535918

Mazzini, A., & Etiope, G. (2017). Mud volcanism: An updated review. *Earth-Science Reviews*, *168*, 81–112. https://doi.org/10.1016/j.earscirev.2017.03.001

Morgan, J. P., Coleman, J. M., & Gagliano, S. M. (1968). Mudlumps: Diapiric structures in Mississippi Delta Sediments. In J. Braunstein, & G. D. O'Brien (Eds.), *Diapirism and diapirs: A symposium* (p. 0). American Association of Petroleum Geologists. https://doi.org/10.1306/M8361C10

Morley, C. K., Tingay, M., Hillis, R., & King, R. (2008). Relationship between structural style, overpressures, and modern stress, Baram Delta Province, northwest Borneo. *Journal of Geophysical Research: Solid Earth*, *113*(B9). https://doi.org/10.1029/2007JB005324

Obradors-Prats, J., Rouainia, M., Aplin, A. C., & Crook, A. J. L. (2017). Hydromechanical modeling of stress, pore pressure, and porosity evolution in fold-and-thrust belt systems. *Journal of Geophysical Research: Solid Earth*, *122*(11), 9383–9403. https://doi.org/10.1002/2017JB014074

Oppo, D., & Capozzi, R. (2016). Spatial association of mud volcano and sandstone intrusions, Boyadag anticline, western Turkmenistan. *Basin Research*, *28*(6), 827–839. https://doi.org/10.1111/bre.12136

Oppo, D., Evans, S., Iacopini, D., Kabir, S. M., Maselli, V., & Jackson, C. A.-L. (2021). Leaky salt: Pipe trails record the history of cross-evaporite fluid escape in the northern Levant Basin, Eastern Mediterranean. *Basin Research*, *33*(3), 1798–1819. https://doi.org/10.1111/bre.12536

Oppo, D., Viola, I., & Capozzi, R. (2017). Fluid sources and stable isotope signatures in authigenic carbonates from the Northern Apennines, Italy. *Marine and Petroleum Geology*, *86*, 606–619. https://doi.org/10.1016/j.marpetgeo.2017.06.016

Osborne, M. J., & Swarbrick, R. E. (1997). Mechanisms for generating overpressure in sedimentary basins: A reevaluation. *AAPG Bulletin*, *81*(6), 1023–1041. https://doi.org/10.1306/522b49c9-1727-11d7-8645000102c1865d

Picotti, V., & Pazzaglia, F. J. (2008). A new active tectonic model for the construction of the Northern Apennines mountain front near Bologna (Italy). *Journal of Geophysical Research: Solid Earth*, *113*(B8). https://doi.org/10.1029/2007JB005307

Reilly, M. J., & Flemings, P. B. (2010). Deep pore pressures and seafloor venting in the Auger Basin, Gulf of Mexico. *Basin Research*, *22*(4), 380–397. https://doi.org/10.1111/j.1365-2117.2010.00481.x

Tingay, M. R. P., Hillis, R. R., Swarbrick, R. E., Morley, C. K., & Damit, A. R. (2007). “Vertically transferred” overpressures in Brunei: Evidence for a new mechanism for the formation of high-magnitude overpressure. *Geology*, *35*(11), 1023–1026. https://doi.org/10.1130/G23906A.1

Traugott, M. O., & Heppard, P. D. (1994). Prediction of pore pressure before and after drilling—taking the risk out of drilling overpressured prospects. *AAPG Hedberg Research Conference*, *70*, 215–246.

Viola, D. O., Franchi, F., Capozzi, R., Dinelli, E., Liverani, B., Taviani, M., & Taviani, M. (2015). Mineralogy, geochemistry, and petrography of methane-derived authigenic carbonates from Enza River, Northern Apennines (Italy). *Marine and Petroleum Geology*, *66*, 566–581. https://doi.org/10.1016/j.marpetgeo.2015.03.011

References From the Supporting Information

Berggren, W. A., Hilgen, F. J., Langereis, C. G., Kent, D. V., Obradovich, J. D., Raffi, I., et al. (1995). Late Neogene chronology: New perspectives in high-resolution stratigraphy. *Geological Society of America Bulletin*, *107*, 1272–1287. https://doi.org/10.1130/0016-7606(1995)107<1272:lncnpi>2.3.co;2

Cande, S. C., & Kent, D. V. (1995). Revised calibration of the geomagnetic polarity time scale for the Late Cretaceous and Cenozoic. *Journal of Geophysical Research*, *100*, 6093–6095. https://doi.org/10.1029/94jb03098

Carcano, C., Livraghi, L., Nerby, A., Rogledi, S., & Terazzi, F. (2007). Campi di Cotignola e S. Potito. Interpretazione congiunta geologico geofisica (*Rel. ESEI n. 0/200*), *in Italian*.

Cita, M. B. (1975). Studi sul Pliocene e sugli strati di passaggio dal Miocene al Pliocene, VIII. Planktonic foraminiferal biozonation of the Mediterranean Pliocene deep sea record. A revision. *Rivista Italiana di Paleontologia e Stratigrafia*, *81*, 527–544. *in Italian*.

Colalongo, M. L., Dondi, L., D'Onofrio, S., & Iaccarino, S. (1982). Schema biostratigrafico a Foraminiferi per il Pliocene e il basso Pleistocene nell'Appennino settentrionale e nella Pianura padana. In G. Cremonini, & F. Ricci Lucchi (Eds.), *Guida alla geologia del margine Appenninico padano. Guida Geologica Regionale* (pp. 121–122). S.G.I. *in Italian*.

Colalongo, M. L., Pasini, G., Raffi, I., Rio, D., Sartoni, S., & Sprovieri, R. (1984). Biochronology of the Italian marine Pliocene and Lower Pleistocene. In *Proc. 27th Int. Geol. Congr. Moscow 1984* (pp. 109–127). Utrecht: VNU Science Press.

Goldsmith, J. R., & Graf, D. L. (1958). Relation between lattice constants and composition of the Ca-Mg carbonates. *American Mineralogy*, *43*, 84–101.

Lumsden, D. (1979). Discrepancy between thin-section and X-ray estimates of dolomite in limestone. *Journal of Sedimentary Research*, *49*, 429–436. https://doi.org/10.1306/212f7761-2b24-11d7-8648000102c1865d

Rio, D., Sprovieri, R., & Thunell, R. (1990). Pliocene-Lower Pleistocene chronostratigraphy: A re-evaluation of Mediterranean type sections. *Geological Society of America Bulletin*, *103*, 1049–1058.

Rio, D., Sprovieri, R., & Di Stefano, E. (1994). The Gelasian Stage: A proposal of a new chronostratigraphic unit of the Pliocene series. *Rivista Italiana di Paleontologia e Stratigrafia*, *100*, 103–124.

Rosenbaum, J., & Sheppard, S. M. (1986). An isotopic study of siderites, dolomites, and ankerites at high temperatures. *Geochimica et Cosmochimica Acta*, *50*, 1147–1150. https://doi.org/10.1016/0016-7037(86)90396-0

Rosenbaum, J. M. (1994). Stable-isotope fractionation between carbon-dioxide and calcite at 900°C. *Geochimica et Cosmochimica Acta*, *58*, 3747–3753. https://doi.org/10.1016/0016-7037(94)90164-3

Sprovieri, R. (1992). Mediterranean Pliocene biochronology: An high resolution record based on quantitative planktonic foraminifera distribution. *Rivista Italiana di Paleontologia e Stratigrafia*, *98*, 61–100.