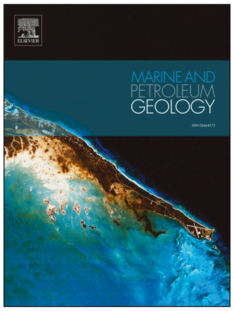

3D outcrop modelling of large discordant breccia bodies in basinal carbonates of the Apulian margin, Italy

Danica Jablonska, Alan Pitts, Claudio Di Celma, Tiziano Volatili, G. Ian Alsop, Emanuele Tondi

PII: S0264-8172(20)30515-8

DOI: https://doi.org/10.1016/j.marpetgeo.2020.104732

Reference: JMPG 104732

To appear in: *Marine and Petroleum Geology*

Received Date: 30 June 2020

Revised Date: 21 September 2020

Accepted Date: 25 September 2020

Please cite this article as: Jablonska, D., Pitts, A., Di Celma, C., Volatili, T., Alsop, G.I., Tondi, E., 3D outcrop modelling of large discordant breccia bodies in basinal carbonates of the Apulian margin, Italy, *Marine and Petroleum Geology* (2020), doi: https://doi.org/10.1016/j.marpetgeo.2020.104732.

Danica Jablonska: Conceptualization, Methodology, Field analysis, Writing-Original draft preparation, Visualization; **Alan Pitts**: Methodology, Software, Field analysis, Writing- Reviewing and Editing, **Claudio Di Celma**: Conceptualization, Writing-Reviewing and Editing; **Tiziano Volatili**: Field analysis, Writing-Reviewing and Editing; **Emanuele Tondi**: Conceptualization, Supervision, Resources; **Ian Alsop**: Conceptualization, Validation, Writing- Reviewing and Editing.

3D outcrop modelling of Large Discordant Breccia Bodies in basinal carbonates of the Apulian margin, Italy

Danica Jablonska, Alan Pitts, Claudio Di Celma, Tiziano Volatili, G. Ian Alsop, Emanuele Tondi

Abstract

Large discordant breccia bodies (LDBBs) are important record keepers of the tectonic and gravitational evolution in platform-to-basinal settings, and have important implications for fluid-flow migration and compartmentalization of tight carbonate reservoirs. In the Gargano Promontory of southern Italy, LDBBs occur within a Cretaceous slope and basinal carbonate succession. We use field mapping and Unmanned Aerial Vehicle (UAV) -based Structure from Motion (SfM) Photogrammetry to document otherwise inaccessible cliff-side exposures of seismic- to subseismic-scale vertical discordant breccias. LDBBs are up to 50 m in width, more than 80 m in height and display internal chaotic or aligned clast fabrics. The formation which generally contains the LDBBs is characterized by beds of cherty pelagic limestone intercalated with calcarenites, calciturbidites and horizons of mass transport deposits. The mass-transport deposits can be correlated across the chaotic breccia bodies, indicating only slight or no vertical displacement across the adjacent walls. The bases of the breccia bodies are always hidden below current sea level, while the rarely exposed tops are capped by bedded intervals of the host rock formation. Timing and origin of the studied breccias were determined using several lines of evidence, such as stratigraphic provenance of clasts in breccias, mutual relationships of structural and sedimentologic features, and previous studies which establish that the age of dolomitizing cements in the LDBBs formed at different times and by different processes (fault shearing and solution collapse). This work investigates the size, shape and geometry of these breccia bodies whilst also providing cm-scale detail of the textural features in otherwise inaccessible outcrops. We suggest that breccias formed as a result of solution exploiting a pre-existing fracture network characterized by large-scale vertical strike-slip or oblique-slip faults. Initial displacement along these faults created a wide fault damage zone, where fluid migration was later focused to create a zone highly susceptible to solution and subsequent periodic sidewall collapse.

1. Introduction

Large discordant breccia bodies (LDBBs) are in this work broadly defined as vertical and laterally discordant intraformational breccias which are of a scale greater than 2 m in width and 2 m in height. Such structural features potentially contain large volumes of clasts that are either chaotically arranged or may display alignment and sorting. LDBBs have been described from around the world occurring in various rock types and geologic settings both at outcrop and in the subsurface (Loucks, 1999, 2004; Broughton 2017). Their presence may be imaged in the subsurface as anomalous vertical zones on seismic reflections, as documented from offshore Bahamas (Principaud et al., 2015) and Scotland (Maestrelli et al., 2017).

In rocks forming geofluid reservoirs, LDBBs can create pathways for the intraformational migration of fluids by enhancing the effective porosity and permeability of the reservoir (Caine et al., 1996; Woodcock et al., 2006). Alternatively, collapsed material infilling the cavern combined with later burial processes (pressure solution and mineralization) can decrease permeability within the breccia body, thereby reducing fluid migration, and contributing to compartmentalization of the reservoir (Broughton, 2017). Reduction in permeability in such cases is encouraged by precipitation of minerals that act as cements with an economic value (Finch, 1992; Loucks, 1999; Leach et al., 2010, Chi et al., 2012). In addition, many dolomite bodies are associated with a brecciated lithofacies that behave as conduits (Katz et al., 2006).

LDBBs occur in an array of settings, including sedimentary environments (Smart et al., 1988; Loucks, 2001; Shanmugam, 2017), volcanic environments (Cas et al., 2011; Walker et al., 2011), along large-scale faults and fault scarps (Thomas, 1970), and in areas with hydrothermally confined explosions (Walsh et al., 2008). LDBBs form by a variety of distinct individual processes (i.e. Wang et al., 2007; Cozzi, 2000) or by the interaction of several contemporaneous processes (Loucks, 2001) that can be challenging to differentiate (Woodcock et al., 2014).

In platform to basinal carbonate settings, LDBBs display various characteristics linked to their dimensions, shapes and petrophysical properties (Shanmugan, 2017). These sets of characteristics, together with the geometrical relationship with the host rock, suggest which of the main processes formed the LDBBs. Carbonate platform and slope environments, especially along-margin areas, are often affected by syndepositional tensional fissures (Cozzi, 2000; Playford et al., 2009; Frost et al. 2012). Such syndepositional fissures are up to 90 m deep with openings ranging from decimeters to meters in width (Frost and Kerans, 2009) and have been interpreted to result from various processes such as gravity-driven sliding (Winterer et al., 1991; Budd et al., 2013), antecedent topography and loading (Hunt and Fitchen, 1999; Frost and Kerans, 2010) and syndepositional tectonics and hydrothermal circulation (Hsü, 1983). Neptunian dikes are the most common brecciated bodies in the platform-to-slope environment (e.g. Smart et al., 1988, Črne et al., 2007, Winterer et al., 1991; Laurita et al., 2016), with host rock fragments resulting from dilatation due to gravitational instability and/or active regional tectonics and differential compaction (Koša et al., 2003). The clast input is derived from the disaggregation of bounding walls, sagging of the overlying layers, or contributions from other sources (e.g. gravity flows). Neptunian dikes often show multiphase evolution (e.g. Winterer et al., 1991; Laurita et al., 2016), while their fill is usually chaotic but may display preferential orientation of the clasts surrounded by a matrix (Cozzi, 2000). They typically occur on high-relief carbonate systems and often form prior to significant burial. Neptunian dikes are frequently found to be sheared by contemporary or later intersecting fault planes and fracture corridors (Parino et al., 2019).

Another mechanism that can produce LDBBs is fracturing and fragmentation that shows a close spatial and kinematic association with larger fault zones. Such breccias are a direct product of abrasion and/or wear during fault slip (Sibson, 1986). However, faults can also produce dilatational breccias, which are hypothesized to form as a result of wall-rock implosion (Thomas, 1971; Gilli et al., 1999; Woodcock et al., 2006; Melosh et al., 2014). The width of fault breccias may range from several centimeters to tens of meters (Walker et al., 2011; Woodcock et al., 2014), depending on the dimensions of the fault. The main mechanisms of breccia filling along the fault plane may involve: i) coseismic filling due to dilatation of the compressed material after energy release (Sibson, 1988; Holland et al., 2006); ii) large void formation produced by slightly oblique slip resulting in pipes later infilled by collapsed material (Park and MacDiarmid, 1970); iii) solution and along-fault widening followed by later collapse material and abrasion (Koša et al., 2003). Gradual abrasion and/or wear during fault slip progressively decreases the grain size of the breccia (Woodcock and Mort, 2008).

Karstic processes are one of the most common phenomena producing discordant breccias in carbonates (Moore and Wade, 2013). They are referred to as “solution-collapse breccias” and are common in areas with subsurface karst development (Gutiérrez et al., 2008). They occur both as a gradual cavern filling following the dissolution of weak zones of surrounding bedrock and subsequent collapse (Moore and Wade, 2013), or as the result of a sudden collapse of a cave system (Loucks, 2001). Catastrophic collapses may occur after preferential dissolution of the underlying strata of more soluble material, e.g. evaporites (Eliassen and Talbot, 2005). The roof collapse of cavities commonly produces an inversely graded breccia with finer chaotic material at the base and coarser material towards the top (Loucks, 2001).

Some LDBBs in the Gargano Promontory were previously described very briefly by Martinis and Pavan (1967), Salvini et al. (1999), Morsilli et al. (2004) and Jablonská et al. (2018). However, their spatial range, textural variation, and 3D geometry with respect to the regional structural setting have not yet been documented. In addition, a process-based explanation for the origin of LDBBs has not been sufficiently developed thus far - largely due to their inaccessibility on vertical cliff faces. In this study, we integrate field mapping and UAV-based Structure from Motion (SfM) Photogrammetry in order to document the overall geometry of the bodies and their marginal zones, their relationship to adjacent structural features, and the sedimentary characteristics of their infill. Moreover, the additional information acquired allows us to address the following questions: what is the main process controlling the formation of the LDBBs? How does the timing of brecciation fit into the regional geologic development of this area? Are these LDBBs representative of a single episode or multiple events?

2. Geological setting

The Gargano Promontory, southern Italy (Fig. 1), comprises a 3.0-3.5 km thick succession of late Jurassic to Eocene platform-to-basin carbonates (Martinis and Pavan 1967; Bernoulli 1972; D'Argenio, 1976; Luperto Sinni and Masse, 1987; Graziano, 1999; Bosellini et al., 1999; Borgomano, 2000). This sequence is intercalated with spectacularly-preserved mass-transport deposits (MTDs) that are laterally persistent and individually reach several meters in thickness (Bosellini et al., 1997; Morsilli et. al, 2004; Hairbian et al., 2016; Jablonská et al., 2016, 2018). The promontory represents a structural high that was formed due to deformation of the entire carbonate succession during the Miocene, giving rise to a broad WNW – ESE trending anticline (Bertotti et al., 1999; Billi et al., 2007).

In the central portion of the promontory, the shallow-water carbonates pass laterally into slope and basinal carbonates (Fig. 1A) with horizontal to very shallowly (20°) E and NE dipping beds (Graziano, 2000). An Upper Jurassic to Lower Cretaceous slope to basinal succession is exposed in the eastern part of the promontory, whilst the far NE coast exposes Upper Cretaceous to Eocene basinal formations (Fig.1B).

The Gargano Promontory was affected by multiple phases of tectonic deformation (Salvini et al., 1999; Tondi et al. 2005). The Late Jurassic - Late Cretaceous is characterized by extensional tectonics (Graziano 1999; Borgomano, 2000; Santantonio, 2012), whereas NE - SW - oriented horizontal compression was the most dominant in the Miocene - Pliocene (Bertotti et al., 1999). The promontory is dissected by major WNW-ESE, NW-SE striking faults, together with minor NE-SW striking faults (Fig. 1A). The first set is represented by the well-known tectonic-plate scale Mattinata fault (Argnani et al., 2009) formed during dextral to sinistral strike-slip motion (Monti et al., 2005; Tondi et al., 2005; Billi, 2007).

Post depositional Cretaceous extension (Winter and Tapponnier, 1991) produced the syn-sedimentary NW-SE oriented faults characterized by dip-slip to oblique-slip kinematics. According to some authors (Masse and Borgomano, 1987; Graziano, 2001; Santantonio et al., 2012), the Early Aptian to -late Albian NE-SW oriented transfer fault controlled the evolution and geometry of the platform margin, and also triggered periodic gravity-driven collapse (Hairabian et al., 2015). Minor NE-SW oriented faults are present in the platform carbonates in the central part (Martinis and Pavan, 1967). Korneva et al. (2016) described these fault sets in the southern Gargano area and attributed them to gravity-driven processes. However, we have also documented NE-SW normal and strike-slip minor or larger faults in the northern Gargano area that either act as margins to the LDBBs or cross-cut the vertical breccias.

The LDBBs are documented mostly in the Maiolica Fm., with some examples in the Casa Varfone Fm. and in the Marne a Fucoidi Fm. (Fig. 1). The Maiolica Fm. is a 300 – 500 m thick succession of basinal carbonates composed of thinly interbedded micrites, wackestones and chert intercalated with gravity flows and MTDs, including Upper Cretaceous megabreccias (Bosellini et al., 1997; Graziano, 2001; Hairabian et al., 2015; Jablonská et al., 2018). This succession is cut by Cretaceous syn-sedimentary normal to strike-slip faults and later reverse- to strike-slip faults (Billi et al., 2007). Some of the LDBBs in the Gargano have been briefly described as “breccia dikes and megabreccia dikes” having syn-sedimentary infill containing clasts derived from the Paleogene succession (Morsilli et al., 2004). The Maiolica Fm. also hosts large quantities of dolomite bodies associated with the Gargano Fault system with a preferential ESE-WNW and NE-SW elongation (Martinis and Pavan, 1967; Rustichelli et al., 2017). These authors have documented vertical brecciated lithofacies at the fronts of the dolomite and limestone facies.

Two main depositional hiatuses occurred during Cretaceous times (Fig.1B): 1) platform and slope related subaerial exposure during the Late Aptian; and 2) an erosional hiatus from the Late Albian to Cenomanian that impacted the whole succession and is marked by laterally extensive bauxite deposits in the platform-to-slope facies (D’Argenio and Mindszenty, 1991), and by the Mt. San Angelo Megabreccias in the basinal carbonates (Neri and Luciani, 1994). During these periods, important 3rd-order sea-level changes resulted in 100-150 m drops in worldwide sea-level (Haq, 2014).

A significant uplift of Gargano Promontory is associated with the formation of a broad anticline during the eastward migration of the Apennine compressional front. It is estimated that the whole promontory underwent tectonic uplift starting in the Miocene, which allowed subaerial conditions to act on the emerged succession (Bertotti et al., 1999). Karst-associated collapses that produced sinkholes were described by Taviani et al. (2012) from the offshore of NE Gargano. These authors noted that the karst phenomenon affects the Plio-Pleistocene calcarenites of the Gravina Formation, and therefore estimated the age of sinkholes to be Late Pleistocene. In addition, similar features to LDBBs were recorded on the Tremiti Islands north of the Gargano

Promontory, where large vertical breccias were associated with either faulting or karst solution collapses (Miccadei et al., 2011).

3. Methods

The LDBBs in the Gargano promontory were documented using traditional geologic field mapping complemented by the use of an Unmanned Aerial Vehicle (UAV) along the pristine coastal exposures, and by field description along the road-cut outcrops inland. Structural and sedimentological measurements and observations including size, shape and geometry of the LDBBs, orientation and character of the margins, breccia-associated fault description, and clast characterization were undertaken both in the field and on Virtual Outcrop Models (VOM). In order to obtain accurate measurements of the largest LDBBs, 6 expansive high-resolution 3D photo-realistic Virtual Outcrop Models (VOM) have been generated.

Additional structural and sedimentological data were gathered. That includes attitudes of bedding, fractures and faults within the hosting formation, breccia mineralization, MTD types and their transport directions calculated from the folds within the MTDs. Thin section analysis was performed to characterize the lithofacies.

The use of the UAV involved conducting photo acquisition by aerial surveys of the cliff-side exposures and processing photos using SfM Photogrammetry (Fig. 2A). This work involved two steps, first collecting the UAV imagery and processing of 3D models in Agisoft Metahsape (formerly Photoscan), followed by detailed analysis and extraction of structural and stratigraphic data using LIME virtual outcrop software.

The acquisition of aerial imagery was conducted using the DJI Phantom 4 Pro with a 12mp onboard camera and ½ inch image sensor, which was flown at distances between ~7 m and ~ 30 m from the outcrop in order to collect a series of overlapping photos to record the entire cliff-faces from sea level to the top of the exposure. The individual outcrop models, which contain the breccias showcased in this work, were composed of between 115-225 input photos used to construct photorealistic 3D virtual outcrop models (VOMs) (Tavani et al., 2014; Corradetti et al., 2017; Pitts et al., 2019) with surface mesh resolutions of greater than 34 million faces, derived point cloud volumes up to 258 million points. The general processing procedure follows the methods outlined by Pitts et al. (2017) and Nesbit et al. (2018) using Agisoft Metashape (formerly Photoscan).

Interpretations, structural measurements, and extraction of quantitative data were made directly on the 3D VOM using LIME geologic analysis software (Buckley et al., 2019) (Fig 2B). Using this novel software, broad physical measurements such as the overall height and width of LDBBs and thicknesses of the surrounding major stratigraphic intervals were recorded. Additionally, detailed measurements, such as the structural attitudes of faults defining the marginal zones of the LDBB as well as other background faults located 10s of meters high on the cliff wall were captured using the 3-point plane fit tool. These digitally acquired data were incorporated with physical field measurements which were made from the limited areas physically accessible along the base of the cliff.

4. Results

4.1. Large discordant breccia distribution

In the Gargano Promontory, 125 LDBBs have been described in the Berrasinian Maiolica Fm., three in the Casa Varfone Fm. with some small-scale examples in the Mattinata Fm. Two examples were documented passing across the boundary between the Maiolica Fm. and the overlying Marne a Fucoidi Fm. (Fig 3). Here we present field analysis and accompanying large 3D virtual outcrop models of three examples of the largest LDBBs in the area to document their overall geometry, margin features, and internal sedimentary textures (Fig. 4).

4.2. General description of the breccia bodies:

4.2.1. Geometry of the breccia bodies

LDBBs are ubiquitous features in slope-to-basin formations of the Gargano Promontory (Fig. 3). The best exposures are preserved on the cliffs of the coastal area where many of these bodies have been partially eroded revealing distinct geometries. In several cases, it is possible to find exposures that permit observations in both the lateral and plan view (Fig. 5A).

In general, the width-height ratio together with the size and orientations of the margins imply a vertical-pipe or sheet-like character to the breccias (Fig. 5 B-E; 6A). However, some LDBBs have complex shapes with irregular margins (Fig. 5 F; 6B). Bedding attitudes in the surrounding strata range from nearly horizontal to 30°, while the attitudes of the LDBBs margins range from vertical (Fig. 6) to 60° (Fig. 5C), and may be partially caused by breccia postdating tilting caused by faulting. Dimensions of the breccias differ; the widths range from 2 to 50 m (Fig. 5), the total exposed height varies from 2 to 80 m, while the length component can be observed with limitations, mostly in plan-view exposures (Fig. 5A) and caverns along the sea cliffs. The greatest documented length of a single exposed breccia was around 45 m. When the exposure is high enough to permit the observation, the vertical dimension is always predominant with width/height ratio ranging from 1:2 to 1:6 and more (Fig. 5B). The base of the LDBBs is never exposed. The tops of the LDBBs are exposed rarely, and when visible, the walls converge towards the top (Fig. 5F).

4.2.2. Margins

The margins of the LDBB display both regular and irregular geometries (Figs. 5, 6 A-D, 7). The regular margins are typically steep (Fig. 5, 7 A-D) or approaching vertical and sharply cross-cut surrounding non-brecciated horizontal strata. Margins often show a close association with a zone of smaller-scale faults and splays (Fig. 5; 6; 7 B, C).

Slicken-lines may be present along the regular, straight margins, (Fig. 7F, G) both on the walls of surrounding strata and on the clasts within the breccia along the contact. They mostly show horizontal to slightly oblique kinematics (Fig. 7G). In some cases, the LDBB margin walls are fractured and the openings are filled with coarse-grained brecciated material (Fig. 7C). The minor faults directly adjacent to the margins largely display poorly developed fault cores, in some cases filled by calcite cements and/or with fine-grained, reddish material with a clay component (Fig. 7C). There are 3 predominant fault sets, oriented NE-SW, NW-SE and NWN-ESE, coinciding with the breccia margins (Fig. 8).

Enhanced fracturing at the breccia margins dissecting both the clasts and the hosting formation was documented in some cases (Fig. 5C). Alternatively, some LDBBs displaying irregular margins do not show any correspondence with neighbouring structural or stratigraphic features. In some cases, individual LDBBs are bound by both regular, sharp contacts on one margin and irregular, wavy contacts on the other margin.

4.2.3. Associated and postdating faults

In most cases, the breccia contacts are straight and vertical (Figs. 5-8). Along these contact planes, the observed striations indicate mostly horizontal to oblique kinematics. Although clasts may display local slicken-lines, they are characterised by remarkably little internal deformation, with no evidence of veining, fracturing or crushing. The marginal fault planes showing some horizontal and oblique-slip movement can be grouped into 3 distinct sets: NE-SW, E-W, SE-NW (Fig. 8).

The sub-horizontal strata surrounding the breccias may display meter- to decameter-scale vertical offset between the two bounding walls, without any evident fault planes that cross-cut the breccia body (Fig. 5). In several cases, the breccia bodies are cut by faults and their apparent vertical offset ranges from 0.1 to 1 m. Cross-cutting faults, depending on their magnitude, can develop damage zones that deform the clasts of the breccia. The predominant orientation of these breccia-cutting faults is NW-SE and NE-SW (Fig. 8). Their kinematics are extensional or transtensional and they often host calcite cement along the fault plane. Some planar structures crosscutting the LDBBs, however, can be interpreted as slip planes with no evidence of a tectonic origin and could be produced by gravity-driven movements (Fig. 5D). The orientation of other faults present in the vicinity of the breccias often coincides with the orientation of the breccia margins (Figs. 7-9). Several slip planes cross-cutting the LDBBs are oriented NW-SE and coincide with the orientation of the faults dissecting the surrounding succession (Fig. 8). The slip planes show no evidence of a tectonic origin and may be caused by gravity-driven sliding.

4.2.4 Orientation of the LDBBs with respect to the principal fault orientations, geometry of the paleoslope and MTD movement.

The Apulian Platform exposed in the Gargano Promontory is oriented NW-SE in the northern part, and NE–SW in the southern part (Fig. 3), which are consistent with the predominant transport directions of the ubiquitous MTDs (Fig. 10). Out of 125 studied breccias, 74 breccias cut the MTDs, out of which in only 23 cases was it possible to obtain significant amounts of measurements within the MTDs (fold limbs and fold axial plane orientation). Out of those 23 cases, 14 breccia margins were perpendicular or at high angles (70-90°) to the MTD flow direction. In several sections, the orientation of LDBBs margins is perpendicular to the dominant direction of mass transport (Fig. 4, 8, 10; Br 18 and Br 72,73). In other cases, these two parameters seem to be independent of one another (Fig. 9, 10), and the LDBBs margins then tend to form parallel to the principal fault set documented in the area.

4.2.5 Clasts

The breccia fill is made up of dismembered strata of micrite, wackestone, chert and occasionally marls, or of more complex lithofacies such as the clasts of debris flow deposits, slumps, fault breccias and clasts of hydraulic breccia (Fig. 11 A-F). In rare cases, dolomite and dedolomitised clasts were noted (Fig. 12). Despite the presence of the dolomitic fluids that evidently permeated the breccias and their surrounding rock, dolomite clasts in a finer limestone matrix were identified in only one case.

The LDBBs are composed of angular to, less commonly sub-rounded clasts surrounded by matrix (Fig. 5 E, 11). Two main types of LDBBs clast arrangement have been recognized: 1) those with chaotic and random organization of fragments which lack any preferred orientation; and 2) those organized with a preferred alignment of clast long axes (Fig. 6 B, C). The type-2 variety contains a pseudo or relic stratigraphic fabric with clasts organized in lineations dipping between 20° to 60° (Fig. 5D) and displaying textures similar to those of synsedimentary breccias (Fig. 4E). There is only weak evidence of clast sorting, with the smallest clasts filling the space between larger clasts and some filling opened fractures in the larger clasts.

The sediment infill is also variable regarding the size of the clasts, ranging from the finest (< mm) grains to boulders (up to 5 m). The clast size depends on the package thickness and on the dimension of the breccia body. In general, the largest clasts comprise undeformed beds or fragments of well amalgamated MTD-horizons, specifically debris flow deposits (Fig. 6 E, 11 A, F). These blocks are part of the surrounding stratigraphy and their relative position (higher or lower in the succession) is detectable in only a few cases based on the matching of ‘marker layers’ or stratigraphic packages, such as chert layers of a certain thickness and colour.

Understanding the vertical position of clasts inside the LDBBs with respect to the original position in the stratigraphy may play a crucial part in deciphering the formation processes of LDBBs. As shown in the Fig. 6 A, B, C, some of the clasts occur much lower with respect to their original stratigraphic level, while some clasts that are closer to the margin, may occur at the same height or at an even higher level than that of the source strata.

The majority of the LDBBs are situated in the Maiolica Fm., and comprise clasts with clear provenance from this formation. However, in the northern part of Gargano several breccia bodies cutting the Maiolica Fm. contain clasts sourced from younger units, such as the Marne a Fucoidi Fm., Monte San Angelo Fm., Monte Saraceno Fm. and Peschici Fm. (Fig. 1).

4.2.6 Matrix and cements

The matrix of the LDBBs is predominantly composed of very fine-grained material derived from the surrounding bedrock, containing micrite (Fig. 11 A) and chert fragments. If the matrix is present, it is yellow to pale yellow in color. This suggests that the matrix is much more influenced by secondary fluids than the clasts within the same breccia which show little or no alteration (Fig. 11 A, B). Calcite cements are pervasive in the upper portion of the breccias, while increased dolomite cementation was recorded either in the lower portion or the whole thickness of the breccias or throughout all the breccia. This is especially evident in the alternation of micritic limestone and wackestone into dolomites and dedolomites both in the LDBBs and adjacent horizontal beds. Some breccias were impacted by dolomitization and later dedolomitization. The circulating magnesium rich fluids lead to recrystallization of the limestone clasts and matrix either partially (Fig. 12 A, B) or completely (Fig. 12 C). In case of complete overprint of the limestone clasts, the breccias were recognised by chert fragments in the massive beige to caramel-brown dolomitic matrix. The contact between the LDBBs and surrounding rock can be fully dolomitized (Fig. 12 A-C) or the dolomite front corresponds to the lithological contrast of LDBBLDBB and beds of tight limestone (Fig. 12 B).

4.2.7 Hydraulic fracturing

At the margins of some discordant breccias, we observed evidence of hydraulic fracturing (Fig. 13). The fractures show cm-scale opening and are filled by a fine grained breccia that comprised angular and sub-angular fragments of micrite and chert. The matrix surrounding the clasts is reddish, composed of fine crypto-carbonate and has higher porosity than the clasts (Fig. 13 D). At the margins marked by reddish filling, the clasts have rims of calcification. Inside the hydraulic breccia, fracture orientation is concordant with that in the surrounding strata but fracture density is higher (Fig.13 A, B). The displacement of the clasts reaches 2 cm normal to the fracture strike. The hydraulic fractures have also been recognised in dolomitized and dedolomitized matrix where they are marked by fractures filled with chert fragments (distinguished from the ghosts of hydraulic fractures that are detectable by the presence of chert fragments in the fractures Fig. 12 D, E).

5. Discussion

LDBBs are ubiquitous features in the outcrops of the Gargano Promontory, and are developed across a range of dimensions with different geometries (pipe-like, sheet-like and “complex” geometries). In a few cases, the margins of the breccia bodies can be correlated with the contacts of neighbouring breccias that have similar dimensions (Fig. 4A). In such cases, the LDBBs can reach a length greater than 100 m; examples of a similar scale have been documented by Woodcock et al. (2014) in the Pembroke peninsula of south Wales. LDBBs documented in our study are bound either by straight or wavy contacts. The straight margins are interpreted to be the result of faulting with extensional, transtensional, or transpressional movement shown by the kinematic markers (Figs. 5 B, 5 C; 7 A, 7 B). Conversely, the irregular margins are interpreted to be the result of karst dissolution or oblique-slip fault kinematics.

LDBBs are bound by fault blocks that often show up to 25 m vertical offset. Although the fault planes are not often directly observed (Fig. 5, 6, 7 A), their presence is inferred by a clear relative offset of stratigraphic marker intervals adjacent to the breccia bodies. Considering that many faults observed in the area display oblique- to strike-slip kinematics, the total displacement along the fault planes may be of significantly greater magnitude.

The preferential alignment of the LDBBs is often connected to their development along specific fault systems and is interpreted either as a network of hypogenic karst systems (Haug et al., 2009; Loucks et al., 2000), fault scarp breccias (Preto et al., 2011) or opening fractures developed by downslope creep from the platform (Frost and Kerans, 2010).

The lithological difference between the breccia bodies and their hosting formation may produce an important contrast with respect to the porosity within the rock volume and impacts the fluid circulation (Rustichelli et al., 2017). These differences may result in localized cementation, as shown in this study by dolomitization and dedolomitization. In Rustichelli (2017), the prevalent orientation of elongated sides of small and medium dolomite bodies is WNW-ESE, while the elongation of larger dolomite bodies is oriented NE-SW. Rustichelli et al. (2017) described small-scale breccias at the dolomite fronts.

5.2. LDBB Formation and related characteristics

We propose a variety of origins for the studied breccias based on structural and sedimentological data obtained during the field survey, combined with geochemical data from the literature. Each process of formation has its own specific characteristics. We now review three different potential mechanisms proposed as models for discordant breccia body formation (Fig. 14):

5.2.1 Syndepositional tensional fissures (Fig. 14 A)

The development of syndepositional tensional features which includes Neptunian dikes, crevasses and synsedimentary normal tectonic and gravity faults, has been recognized in previous works in the platform to slope Mesozoic carbonates in the Tethys region (Winterer et al., 1991; Lehner et al.,1991; Wieczorek and Olszewska, 2001; Črne et al., 2007) (Fig. 14 A). In the Gargano Promontory, syndepositional tensional features may have developed due to extensional syndepositional tectonics (plausible during the Early Cretaceous) or as a result of gravity-driven movement as is illustrated by the presence of both tectonically- and gravity-driven faults (Korneva et al., 2015). Moreover, MTDs are pervasive in the Maiolica Fm. (Bosellini, 1999; Hairabian et al., 2015; Jablonská et al., 2017) and such a mass wasting (block sliding, slumping and creep) can produce gravitational extensional voids and crevasses (Winterer et al., 1991), providing space for emplacement of younger material in the older surrounding rocks (Bates and Jackson, 1980). Slides and sliding blocks comprise relatively undeformed strata reaching hundreds of meters without any evidence of deformation and may produce crevasses that may be later filled by collapsed material (Talling et al., 2007). The material from the dismembering of lithified walls can partially fill the void, resulting in multiple phases of filling associated with continued downslope movement. In the studied area, the LDBBs margins are often perpendicular to the MTD direction (Fig. 5, 8 and 10), and this may be associated with the overall slow downslope sliding. While the margins of some LDBBs coincide with the paleoslope strike (Fig 5 A), not all their margins necessarily show one preferential orientation.

The role of gravity-driven deformation along the slope margin – basinal carbonates is confirmed by the numerous MTDs documented in previous studies (e.g. Morsilli and Bosellini, 2001, Jablonská et al., 2018). Such mass wasting may produce fissures that can be later filled by detritus, similar to that documented in the Lias of the Southern Alps (Winterer, 1991) or the Apula margin (Laurita et al., 2016).

5.2.1. Fault-related breccia (Fig. 14 B)

At the studied sites, NW-SE oriented normal faults, WNW-ESE and NE-SW oriented oblique-slip faults and E-W oriented strike-slip faults were observed in the vicinity of the LDBBs (Fig. 6- 9). The vertical offset of most of these faults varies between a few tens of centimeters to tens of meters. Clear offset of the stratigraphic intervals was observed on either side of the breccias and is evidence that movement along the fault plane occurred at the position of the LDBBs (Fig. 5, 6, 14 B). In many cases, such faults belong to a larger conjugate fault system (Fig. 6), possibly a negative flower structure.

Along the straight contacts of LDBBs and their surrounding strata, a thin (0.5 - 20 cm) fault core filled with reddish gouge may be observed (Fig. 7 B, C; Fig. 10). The abundant horizontal and oblique-slip kinematic indicators at the margins (Fig. 7 F, G) and chaotic clasts within the breccias indicate continued tectonic activity along these LDBBs.

Careful correlation of breccia mega-clasts with the surrounding stratigraphy suggests oblique transport with 20 – 40 cm vertical displacement (Fig. 6), which may be achieved by fault action with transpressive kinematics. Moreover, enhanced fracturing impacting the surrounding walls indicates a damage zone linked to continued movement on the adjacent faults, or the damage zone of the fault along which LDBBs subsequently developed (Fig. 6 E, F). Our structural evidence suggests the presence of a wide brecciated zone flanked by a distinct damage zone with a sharp transition to the undeformed or very little deformed bedrock. However, the width of the breccia is consistent with a "fault corridor", which may be characterized by several fault planes that give rise to a broad and coalesced brecciated zone, similarly to that described by Woodcock et al. (2014). Fault-related breccias produced by abrasion and dilatation are well documented in large-scale fault zones (Walsh et al., 2008). In the Gargano Promontory, breccia of such a scale is related to the E-W oriented Mattinata Fault (Salvini et al., 1999), an important crustal fault that accumulated more than 2 km horizontal displacement (Tondi et al., 2005).

5.2.2. Solution collapse breccias (Fig. 14 C)

The studied breccias also show convincing evidence of solution and collapse (Fig. 14 C). Chaotically arranged clasts with no evidence of sorting may suggest a catastrophic collapse of a large-scale cavern. This inference is supported by the presence of several large megablocks near the exposed base of the breccia bodies which have been linked to higher stratigraphic intervals (Fig. 6 A, E).

Karst-associated collapse breccias are often the product of cavern failure, producing sinkholes that are later filled by collapsed material as breccias or as sagging strata (Loucks, 2001). The cavern structures are frequently associated with zones of enhanced fluid percolation, such as along-strike migration in fault zones and fracture corridors (Bagni et al., 2020).

Irregular breccia margins support the cavern-filling hypothesis. Even some straight margins may be developed as slip planes due to gravitational collapse during the sinkhole formation and may continue to develop and be progressively filled in stages (Ezersky and Frumkin, 2013; Broughton, 2017).

Several sinkholes of sub-aerial origin in Plio-Pleistocene calcarenites were described by Taviani et al. (2012) from offshore Gargano Promontory. These sinkholes have a maximum recorded depth of 20 m (although their total height was not possible to obtain) and their diameter is up to 120 m. These features are aligned in a NE-SW direction which, according to Taviani et al. (2012), is an indication of structural or lithological control. Some of the LDBBs (identified in the northern portion of the study area, Br1 and 2, Br 126) contain clasts belonging to a formation younger than the Maiolica Fm. (e.g. Marne a Fucoidi Fm., Monte San Angelo Fm. and Peschici Fm.). The breccias in the presented study resemble those found in filled sinkholes, with sharp lateral boundaries against surrounding quasi-horizontal strata.

Dissolution of carbonates occurs predominantly in sub-aerial environments with meteoric diagenetic processes (Loucks, 2000; Santo et al., 2010) or in submarine conditions if related to ascending brines with a strong corrosive potential (Smart et al., 1988) or brackish fluid mixing, as documented offshore Florida (Land and Paul, 2011). Several studies have also described massive collapses associated with solution and development of karst in underlying evaporite layers (Broughton, 2017; Frumkin et al., 2011; Friedman, 1997).

5.2.3. Conceptual model of LDBBs origin

LDBBs in the study area are most likely formed by a combination of several processes. Clast provenance from specific stratigraphic levels has shown that some boulders were incorporated into the void from levels more than 25 m above. Whereas, some solitary clasts within the same breccias but closer to the margin, are found in close proximity to their source strata and did not travel far (Fig. 5). The vertical breccias may play a role as a weak interface along which a later fault may propagate, as documented in the Apulian Platform carbonates by Laurita et al. (2016).

The timing of the LDBBs formation can provide further constraints about their origin and their place in the regional geologic framework. Some features, such as age of various clasts, breccia-cutting faults and dolomitization of the breccias may indicate the timing. According to Rustichelli et al. (2017), the dolomitization processes of the slope and basinal succession is constrained to be Late Jurassic to Early Cretaceous in age. Since there are several dolomitized breccia bodies (Fig. 3, Fig. 12), dolomitization is estimated to post-date the breccia formation. However, the subaerial exposure needed for solution collapse may place the LDBBs either in the Upper Cretaceous with a significant regional hiatus caused by relative sea-level fall (Graziano, 2000), or post-Miocene which is characterized by a significant uplift associated with the development of the broad anticline.

Our data indicate that the formation of these breccias cannot be explained by a single process alone and instead they must be considered as being generated by multiple mechanisms. The breccias are not easily separated from the background structural fault network surrounding them, and they also show clear evidence of solution collapse. Therefore, we favour an interpretation that these breccias formed as a result of solution exploitation of a pre-existing fault network characterized by large-scale vertical strike-slip or oblique-slip faults with decameter scale offset. Initial displacement along these faults created a wide fault damage zone, where localized fluid migration created a zone highly susceptible to solution and subsequent periodic sidewall collapse (Fig. 15).

5.2.4 Value f UAV-based photogrammetry-derived VOMs

The VOM survey has clearly provided valuable information in addition to that gathered during the field survey. It enabled us to obtain more data and to better understand the structural relationships including: the orientation and geometry of the LDBBs, 3D architecture and orientation of the platform margin, the predominant direction of the MTDs, and fault orientations in each studied location. While some inconsistencies were documented with low angle features (Fig.8 – Br 72), these cases were clarified by limited manual field measurements taken in the accessible lower part of the outcrop, while data obtained from photogrammetry constrained the upper part of the outcrop which was otherwise unreachable. Collectively, these data provide much better constraints than observations and (biased) sampling based on one approach alone.

6. Conclusions

Large discordant breccias are common features exposed in the basinal and slope carbonates of the Gargano Promontory. These breccias cut Cretaceous slope and basinal carbonates and can reach heights > 80 m and widths > 40 m. The chaotic appearance of the filling suggests large magnitude collapses. Several examples of the breccias show both chaotic clast arrangement and an aligned texture, with apparent-clast stratification forming dip angles < 60°, which would suggest both catastrophic and sequential filling.

In terms of the timing of formation, the dolomitic and dedolomitized mineralization of the LDBBs is dated to during Middle - Late Cretaceous. There are several breccias where clasts of younger formations were documented.

We suggest three main mechanisms for LDBBs formation: gravity-driven openings, karstic solution collapse and tectonically-induced dilatational breccia. The fact that some breccias have been fully or partially dolomitized implies that at the time dolomitizing fluids passed through the rocks, the permeability of the protolith was relatively high. In lithofacies such as pelagic carbonates, relatively high permeability would indicate a pre-existing fracture network.

The results presented in this paper also demonstrate the potential for using computer aided analysis of UAV-based photogrammetry-derived VOMs to acquire structural and stratigraphic data, and their spatial relationships, from otherwise inaccessible cliff-side exposures. A high- resolution, cm-scale 3D photorealistic model was obtained of several expansive cliff-faces in the Gargano Promontory where LDBBs and their surrounding related stratigraphic and structural features are well exposed. The use of the 3D Virtual Outcrop models in this study allowed the observation and direct measurement of fault surfaces that characterize the breccia boundaries as well as the marginal zone which significantly enhanced the datasets obtained in the field. The cliff faces would have been otherwise completely inaccessible, and observations of the 3D aspects of the margins and textures and direct measurements limited. The LIME virtual outcrop analysis software provides an incredibly valuable tool for making measurements and interpretations directly on the Virtual Outcrop Model.

ACKNOWLEDGEMENTS

This work has been supported by Reservoir Characterisation Project (www.rechproject.com) ‘Characterisation and modelling of natural reservoirs of geofluids in fractured carbonate rocks’, funded by the University of Camerino, coordinator Emanuele Tondi. We acknowledge use of Rick Allmendinger’s stereonet programme R. W. Allmendinger © 2006–2014). An additional thanks to Simon Buckley and the Virtual Outcrop Geology group at the University of Aberdeen for assistance using their LIME software for the this project. We would like to express our gratitude to the editors of this special issue and anonymous reviewers for their insightful comments and for their useful suggestions that led to the improvement of the article’s quality.

References

Alsop, G.I., Weinberger, R. 2020. Are slump folds reliable indicators of downslope flow in recent mass transport deposits? Journal of Structural Geology 135, 104037. https://doi.org/10.1016/j.jsg.2020.104037

Argnani A., Rovere M., Bonazzi C., 2009. Tectonics of the Mattinata fault, offshore south Gargano (southern Adriatic Sea, Italy): Implications for active deformation and seismotectonics in the foreland of the Southern Apennines. Geological Society of America Bulletin, 121, 1421-1440.

Bagni, F.L., Bezerra, F.H., Balsamo, F., Maia, R.P., Dall'Aglio, M., Karst dissolution along fracture corridors in an anticline hinge, Jandaíra Formation, Brazil: Implications for reservoir quality, Marine and Petroleum Geology (2020), doi: https://doi.org/10.1016/j.marpetgeo.2020.104249.

Bates, R. L., Jackson, J. A., 1980. Glossary of Geology. AGI, Falls Church, 751.

Bernoulli, D., 1972. North Atlantic and Mediterranean Mesozoic facies: a comparision. In “Initial Reports of the Deep Sea Drilling Project” (C.D. Hollister, J.I.Ewing et al. eds.), 11, 801-871.

Bertotti, G., Casolari, E., Picotti, V., 1999. The Gargano Promontory: a Neogene contractional belt within the Adriatic plate. Terra Nova 11, 168-173.

Billi A., Gambini, R., Nicolai, C., Storti F., 2007. Neogene-Quaternary intraforeland transpression along a Mesozoic platform-basin margin: The Gargano fault system, Adria, Italy. Geosphere, 3, 1-15.

Borgomano, J.R.F., 2000. The Upper Cretaceous carbonates of the Gargano-Murge region, southern Italy: A model of platform-to-basin transition. AAPG Bulletin, 84, 1561–1588.

Bosellini, A., Morsilli, M., 1997. A Lower Cretaceous drowning unconformity on the eastern flank of the Apulia Platform (Gargano Promontory, southern Italy). Cretaceous Research 18, 51-61.

Bosellini, A., Morsilli, M., Neri,C. ,1999. Long-term event stratigraphy of the Apulia Platform margin (Upper Jurassic to Eocene, Gargano, southern Italy). J. Sediment. Res., 69, 1241–1252

Broughton, P.L., 2017. Breccia pipe and sinkhole linked fluidized beds and debris flows in the Athabasca Oil Sands dynamics of evaporite karst collapse-induced fault block collisions. Bulletin of Canadian Petroleum Geology. Vol. 65, Number 1.

Buckley, S.J., Ringdal, K., Naumann, N., Dolva, B., Kurz, T.H., Howell, J.A., Dewez, T.J.B., 2019. LIME: Software for 3-D visualization, interpretation, and communication of virtual geoscience models, Geosphere, 15(1): 222-235. doi:10.1130/GES02002.1.

Budd, D.A., Frost, E.L., Huntington, K.W., Allwardt, P.F., 2013. Syndepositional deformation features in high-relief carbonate platforms: long-lived conduits for diagenetic fluids. J. Sediment. Res. 83 (1), 12–36.

Caine, J.S., Evans, J.P., Forster, C.B., 1996. Fault zone architecture and permeability structure. Geology, 24, 1025-1028.

Cas, R., Giordano, G., Balsamo, F., Esposito, A., Lo Mastro, S., 2011. Hydrothermal breccia textures and processes: Lisca Bianca Islet, Panarea, Eolian Islands, Italy. Economic Geology, v. 106, p. 437-450.

Chi, G., Xue, C., Qing, H., Xue,W., Zhang, J., Sun, Y., 2012. Hydrodynamic analysis of clastic injection and hydraulic fracturing structures in the Jinding Zn-Pb deposit, Yunnan, China. Geosci. Front., 3, 73–84.

Corradetti, A., Tavani, S., Russo, M., Cazo Arubes, P. and Granado, P., 2017. Quantitative analysis of folds by means of orthorectified photogrammetric 3D models: a case study from Mt. Catria, Northern Apennines, Italy. The Photogrammetric Record 32(160): 480–496. https://doi.org/10.1111/phor.12212

Cozzi A., 2000. Synsedimentary tensional features in Upper Triassic shallow-water platform carbonates of the Carnian Prealps (northern Italy) and their importance as paleostress indicators. Basin research. 12, 133-146.

Črne, A.E., Šmuc, A., Skaberne, D., 2007. Jurassic neptunian dikes at Mt Mangart (Julian Alps, NW Slovenia). Facies 53 (2), 249–265. https://doi.org/10.1007/s10347-007-0102-8.

D'Argenio, 1976

D'Argenio, B. and Mindszenty, A. (1991). Karst bauxites at regional unconformities and geotectonic correlation in the Cretaceous of the Mediterranean.Bollettino Società Geologica Italiana 110, 85-92.

Eliassen, A. and Talbot, M.R., 2005. Solution-collapse breccias of the Minkinfjellet and Wordiekammen Formations, Central Spitsbergen, Svalbard: a large gypsum paleokarst system. Sedimentology (2005) 52, 775–794

Ezersky, M., Frumkin, A., 2013. Fault-dissolution front relations and the Dead Sea sinkhole problem. Geomorphology, v. 201, p. 35–44.

Finch, W.I., 1992. Descriptive model of solution-collapse breccia pipe uranium deposits. U.S. Geological Survey Bulletin, 2004. In: Bliss, J.D. (Ed.), Developments in Mineral Deposit Modelling, 33-35.

Friedman, G. M., 1997. Dissolution-collapse breccias and paleokarst resulting from dissolution of evaporite rocks, especially sulfates. Carbonates and Evaporites, 12(1), 53–63. doi:10.1007/bf03175802.

Frost, III, E. L., Kerans, C., 2010. Controls on syndepositional fracture patterns, Devonian reef complexes, Canning Basin, Western Australia. Journal of Structural Geology 32, 1231–1249.

Frost, III, E. L., Kerans, C., 2019. Platform-margin trajectory as a control on Syndepositional fracture Patterns, Canning Basin, Western Australia Journal of Sedimentary Research, 79, 44-55.

Frumkin, A., Ezersky, M., Al-Zoubi, A., Akkawi, E., Abueladas, A-R., 2011. The Dead Sea sinkhole hazard: Geophysical assessment of salt dissolution and collapse. Geomorphology, v. 134, p. 102–117.

Gilli, E., Levreet, A., Sollogoub, P., Delange, P., 1999. Research on the February 18, 1996 earthquake in the caves of Saint-Paul-de-Fenouillet area (eastern Pyrenees, France). Geodinamica Acta 12, 143–158.

Google Earth. Retrieved May 12, 2019, from: https://earth.google.com/web/@42.0704002,16.21249807,-55538.79210367a,62737.24758307d,35y,2.24086043h,27.24780939t,0.0646r?utm_source=earth7&utm_campaign=vine&hl=en

Graziano, R., 1999. The early cretaceous drowning unconformities of the Apulia carbonate platform (Gargano Promontory, southern Italy): local fingerprints of global palaeoceanographic events. Terra Nova 11, 245–250.

Graziano, R., 2000. The Aptian-Albian of the Apulia carbonate platform (Gargano Promontory, southern Italy): evidence of paleoceanographic and tectonic controls on the stratigraphic architecture of the platform margin. Cretaceous Research, 21, 107-126.

Graziano, R., 2001. The Cretaceous megabreccias of the Gargano Promontory (Apulia,southern Italy): their stratigraphic and genetic meaning in the evolutionary frameworkof the Apulia carbonate platform. Terra Nova 13, 110–116.

Gutiérrez, F., Guerrero, J. and Lucha, P., 2008. A genetic classification of sinkholes illustrated from evaporite paleokarst exposures in Spain. Environ Geol 53: 993.

Hairabian, A., Borgomano, J.R.F., Masse, J.-P.,Nardon, S., 2015. 3-D stratigraphic architecture, sedimentary processes and controlling factors of Cretaceous deep-water resedimented carbonates (Gargano Peninsula, SE Italy). Sedimentary Geology, 317, 116–136.

Haq, B. U., 2014. Cretaceous eustasy revisited: Global and Planetary Change, v. 113, p. 44–58, https:// doi.org/10.1016/j.gloplacha.2013.12.007

Haug, K., Chao, D., Hein, F. and Greene, P., 2009. Mapping surficial features in the Athabasca oil sands area using airborne LIDAR. Abstracts, 2009 Gussow Geoscience Conference, Engineering Sustainable Oil Sands Development. Canadian Society of Petroleum Geologists, Banff, Alberta.

Holland, M., Urai ,J. L., Martel, S., 2006. The internal structure of fault zones in basaltic sequences. Earth and Planetary Science Letters, 248, 301–315

Hsü, K.J., 1983. Neptunic dikes and their relation to the hydrodynamic circulation of submarine hydrothermal systems. Geology, 11 (8), 455–457. https://doi.org/10.1130/0091-7613(1983)11<455:NDATRT>2.0.CO;2

Hunt, D., Fitchen, W.M., 1999. Compaction and the dynamics of carbonate-platform development: insights from the Permian Delaware and Midland basins, Southeast New Mexico and West Texas, USA. In: Advances in Carbonate Sequence Stratigraphy Application to Reservoirs Outcrops and Models SEPM Special Publication. Society for Sedimentary Geology, pp. 75–106.

Jablonská, D., Di Celma, C.N., Alsop, G.I., Tondi, E., 2018. Internal architecture of mass-transport deposits in basinal carbonates: A case study from southern Italy. Sedimentology, 65, 1246–1276.

Jablonská, D., Di Celma, C., Korneva, I., Tondi, E., Alsop, I., 2016. Mass-transport deposits within basinal carbonates from southern Italy. Italian Journal of Geosciences, 135, 30–40.

Katz, D.A., Eberli, G.P., Swart, P.K., Langhorne Jr., B.S., 2006. Tectonic-hydrothermal brecciation associated with calcite precipitation and permeability destruction in Mississippian carbonate reservoirs, Montana and Wyoming. AAPG Bulletin, 90 (11), 1803-1841.

Korneva, I., Tondi, E., Jablonska, D., Di Celma, C., Alsop, I. and Agosta, F., 2016. Distinguishing tectonically- and gravity-driven synsedimentary deformation structures along the Apulian platform margin (Gargano Promontory, southern Italy) Mar. Pet. Geol., 73, 479–491.

Koša, E., Hunt, D., Fitchen, W.M., Bockel-Rebelle, M.-O., Roberts, G., 2003. The heterogeneity of palaeocavern systems developed along syndepositional fault zones: the Upper Permian Capitan Platform, Guadalupe Mountains,U.S.A. In: Ahr, W.M., Harris, P.M., Morgan, W.A. & Somerville, I.D. (eds) Permo-Carboniferous carbonate platforms and reefs. Society of Economic Paleontologists and Mineralogists, Special Publications, 78, 291–322.

Land, L.A., Paul,C.K., 2000. Submarine karst belt rimming the continental slope in the Straits of Florida. Geo-Marine Letters, 20,123-132.

Laurita S., Agosta F., Cavalcante F., Rustichelli A., Giorgioni M., 2016. Shearing of syn-sedimentary carbonate breccia along strike-slip faults, Altamura Fm., Southern Italy, in Italian Journal of Geosciences, 135, 41-54.

Leach, D.L., Taylor, R.D., Fey, D.L., Diehl, S.F. and Saltus, R.W., 2010. A deposit model for Mississippi Valley-Type lead zinc ores: chapter A. In: Mineral Deposit Models for Resource Assessment. USGS Scientific Investigations Report 2010-5070-A, 64.

Lehner, B.L., 1991. Neptunian dykes along a drowned carbonate platform margin: an indication for recurrent extensional tectonic activity? Terra. Nova 3, 593–602.

Loucks, R. G., 1999. Paleocave carbonate reservoirs: origins, burial depth modifications, spatial complexity, and reservoir implications: AAPG Bulletin, v. 83, 1795– 1834.

Loucks, R.G., 2001. Modern analogs for paleocave-sediment fills and their importance in identifying paleocave reservoirs. Transactions-Gulf Coast Association of Geological Societies, 46, 195-206.

Loucks, R. G., P. Mescher, G. A. McMechan, 2000. Architecture of a coalesced, collapsed-paleocave system in the Lower Ordovician Ellenburger Group, Dean Word Quarry, Marble Falls, Texas.- Final report prepared for the Gas Research Institute, GRI00/0122, CD-ROM.

Loucks, R. G., Mescher, P., McMechan, G. A., 2004. Three-dimensional architecture of a coalesced, collapsed-paleocave system in the Lower Ordovician Ellenburger Group, central Texas. AAPG Bulletin 88(5), 545-564. DOI: 10.1306/12220303072

Luperto Sinni, E., Masse, J.P., 1987. Données nouvelles sur la stratigraphie et la micropaléontologie des séries carbonatées de talus et de basin du Crétacé inférieur du Gargano (Italie méridionale). Rivista Italiana di Paleontologia e Stratigrafia 93, 347-378.

Maestrelli, D. , Iacopini , D. , Jihad , A. , Bond , C. E., Bonini , M. 2017. Seismic and structural characterization of fluid escape pipes using 3D and partial stack seismic from the Loyal field (UK): A multiphase and repeated intrusive mechanism, Marine and Petroleum Geology, vol. 88 , 489-510.

Martinis, B. and Pavan, G., 1967. Note Illustrative Della Carta Geologica D'Italia Alla Scala 1:100000, Foglio 157, Monte Sant'Angelo. Servizio Geologico d'Italia, Roma, 56.

Melosh, B.L., Rowe, C. D., Smit, L., Groenewald, C., Lambert, C. W., Macey, P., 2014. Snap, Crackle, Pop: Dilational fault breccias record seismic slip below the brittle–plastic transition. Earth and Planetary Science Letters 403 (2014) 432–445.

Miccadei, E., Mascioli, F., & Piacentini, T. (2011a). Quaternary geomorphological evolution of the Tremiti Islands (Puglia,Italy). Quaternary International, 232, 3–15.

Monti, F., Brozzetti, F., Lavecchia, G., 2005. Structural and kinematic analysis of the Mattinata fault zone (Gargano, southern Italy): Implications for the active deformation field: Convegno Gruppo Nazionale Geofisica della Terra Solida 2005: Trieste, Tergeste grafica, Abstract book, v. 24, 36–37.

Moore, C.H, Wade, W.J, 2013. Carbonate reservoirs: Porosity and Diagenesis in a Sequence Stratigraphic Framework. V. 67, 392. ISBN: 9780444538314

Morsilli, M., Bosellini, A., 1997. Carbonate facies zonation of the Upper Jurassic-Lower Cretaceous Apulia Platform margin (Gargano Promontory, southern Italy). Rivista Italiana di Paleontologia e Stratigrafi a 103, 193-206.

Morsilli, M., Rusciadelli, G., Bosellini, A., 2004. The Apulia carbonate platform-margin and slope, Late Jurassic to Eocene of the Maiella Mt. and the Gargano Promontory: Physical stratigraphy and architecture. 32nd Int. Geol. Congress. (3). 14-36.

Neri, C., Luciani, V., 1994, The Monte S. Angelo Sequence (Late Cretaceous–Paleocene, Gargano Promontory, southern Italy): physical stratigraphy and biostratigraphy: Giornale di Geologia, v. 56, p. 149–165

Nesbit, P. R., Durkin, P. R., Hugenholtz, C. H., Hubbard, S. M., Kucharczyk, M., 2018. 3-D stratigraphic mapping using a digital outcrop model derived from UAV images and structure-from-motion photogrammetry, *14*(6), 1–18. https://doi.org/10.1130/GES01688.1/4457638/ges01688.pdf

Parino, N., Agosta, F., Di Stefano, P., Napoli, G., Pepe, F., Renda, P., 2019. Fluid storage and migration properties of sheared Neptunian dykes. Marine and Petroleum Geology 102, 521-534

Park, F. C. Jr, MacDiarmid, R. A., 1970. Ore Deposits. Geological Magazine, vol. 109, issue 1, 69-69

Pitts, A. D., Casciano, C. I., Patacci, M., Longhitano, S. G., Di Celma, C., & McCaffrey, W. D. (2017). Integrating traditional field methods with emerging digital techniques for enhanced outcrop analysis of deep water channel-fill deposits. *Marine and Petroleum Geology*, *87*. https://doi.org/10.1016/j.marpetgeo.2017.05.001

Pitts, A. D., Jablonská, D., Donato, V. Di, Mazzoli, S., Spina, V., Celma, C. Di, & Tondi, E. (2020). Sedimentological and stratigraphic signature of the Plio-Pleistocene tectonic events in the Southern Apennines, Italy: The Calvello-Anzi Basin case study. *Marine and Petroleum Geology*, *116* (December 2019), 104198. https://doi.org/10.1016/j.marpetgeo.2019.104198.

Playford, P. E., Hocking, R. M., Cockbain, A. E., 2009. Devonian reef complexes of the Canning Basin, Western Australia. Geological Survey of Western Australia, Bulletin 145, 444.

Principaud, M., Mulder, T., Gillet, H., and Borgomano, J., 2015. Large-scale carbonate submarine mass-wasting along the northwestern slope of the Great Bahama Bank (Bahamas): morphology, architecture, and mechanisms. Sed. Geol., 317, 27–42.

Rustichelli, A., Iannace, A., Tondi, E., Di Celma, C., Cilona, A., Giorgioni, M., Parente, M., Girundo, M., Invernizzi, C., 2017. Fault□controlled dolomite bodies as palaeotectonic indicators and geofluid reservoirs: New insights from Gargano Promontory outcrops Sedimentology, 64, 1871–1900.

Salvini, F., Billi, A., Wise, D. U., 1999. Strike-slip fault-propagation cleavage in carbonate rocks: the Mattinata Fault Zone, Southern Apennines, Italy. *Journal of Structural Geology*. 21, 1731-1749.

Santantonio M., Scrocca D., Lipparini L., 2012. The Ombrina-Rospo Plateau (Apulian Platform): Evolution of a carbonate platform and its margins during the Jurassic and Cretaceous. Marine and Petroleum Geology, Special Issue: The Geology of the Periadriatic Basin and of the Adriatic Sea, v. 42, p. 4 -29.

Santo, A., Ascione, A., Del Prete, S., Di Crescenzo, G. and Santangelo, N., 2010. Collapse sinkholes distribution in the carbonate massifs of central and southern Apennines. *Acta Carsologica*. 40/1, 95-113.

Shanmugan, G., 2017. The fallacy of interpreting SSDS with different types of breccias as seismites amid the multifarious origins of earthquakes: Implications. Journal of Palaeogeography, 2017, 6(1): 12-44. http://dx.doi.org/10.1016/j.jop.2016.09.001

Sibson, R.H., 1986. Brecciation processes in fault zones: inferences from earthquake rupturing. Pure and Applied Geophysics, 124, 159–175.,

Smart, P., L., Palmer, R.J., Whitaker, F., Wright, V. P., 1988. Neptunian Dikes and Fissure Fills: An Overview and Account of Some Modern Examples. Paleokarst, 149-162.

Tavani S., Granado P., Girundo M., Iannace A., Arbues P., Muñoz J.A. and Mazzoli S., 2014. Building a virtual outcrop, extracting geological information from it, and sharing the results in Google Earth via OpenPlot and Photoscan: An example from the Khaviz Anticline (Iran). Computers & Geosciences, 63, 44-53.

Taviani, M., Angeletti, L., Campiani, E., Ceregato, A., Foglini, F., Maselli, V., Morsilli, M., Parise, M., Trincardi, F., 2012. Drowned karst landscape offshore the Apulian margin (Southern Adriatic Sea, Italy). Journal of Cave and Karst Studies, v. 74, no. 2, p. 197–212. DOI:10.4311/2011JCKS0204

Talling, P.J., Wynn, R.B., Masson, D.G., Frenz, M., Cronin, B.T. and Schiebel, R., 2007. Onset of submarine debris flow deposition far from original giant landslide. *Nature*, vol. 450, 541.

Thomas, T.M., 1971. Gash-breccias of South Pembrokeshire: fossil karstic phenomena?Trans. Inst. Br. Geogr. 54, 89-100.

Tondi, E., Piccardi, L., Cacon, S., Kontny, B., Cello, G., 2005. Structural and time constraints for dextral shear along the seismogenic Mattinata fault (Gargano, southern Italy): Journal of Geodynamics, v. 40, 134–152, doi: 10.1016/j.jog.2005.07.003.

Walker, R. J., Holdsworth, R. E., Imber, J., Ellis, D., 2011. The development of cavities and clastic infills along fault-related fractures in Tertiary basalts on the NE Atlantic margin. Journal of Structural Geology. 33, 92-106.

Walsh, P., Battiau-Queney, Y., Howells, S., Ollier, C., Rowberry, M., 2008. The gash breccias of the Pembroke Peninsula, SW Wales. Geol. Today 24, 13

Wang, A.J., Gao, L., Liu, J.L., Cao, D.H., Xiu, Q.Y., Fan, S.J., 2007. Genesis of the breccia in the host rocks of the super-large Jinding Pb-Zn deposit. Acta Geologica Sinica 81, 891-911.

Winter, T., Tapponnier, P., 1991. Extension majeure post-Jurassique et ante-Miocène dans le centre de l'Italie: données microtectoniques Bulletin de la Societé Geologiques de France, 162, 1095-1108.

Winterer, E.L., Metzler, C.V. and Sarti, M., 1991. Neptunian dykes and associated breccias (Southern Alps, Italy and Switzerland): role of gravity sliding in open and closed systems. Sedimentology (1991) 38,381-404.

Mort, K. and Woodcock, N. H., 2008. Quantifying fault breccia geometry: Dent Fault, NW England. Journal of Structural Geology, 30(6), 701–709. DOI:10.1016/j.jsg.2008.02.005

Woodcock, N.H., Omma, J.E., Dickson, J.A.D., 2006. Chaotic breccia along the Dent Fault, NW England: implosion or collapse of a fault void? Journal of the Geological Society London, 163, 431-446.

Woodcock, N.H., Mort, K., 2008. Classification of fault breccias and related fault rocks. Geol. Mag. 145, 435-440.

Woodcock, N.H., Miller, A.V.M., Woodhouse, C.D., 2014. Chaotic breccia zones on the Pembroke Peninsula, south Wales: evidence for collapse into voids along dilational faults. Journal of Structural Geology, 69, 91-107.

Wieczorek, J., Olszewska, B., 2001. Cretaceous neptunian dykes of the Cracow Upland. Geol Saxon 46 (47), 139–147.

1) The large vertical breccia bodies (LVBBs) are ubiquitous in slope-to-basinal carbonates, Gargano Promontory, Southern Italy
2) The LVBBs can be up to 80 m high, 40 m wide and over 60 m long and they display chaotic clast arrangement or occasional clast alignment
3) The LVBBs follow the fault network in the studied area
4) Structural features and occasional pervasive dolomite cements suggest various origin (solution breccia collapses, fault –related dilatational breccia) and timing (Cretaceous and Miocene) of formation

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: