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Record of Late Neogene seismites in turbidite deposits of the Tafna Basin (NW Algeria)

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The wide variety of soft-sediment deformation structures (SSDS) developed within deposits of the same age may hinder the interpretation of their origin. Some types of SSDS may appear similar though have different trigger mechanisms, while others may result from a specific mechanism. Furthermore, the development of particular SSDS may be influenced by several synchronous or semi-synchronous factors. This study deals with the recognition of SSDS trigger mechanisms with respect to lithological and deformational features of the deposits concerned. Turbidite deposits of late Neogene age in the Hadjret El Gat area (Tafna Basin) contain different types of SSDS associated with (1) slope processes (e.g., slump folds) and induced overburden pressure, coupled with broken beds and overloading structures, and (2) liquefaction and fluidisation phenomena, leading to the development of load structures, ball-and-pillow structures, water-escape structures and syndepositional faults. These two mechanisms of SSDS formation in the study area are thought to result from seismically-induced triggers. Recognition of a vertically-repeated, sandwich-like arrangement of deformed and undeformed layers along with the SSDS features ("trapped" within beds) suggests that these internally-deformed beds are seismites, the first recognized in the Tafna Basin of NW Algeria. Large earthquakes may trigger seismic waves energetic enough to deform strata and induce the development of SSDS. This hypothesis is supported here by tectonic evidence, given deposition of the Tafna Basin strata in the convergence zone between Africa and Eurasia, active since the late Neogene.

Key words: soft-sediment deformation structures, liquefaction, seismites, mass flows, turbidite; tectonic activity, Tafna Basin, Neogene, Miocene.

INTRODUCTION

Soft-sediment deformation structures (SSDS) are found in all depositional environments, including lacustrine/glaciolacustrine, marine, fluvial/glaciofluvial, lagoonal, periglacial one etc. (Seilacher, 1969; Allen, 1977; Owen, 1987, 1996; Jones and Omoto, 2000; Moretti, 2000; Moretti et al., 2001; Mazumder et al., 2006; Montenat et al., 2007; Owen and Moretti, 2011; Owen et al., 2011; Pisarska-Jamroży and Zieliński, 2012; Pisarska-Jamroży, 2013; Pisarska-Jamroży and Weckwerth, 2013; Bhat et al., 2016; Umair and Syed Ahmad, 2018; Koç-Taşgın and Altun, 2019). Such deformation structures are thought to be formed during or shortly after deposition (Rossetti, 1999) leading to rearrangement of the original sedimentary structures (Maltman, 1984).

SSDS are a widely reported phenomenon in a variety of tectonic settings, including passive continental margins, subduction zones, and strike-slip environments (Waldron and Gagnon, 2011). They may also be induced by exogenic forcing e.g., glacio-isostatic rebound (Brandes et al., 2015; Van Loon et al., 2016; Woźniak and Pisarska-Jamroży, 2018; Pisarska-Jamroży et al., 2018, 2019a, b; Pisarska-Jamroży and Woźniak, 2019). Moreover, SSDS may preserve the records of changes that sediments have undergone due to 1) gravity-driven processes operating on a palaeoslope; these include the folds and flexures commonly developing within slumps (e.g., Farrell and Eaton, 1987; Bradley and Hanson, 1997; Alsop et al., 2007; Pisarska-Jamroży, 2006, 2008); 2) liquefaction and/or fluidisation induced by earthquakes; these include load casts,

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pseudonodules, ball-and-pillow structures, water-escape structures (Allen, 1982; Owen, 1987; Moretti and Ronchi, 2011).

Many attempts have been made to infer the genesis of the SSDS on the basis of lithological features (e.g., Woźniak and Pisarska-Jamroży, 2016; Belzyt et al., 2021; Woźniak et al., 2021). However, the discrimination of several trigger mechanisms that were operating simultaneously (or semi-synchronously) remains a challenge. No objective criteria to distinguish them have yet been established (cf. Mulder et al., 2011; Shanmugam, 2016).

This study (1) reconstructs the development of SSDS recorded in the Hadjret El Gat turbidite succession in the Miocene Tafna Basin (northwestern Algeria) (2) defines diagnostic features for SSDS of seismic origin, and (3) determines features of SSDS that develop synchronously or semi-synchronously as a consequence of both seismic and mass flow processes.

GEOLOGICAL SETTING

The Tafna Basin is an intramontane Neogene basin located on the northern coast of Algeria (Fig. 1A). It is bordered by the Mediterranean Sea to the north and by the Tlemcen Mountains, Traras Mountains and Tessala Mountains to the south, west and east, respectively (Fig. 1B). The Miocene of the Tafna Basin includes deposits of both marine and continental origin (Mahboubi et al., 2015; Benzina et al., 2023). There are few biostratigraphic studies of these deposits. Guardia (1975) interpreted their Serravallian age from the presence of *Globoratalia mayeri* and *Globorotalia menardii* that correspond to N14, N15 and N17 of the Blow biozonation. Furthermore, Mazouzi (2004) assigned a Serravallian age to the turbidite deposits due to the presence of the calcareous nannofossil species *Discoaster kugleri, D. bellus* and *D. calcaris*. This interval corresponds to the reddish clayey marls of the Lower Chelif Basin (Benzina et al., 2019), with Boucif (2006) and Benzina (2014) reconstructing the geodynamic and sedimentological evolution of the basin.

Some authors inferred recurring seismic activity during the sedimentation of the turbidite deposits in the Hadjret El Gat area. According to Glangeaud (1951), Dubourdieu (1962) and Andrieux (1971), the Tafna Basin was tectonically active during the late Neogene (Miocene), being dominated by extensional tectonics during the Serravallian-Lower Tortonian and compressional tectonics during the upper Tortonian-Messinian. This interval of seismic activity was followed by volcanic (rhyolitic) activity from the late Miocene at ~14 Ma (Megartsi, 1985). Boukhedimi et al. (2017) and Guessoum et al. (2018), in their studies of the coastal Quaternary deposits from NW Algeria, indicated seismic activity during this period.

The Hadjret El Gat section under study (Fig. 1B) occupies the central part of the Tafna Basin. The N–S oriented section is located ~30 km south of the coastline and 30 km north of the city of Tlemcen (Fig. 1A). The Hadjret El Gat section (300 m thick) comprises alternations of thick-bedded slumped sandstones (with turbidite features, see Fig. 2E) with bluish marls (Fig. 2). It was divided into seven members (see M1–M7 in Fig. 2A) ranging from 12 to 45 m in thickness (Fig. 2B–F), the marine deposits of Hadjret El Gat being unconformably overlain by Quaternary fluvial terrace deposits that consist mainly of polygenetic conglomerates, gravels and silts with a reddish mud matrix (Fig. 2F).

METHODS

The 300 m thick sedimentary succession at Hadjret El Gat was divided into seven members (Fig. 2A) by Benzina (2014). Deformation structures recorded in the sandstone-marls beds (Fig. 2) were investigated and described. Observed SSDS were studied in relation to lateral sedimentary variations, changes in the style and intensity of deformation, and the dimensions, shapes and position of deformation structures within the beds.

Interpretation of lithological features of the SSDS aimed at determining the processes generating them. Two groups of deformation structures were identified and associated: (1) liquefaction phenomena, i.e. unstable density contrasts when sediment becomes liquidised (load structures, pseudonodules, ball-and-pillow structures, water-escape structures); and (2) mass movements (e.g., folds, broken beds, overloading structures). Criteria adopted from Owen and Moretti (2011) were used diagnostically, to identify the trigger(s) of the deformation structures.

RESULTS AND INTERPRETATION

The SSDS commonly occurring within the Hadjret El Gat succession were divided into two genetically-related groups associated with: (1) mass movements, and (2) liquefaction and fluidisation phenomena. The SSDS-hosted beds are tilted and overturned towards the NNE. This direction corresponds to an asymmetrical anticline on the southern side of Mt. Djedir (Benzina, 2014).

SOFT-SEDIMENT DEFORMATION STRUCTURES LINKED WITH MASS MOVEMENTS

Description. The vertical succession of sandstones interbedded with marls at Hadjret El Gat includes numerous medium- to large-scale folds (ranging from 0.50 m up to >20 m; Fig. 3B–D) with an overall vergence towards the south. These folded beds bear numerous broken (Fig. 4A–C) and overloading structures (Fig. 4D, E). The latter form massive, south-inclined bodies, the lowermost parts of which are thickened and the uppermost parts bevelled (Fig. 4B, C). Furthermore, their lowermost parts are enriched in shallow marine fossils, such as bivalves and gastropods (Fig. 4F).

INTERPRETATION

The generally unidirectional inclination of folds recorded at Hadjret El Gat, towards the south, indicates their slump-induced origin. They are usually accompanied by broken beds. Both structures develop due to the stretching of beds as these move downslope. Inclined overloading structures originate from the sudden and rapid sliding of unconsolidated sediments on a slope (Fig. 4A, E) as previously reported by Doe and Dott (1980) and Jones and Rust (1983). Downslope movement of sediments recorded in the Hadjret El Gat section is indicated by (1) the shape of overloading structures, which follows the direction of sliding (Fig. 4A–C), and (2) an increase in the content of shallow marine fossils in the lowermost parts of overloading structures, resulting from redeposition processes on the slope (Fig. 4F).

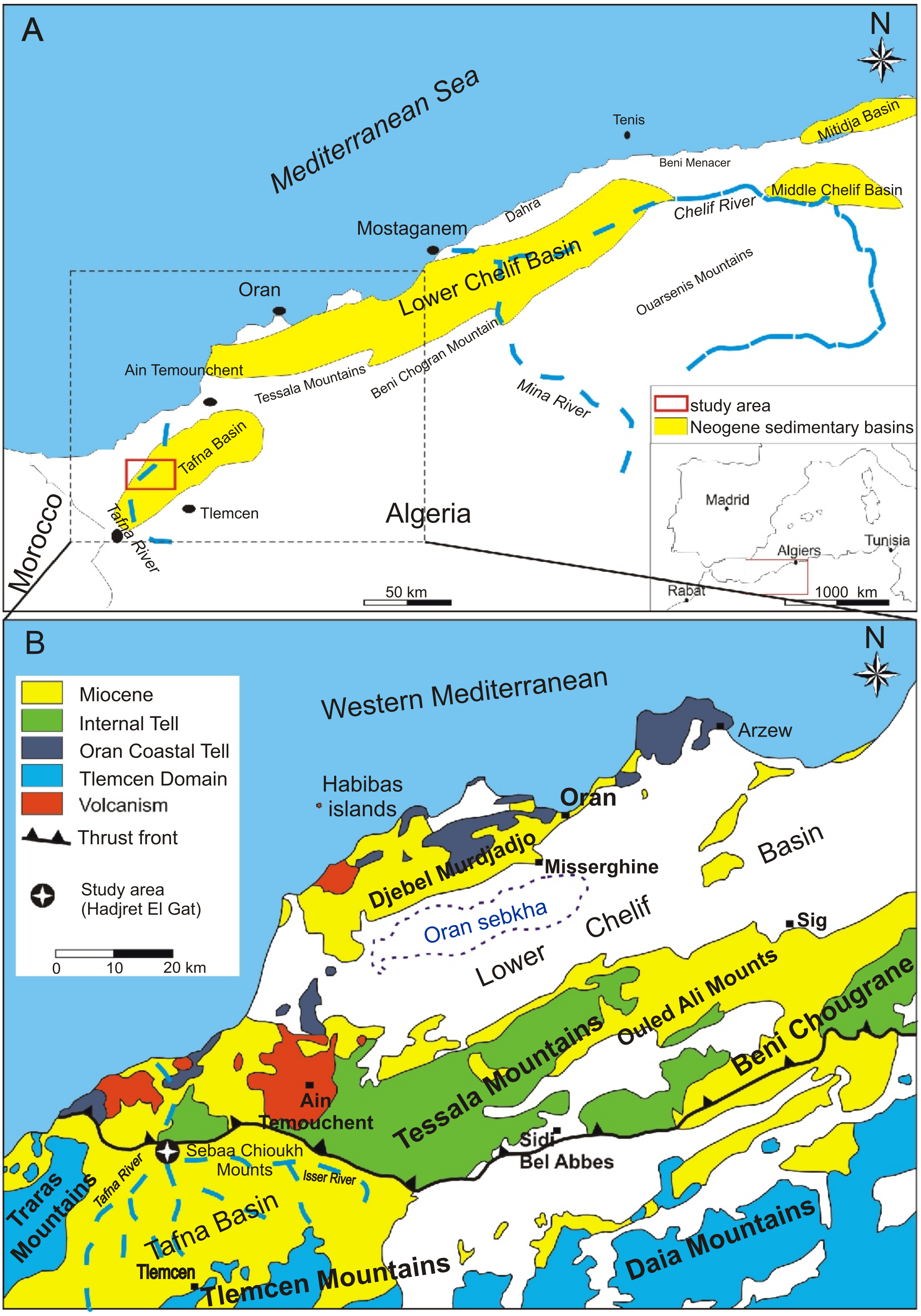

Fig. 1. Geological map of the study area

A – location of the Neogene basins of NW Algeria;
B – location of the Hadjret El Gat section in the Tafna Basin (Naimi et al., 2021, modified)

Slump folds commonly recorded in unconsolidated sediments are interpreted as direct evidence of downslope movement resulting from the partial loss of sediment strength and applied shear due to gravity (cf. Collision, 1994). This downwards movement of sediments depends on their angle of repose, the values of which vary when the sediments' mass increases (Alves and Lourenço, 2010; Alves, 2015). However, the common occurrence of slump folds in the Hadjret El Gat section may also indicate sedimentary instability due to recurring earthquakes (cf. Ross et al., 2013; Valente et al., 2014).

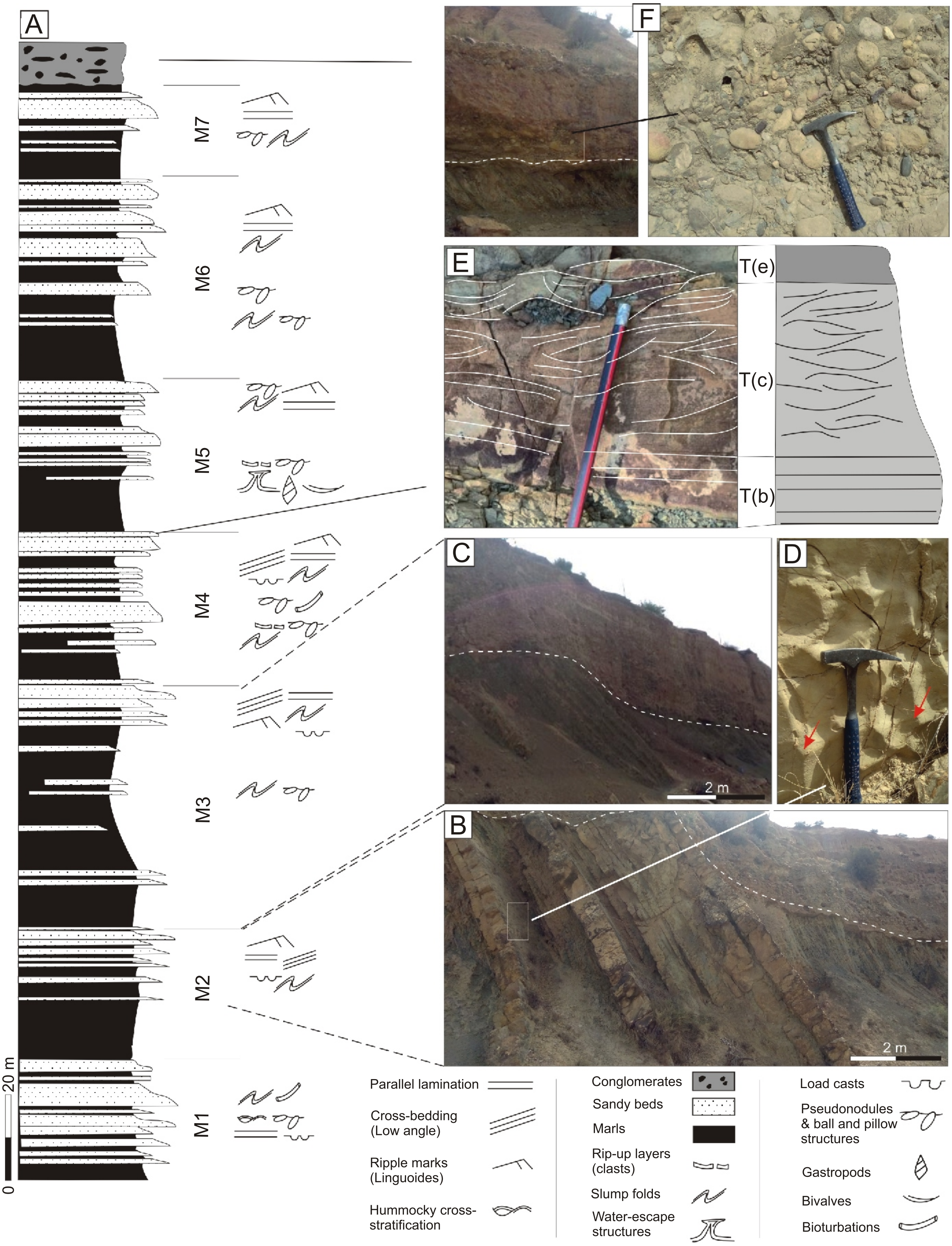

Fig. 2. Sedimentary succession of the Hadjret El Gat with details (after Benzina, 2014)

A – stratigraphic log of the Hadjret El Gat section divided into seven sedimentary members (M1–M7); **B** – sandstone beds overlain unconformably by conglomerates; **C** – marl beds overlain unconformably by conglomerates; **D** – linguoid ripples (red arrows indicate palaeocurrent direction); **E** – part of a Bouma sequence observed in the Hadjret El Gat section with identified T(c), T(b) and T(e) units; **F** – polygenetic conglomerates

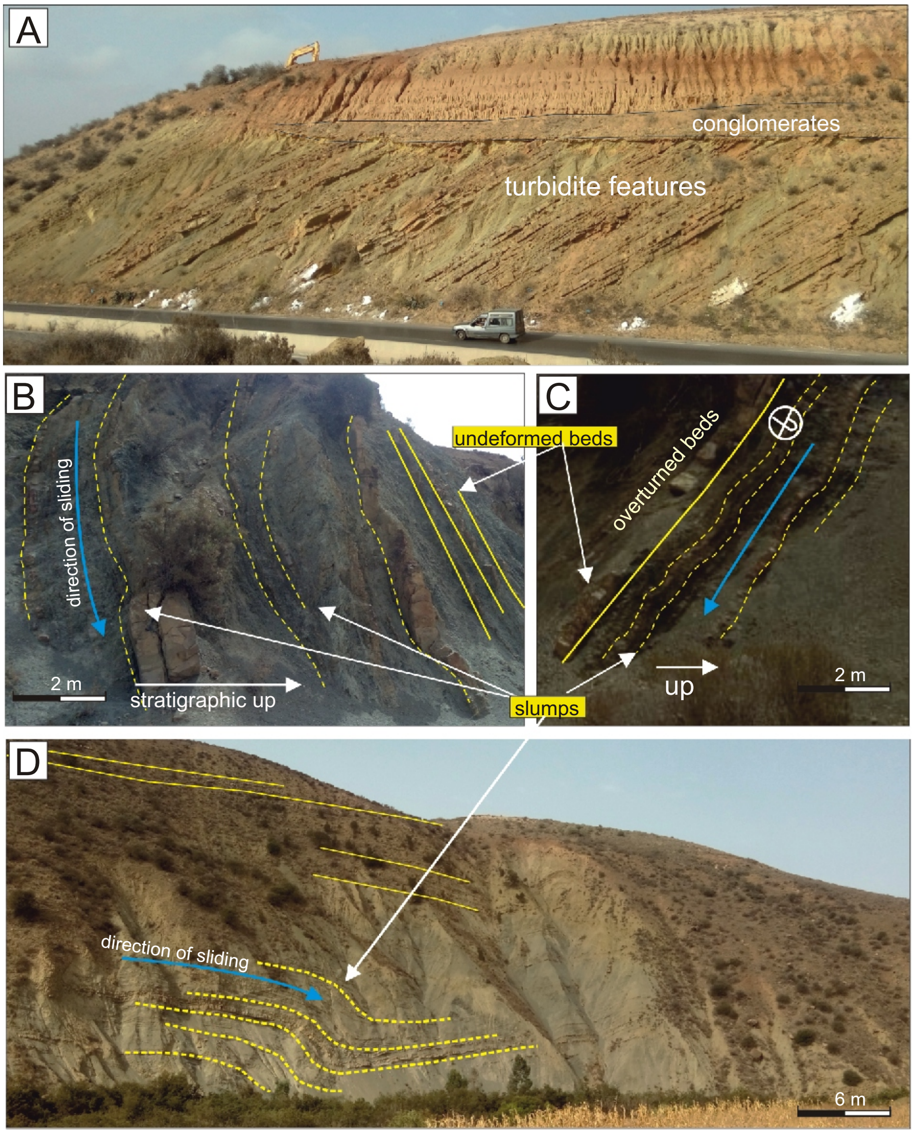

Fig. 3. Stratigraphic position of sandstones with soft-sediment deformation structures

A – turbidite deposits observed in the lowermost part of the Hadjret El Gat section; **B** – small- to medium-scale slump folds in (M4) showing sediment overloading parallel to the undeformed beds and the direction of sliding; **C** – overturned set of beds in (M6) showing undeformed bed directed parallel to the slump folds; **D** – large-scale slump folds in (M3) indicating the direction of sliding

SOFT-SEDIMENT DEFORMATION STRUCTURES LINKED WITH LIQUEFACTION AND FLUIDISATION PHENOMENA

LOAD STRUCTURES
(LOAD CASTS AND PSEUDONODULES)

Description. Load casts are abundant at the boundary between the medium- and coarse-grained sandstones and the overlying mudstones. They are characteristically semi-circular, a few centimeters across (Fig. 5A). Well-developed load casts of centimetre-scale with internal co-shaped lamination are also observed in cross-section (Fig. 5B). Moreover, the sandstones contain small and medium-scale pseudonodules (from 0.5 to 1 m wide), which are equidimensional and spheroidal in shape (Fig. 5C–E). They commonly appear in attached forms, mainly in thin layers of the fine- and medium-grained sandstones.

Interpretation. Load casts formed at the boundary between sand and overlying mud are commonly found in different environments indicating unequal loading or reversed density gradients due to seismic shaking (Mohindra and Thakur, 1998; Owen, 2003; McCalpin, 2009; Topal and Özkul, 2014; Roy and Banerjee, 2016; Mazumder et al., 2016; Rana et al., 2016; Woźniak et al., 2016; He et al., 2018; Belzyt et al., 2021). In the Hadjret El Gat section, the medium or coarse-grained unconsolidated sands sank into the underlying mud (Fig. 5A). The morphology of load structures is controlled by several factors, such as the duration of the liquidised state, the magnitude of the density gradient, and kinematic viscosity (cf. Chiarella et al., 2016). The most advanced stage of their formation, when load casts cut into water-saturated fine-grained sediments, is represented by pseudonodules (cf. Kuenen, 1958), formed by the sagging of sandy load casts into underlying silty/sandy liquefied sediments (cf. Olivera et al., 2011; Yang et al., 2016).

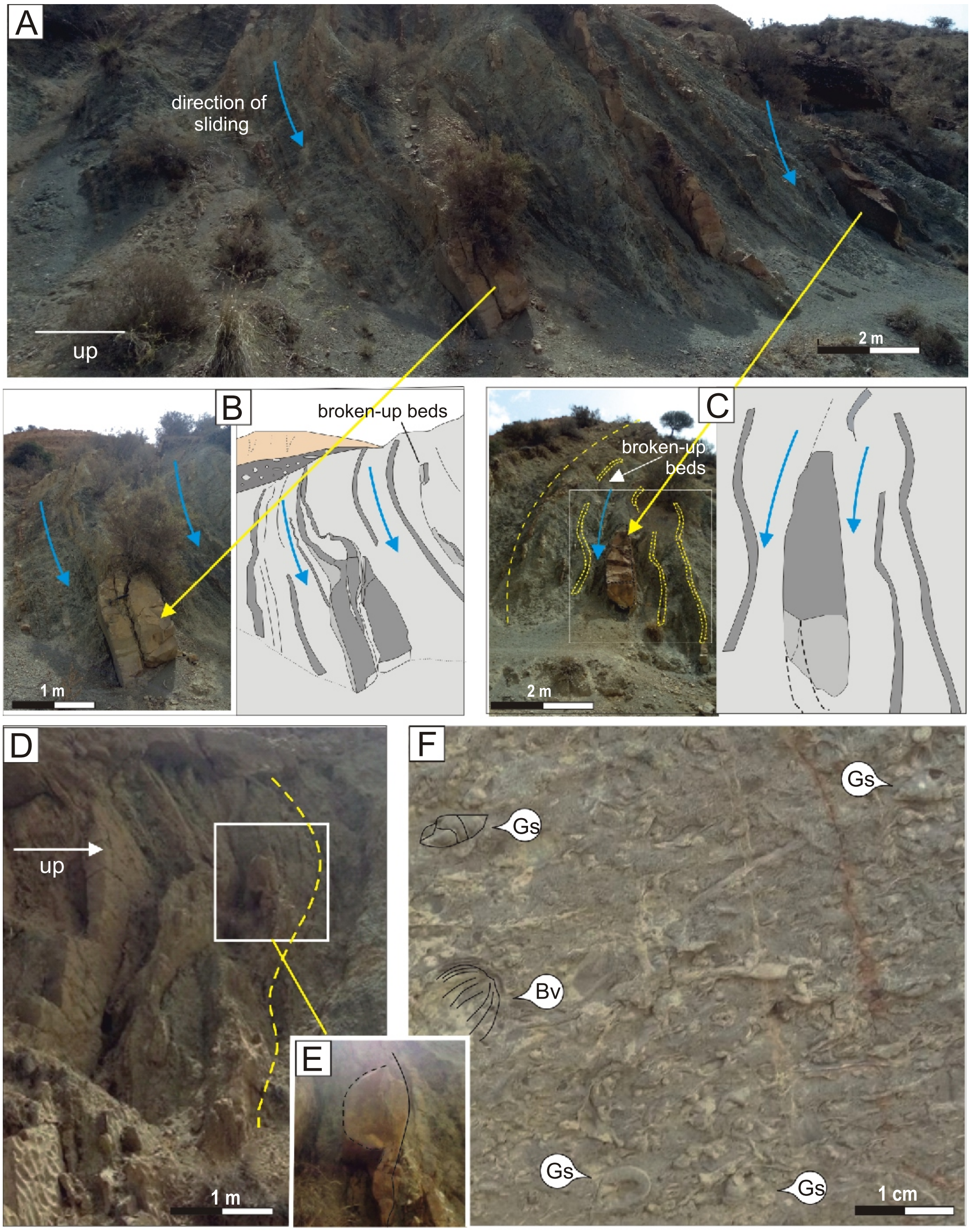

Fig. 4. Mass-movement features in the Hadjret El Gat section

A – alternation of marls and slump-fold beds; **B**, **C** – detached structure of massive sediment overloading in (M4) associated with slump folds and broken beds; **D** – attached structure of massive sediment overloading in (M3) associated with slumps folds and broken beds; **E** – in (M3) shows an overloading structure; **F** – bottommost surface of deposits enriched in shallow marine fossils from (M4): Gs – gastropods, Bv – bivalves

BALL-AND-PILLOW STRUCTURES

Description. Ball-and-pillow structures are not as abundant in the section studied as the load structures described above. They are observed mainly in 2–3 m thick sandstones that occupy the lowest part of the section. These structures are infilled with massive coarse-grained sand and surrounded by fine-grained sands (Fig. 5F–I). The ball-and-pillow structures are usually 0.5 m in diameter and subspherical or circular in shape (Fig. 5H). These structures are slightly curved or inclined towards the SE, which corresponds to the inclination of layers in which they are hosted.

Interpretation. Ball-and-pillow structures are formed due to the penetration of less dense sediments into overlying sediments of higher density (cf. Collison, 1994). The mobilisation of these less dense sediments occurs due to liquefaction induced most commonly by earthquake shaking (cf. Oliveira et al., 2011; Bhat et al., 2016; Roy and Banerjee, 2016). The inclination of ball-and-pillow structures and their hosting layers in the same direction suggests their semi-synchronous origin. After the

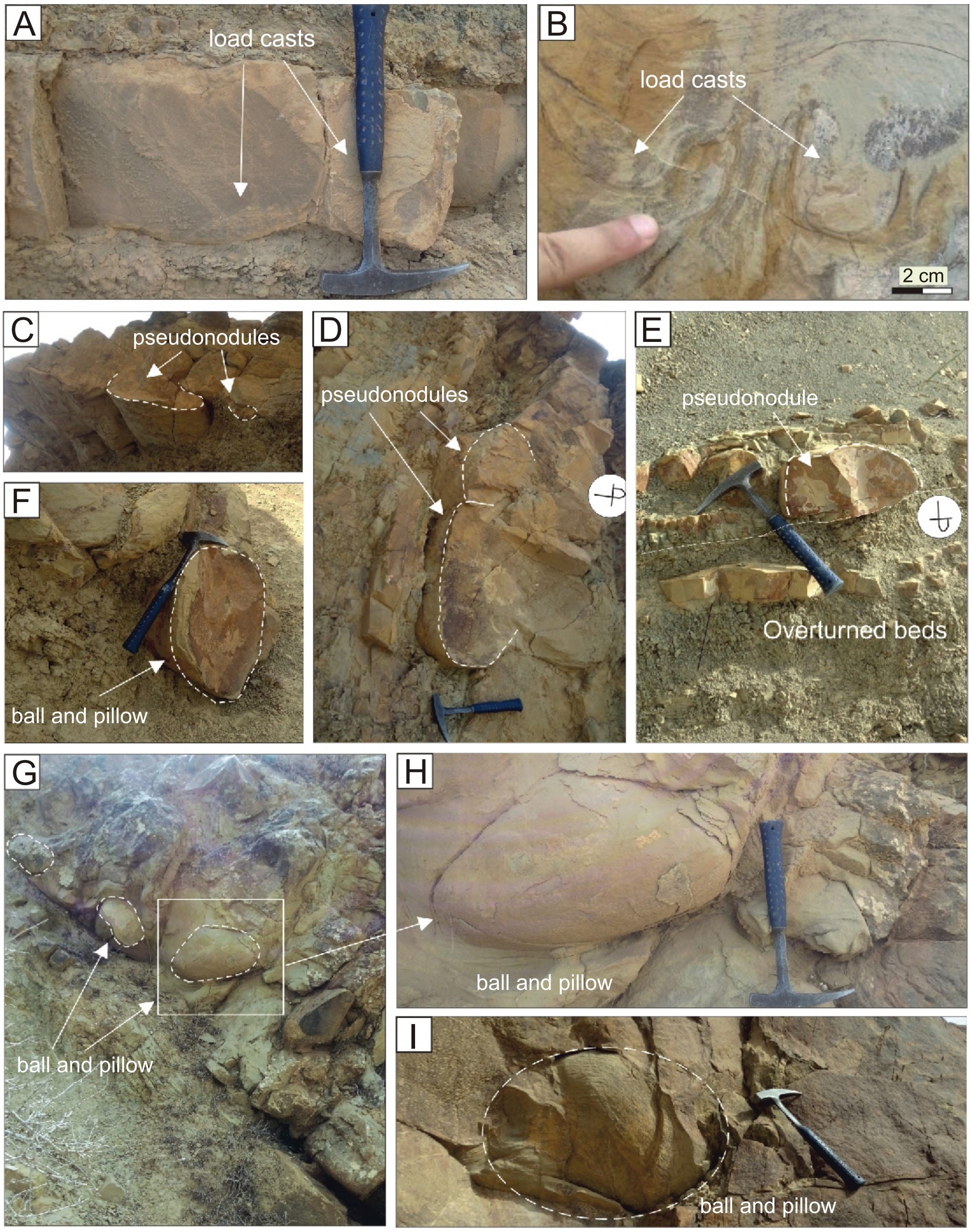

Fig. 5. Deformation structures associated with liquefaction phenomena recorded in the Hadjret El Gat section

A, **B** – load casts in sandstones in (M6, M2) respectively; **C–E** – from (M3, M7) pseudonodules of different shapes and sizes; **F–I** – ball-and-pillow structures in (M1, M3 and M5)

main phase of formation, ball-and-pillow structures underwent deformation (in a saturated, plastic state) due to mass flow processes.

WATER-ESCAPE STRUCTURES

Description. Water-escape structures are observed only within some of the beds studied beds in the lower and middle parts of the Hadjret El Gat section (Fig. 6A–C). These cm-sized, convex structures disturb the horizontally-laminated sandstones.

Interpretation. Water-escape structures are formed when the pore-fluid pressure in the sediment exceeds its threshold value due to the sedimentary overload (cf. Lowe, 1975; Allen, 1982) or to progressive seismic processes (cf. Dasgupta and Chatterjee, 2019). As a consequence of these, large amounts of fluid become released due to compaction of sediments and contribute to water-escape structure development (Odonne et al., 2011). The primary lamination of the deposits studied was

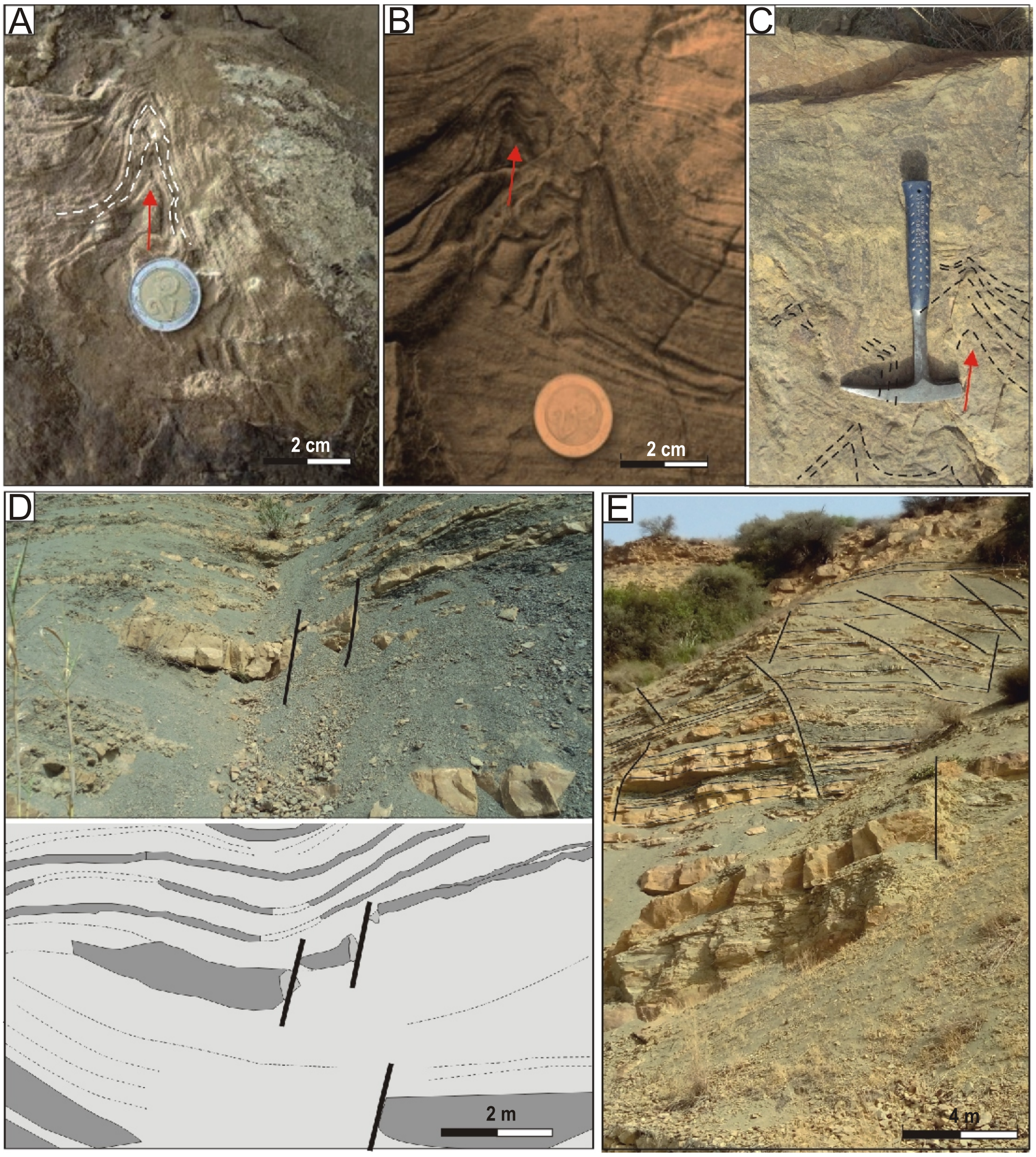

Fig. 6. Deformation structures associated with liquefaction and fluidisation phenomena in the Hadjret El Gat section

A–C – water-escape structures in (M4, M2); red arrows indicate the direction of fluid/sediment movement; **D** – synsedimentary faults and their interpretation in (M4) (the lower one sketched); **E** – parallel-oriented synsedimentary faults in (M4)

destroyed due to fluidization accompanied by upward injection of sediments (Lowe, 1975; Hurst and Cartwright, 2007; Hurst et al., 2011). The curved orientation of the water-escape structures resulted from path trajectories along fault and other heterogeneities in the sediment (cf. Chiarella et al., 2016).

FAULTS

Description. Several, well-exposed normal faults are present in the Hadjret El Gat section. Beds with faults are interbedded with undeformed beds, forming a sandwich-like sedimentary arrangement (Fig. 6D, E). The fault offsets range from centimetres up to tens of centimetres. The faults recorded are vertically- to subvertically-oriented (Fig. 6D) with straight planes. They are inclined towards the SSE.

Interpretation. The faults observed developed within horizontally-arranged beds and are interpreted as synsedimentary (cf. Bhat et al., 2016), their development depending on the rheology of the sediments during faulting (cf. Mazumder et al., 2016). Miyata (1990) associated synsedimentary faults with local seismic activity. The instantaneous action of stress leads to an increase in pore pressure and then to the formation of semi-brittle types of SSDS (Vanneste et al., 1999; Singh and Jain, 2007).

DISCUSSION

The study area belongs to the Tafna Basin, influenced by the Algerian active continental margin. The latter is commonly regarded as a plate boundary between Africa and Eurasia, and corresponds to a seismically-active convergent zone (Boukhedimi et al., 2017). Furthermore, late Neogene (Miocene) sedimentation in the Tafna Basin was dominated by both extensional (Serravallian-Lower Tortonian) and compressional (upper Tortonian-Messinian) tectonics (Glangeaud, 1951; Dubourdieu, 1962; Andrieux, 1971) followed by volcanic activity during the late Miocene (Megartsi, 1985). The continuation of seismic activity in the Tafna Basin after the turbidite deposition is indicated by the presence of faults and other morphological lineaments in the Hadjret El Gat area (the southern part of overturned strata on Mt. Djedir) (Benzina, 2014). Moreover, the presence of seismites in the Quaternary terrace deposits was previously noted in the Bieder, Ghazaouat and Terga areas (Boukhedimi et al., 2017).

The SSDS recorded in the Hadjret El Gat section are interpreted as formed by seismic processes combined with processes related to gravity and slope-control interactions. The presence of different types of SSDS, including load structures, ball-and-pillow structures, water-escape structures, synsedimentary faults and slump structures (slump folds, broken beds, overloading structures) may point to their synchronous development (cf. Kundu et al., 2011). All these SSDS are preserved in a spatially-extensive single stratigraphic interval. Internally-deformed beds are sandwiched within and parallel to undeformed beds. Their vertical alternation indicates earthquakes with associated aftershocks (cf. Owen, 1995) as the main trigger mechanism. All these arguments points to the interpretation of SSDS recorded in the Hadjret El Gat section as seismites formed during earthquakes with a minimum magnitude of 4.5 (cf. Ambraseys, 1988; Marco and Agnon, 1995; Rodríguez--Pascua et al., 2000).

SSDS observed within the sandy turbidite deposits in the Hadjret El Gat section were formed when the degree of lithification of the siliciclastic sediments was relatively low. Van Loon (2009) stated that such deformation structures may develop within unconsolidated sediments or sediments that are not completely lithified. Plastic deformation of ball-and-pillow structures and their inclination in the same direction as their hosting layers suggest a semi-synchronous origin of ball-and-pillow structures and sliding of the latter. The sliding process seems to have been influenced by a set of parameters associated with pore-fluid pressure resulting from compaction of fine-grained sediments (cf. Odonne et al., 2011). Development of SSDS due to submarine sliding appears to have been controlled by active displacement (cf. Odonne et al., 2011). Gravity flow of slump sediments that move on a steep slope evolves into turbidity currents in subaqueous settings (cf. Shanmugam, 2016; Vandekerkhove et al., 2020). Several alternations of broken sandy beds that bear overloading structures are evidence of the repeated rapid sliding of sediments on a slope due to seismic activity; whereas large-scale slump structures may reflect earthquakes of a larger magnitude (cf. Bowman et al., 2004).

Earth tremors were responsible for initiation of slumping and liquefaction at the Hadjret El Gat site. Shear stress and accumulation of shear strain resulting from earthquakes caused a breakdown of the grain framework and an increase in pore-water pressure, which resulted in liquefaction and fluidization of the sediments (e.g., Obermeier et al., 2005; Obermeier, 2009). Mobilisation of grains in the liquefied sediments contributed to the formation of SSDS such as load casts, pseudonodules, ball-and-pillow structures, water-escape structures and synsedimentary faults. The wide spectrum of SSDS recorded at the study site is thought to have been developed as a result of 1) shear stresses associated with overburden pressure on slopes, and 2) liquefaction, both triggered by seismic shocks.

CONCLUSIONS

The SSDS recognized in the Hadjret El Gat section in the Tafna Basin, active seismically since the late Miocene, evolved during earthquakes. A sedimentological investigation led to the following conclusions:

1. Co-occurrence of different types of SSDS in vertically-alternating, sandwich-like beds in the Hadjret El Gat section indicates their interpretation as seismites.
2. Ball-and-pillow structures, water-escape structures and load structures ‘trapped’ within the sandstone result from liquefaction and fluidisation phenomena caused by earthquakes and aftershocks.
3. Vertically-alternating slump folds accompanied by broken beds and overloading structures within the sandstone beds are associated with instability of sediments on a slope, which was probably caused by multiple earthquakes and aftershocks.
4. The inclination of the ball-and-pillow structures and the hosting layers in the same direction indicate synchronity (semi-synchronicity) of the deformation processes. The ball-and-pillow structures underwent plastic deformation due to mass flow processes.
5. The seismites in the Hadjret El Gat section may have developed in the Late Neogene or shortly after late Neogene seismic activity.

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REFERENCES

Allen, J.R., 1977. The possible mechanics of convolute lamination in graded sand beds. Journal of the Geological Society, **134**: 19–31. https://doi.org/10.1144/gsjgs.134.1.0019

Allen, J.R., 1982. Sedimentary Structure: their Character and Physical Basis Volume II. Elsevier Science Publishers, Amsterdam.

Alsop, G.I., Holdsworth, R.E., McCaffrey, K.J.W., 2007. Scale invariant sheath folds in salt, sediments and shear zones. Journal of Structural Geology, **29**: 1585–1604. https://doi.org/10.1016/j.jsg.2007.07.012

Alves, T.M., 2015. Submarine slide blocks and associated soft-sediment deformation in deep-water basins: a review. Marine and Petroleum Geology, **67**: 262–285. https://doi.org/10.1016/j.marpetgeo.2015.05.010

Alves, T.M., Lourenço, S.D., 2010. Geomorphologic features related to gravitational collapse: submarine landsliding to lateral spreading on a Late Miocene – Quaternary slope (SE Crete, eastern Mediterranean). Geomorphology, **123**: 13–33. https://doi.org/10.1016/j.geomorph.2010.04.030

Ambraseys, N., 1988. Engineering seismology. Earthquake Engineering and Structural Dynamics, **17**: 1–105. https://doi.org/10.1002/eqe.4290170102

Andrieux, J., 1971. La structure du Rif central. Etude des relations entre la tectonique de compression et les nappes de glissement dans un tronçon de chaine alpine. Notes et Mémoires. Service Géologique du Maroc, **235**.

Belzyt, S., Pisarska-Jamroży, M., Bitinas, A., Woronko, B., Phillips, E.R., Piotrowski, J.A., Jusienė, A., 2021. Repetitive Late Pleistocene soft-sediment deformation by seismicity-induced liquefaction in north-western Lithuania. Sedimentology, **68**: 3033–3056. https://doi.org/10.1111/sed.12883

Benzina, M., 2014. Evolution tecto-sédimentaire du bassin de la Tafna (Tlemcen, Algérie nord occidentale). MSc Thesis, Université de Tlemcen, Algerie.

Benzina, M., Hebib, H., Bensalah, M., 2019. New insights in late Miocene lower Chelif basin biostratigraphy based on planktonic foraminifera (Algeria). Revue de Micropaléontologie, **62**: 9–24. https://doi.org/10.1016/j.revmic.2018.10.005

Benzina, M., Cherif, A., Naimi, M.N., Hebib, H., Bensalah, M., 2023. Ichnological analysis and depositional setting of late Miocene marginal marine deposits from the Tafna Basin (northwestern Algeria). Geological Society Special Publications, **522**: SP522–2022. doi: 10.1144/SP522-2022-275

Bhat, G.R., Bali, B.S., Balaji, S., Iqbal, S., Balakrishna, V., 2016. Earthquake triggered soft sediment deformational structures (seismites) in the Karewa Formations of Kashmir Valley – an indicator for paleoseismicity. Journal of the Geological Society of India, **87**: 439–452. https://doi.org/10.1007/s12594-016-0412-y

Bowman, D., Korjenkov, A., Porat, N., 2004. Late-Pleistocene seismites from Lake Issyk-Kul, the tien shan range, Kyrghyzstan. Sedimentary Geology, **163**: 211–228. https://doi.org/10.1016/S0037-0738(03)00194-5

Boucif, A., 2006. La tendance de l'activité sismique qui affecte le bassin Néogène de la Tafna. MSc Thesis, Université de Tlemcen, Algerie.

Boukhedimi, M.A., Louni-Hacini, A., Bouhadad, Y., 2017. Evidence of seismites in coastal Quaternary deposits of western Oranie (northwestern Algeria). Journal of Seismology, **21**: 539–549. https://doi.org/10.1007/s10950-016-9616-2

Bradley, D., Hanson, L., 1997. Paleoslope analysis of slump folds in the Devonian flysh of marine. The Journal of Geology, **106**: 305–318. https://doi.org/10.1086/516024

Brandes, C., Steffen, H., Steffen, R., Wu, P., 2015. Intraplate seismicity in northern Central Europe is induced by the last glaciation. Geology, **43**: 611–614. https://doi.org/10.1130/G36710.1

Chiarella, D., Moretti, M., Longhitano, S.G., Mut, F., 2016. Deformed cross-stratified deposits in the Early Pleistocene tidally-dominated Catanzaro strait-fill succession, Calabrian Arc (Southern Italy): triggering mechanisms and environmental significance. Sedimentary Geology, **344**: 277–289. https://doi.org/10.1016/j.sedgeo.2016.05.003

Collinson, J., 1994. Sedimentary deformational structures. In: The Geological Deformation of Sediments (ed. A. Maltman). Springer, Dordrecht. https://doi.org/10.1007/978-94-011-0731-0_4

Dasgupta, P., Chatterjee, A., 2019. Formation of water-escape structure during shock-induced fluidization: the role of permeability contrast. Journal of Structural Geology, **124**: 1–7. https://doi.org/10.1016/j.jsg.2019.04.002

Doe, T.W., Dott, R.H., 1980. Genetic significance of deformed cross bedding-with examples from the Navajo and Weber sandstones of Utah. Journal of Sedimentary Petrology, **50**: 793–812. https://doi.org/10.1306/212F7AEF-2B24-11D7-8648000102C1865D

Dubourdieu, G., 1962. Dynamique wegenerienne de l'Afrique du nord. In: Livre a la mémoire du Professeure P. FALLOT. Mémoire hors-série-Société géologique de France, **1**: 627–644.

Farrell, S.G., Eaton, S., 1987. Slump strain in the Tertiary of Cyprus and the Spanish Pyrenees. Definition of palaeoslopes and models of soft-sediment deformation. Geological Society Special Publications, **29**: 181–196. https://doi.org/10.1144/GSL.SP.1987.029.01.15

Glangeaud, L., 1951. Interprétation tectonophysiques des caractères structuraux et paléogéographiques de la méditerranée occidentale. Bulletin de la Société géologique de France, **6**: 735–762.

Guardia, P., 1975. Géodynamique de la marge alpine du continent africain d'après l'étude de l'Oranie nord occidentale (Algérie). Relations structurales et paléogéographiques entre le Rif externe, le Tell et l'Avant-pays atlasique. Ph.D. Thesis, Nice University, France.

Guessoum, N., Benhamouche, A.A., Bouhadad, Y., Bourenane, H., Abbouda, M., 2018. Field evidence of Quaternary seismites in the Mostaganem-Relizane (western Algeria) region: seismotectonic implication. Arabian Journal of Geosciences, **11**: 1–13. https://doi.org/10.1007/s12517-018-4009-1

He, B., Qiao, X., Li, H., Su, D., 2018. Soft Sediment Deformation Structures Triggered by the Earthquakes: Response to the High Frequent Tectonic Events during the Main Tectonic Movements. Tectonics: Problems of Regional Settings.

Hurst, A., Cartwright, J., 2007. Relevance of sand injectites to hydrocarbon exploration and production. AAPG Memoir, **87**: 1–19.

Hurst, A., Scott, A., Vigorito, M., 2011. Physical characteristics of sand injectites. Earth-Science Reviews, **106**: 215–246. https://doi.org/10.1016/j.earscirev.2011.02.004.

Jones, B.G., Rust, B.R., 1983. Massive sandstone facies in the Hawkesbury sandstone, a Triassic fluvial deposit near Sydney, Australia. Journal of Sedimentary Petrology, **53**: 1249–1259. https://doi.org/10.1306/212F8355-2B24-11D7-8648000102C1865D

Jones, A.P., Omoto, K., 2000. Towards establishing criteria for identifying trigger mechanisms for soft-sediment deformation: a case study of Late Pleistocene lacustrine sands and clays, Onikobe and Nakayamadaira Basins, northeastern Japan. Sedimentology, **47**: 1211–1226. https://doi.org/10.1046/j.1365-3091.2000.00355.x

Koç-Taşgın, C., Altun, F., 2019. Soft-sediment deformation: deep-water slope deposits of a back-arc basin (middle Eocene-Oligocene Kırkgeçit Formation, Elazığ Basin), Eastern Turkey. Arabian Journal of Geosciences, **12**: 773. https://doi.org/10.1007/s12517-019-4872-4

Kuenen, Ph.H., 1958. Experiments in geology. Geological Magazine, **23**: 1–8. https://doi.org/10.1144/transglas.23.centenary.1

Kundu, A., Goswami, B., Eriksson, P.G., 2011. Palaeoseismicity in relation to basin tectonics as revealed from soft-sediment deformation structures of the Lower Triassic Panchet formation, Raniganj basin (Damodar valley), eastern India. Journal of Earth System Science, **120**: 167–181. https://doi.org/10.1007/s12040-011-0071-8

Lowe, D.R., 1975. Water escape structures in coarse grained sediments. Sedimentology, **22**: 157–204. https://doi.org/10.1111/j.1365-3091.1975.tb00290.x

Mahboubi, S., Bennami, M., Jaeger, J.J., 2015. New datation of the Tafna Basin (Algeria): a combination between biochronological and magnetostratigraphical data. Palaevertebrata, Montpellier, **39**: 1–11.

Maltman, A., 1984. On the term soft-sediment deformation. Journal of Structural Geology, **6**: 589–592. https://doi.org/10.1016/0191-8141(84)90069-5

Marco, S., Agnon, A., 1995. Prehistoric earthquake deformations near Masada, Dead Sea graben. Geology, **23**: 695–698. https://doi.org/10.1130/0091-7613(1995)023%3C0695:PEDNMD%3E2.3.CO

Mazouzi, A., 2004. La sédimentation détritique profond de la formation des "Grés d'Aďn El Kihal" (Serravallien) dans la région d'El Fhoul (Bassin de la Tafna, Algerie Nord-Occidental). Mémoire ingéniorat. University Oran, Algerie.

Mazumder, R., van Loon, A.J., Arima, M., 2006. Soft-sediment deformation structures in the Earth's oldest seismites. Sedimentary Geology, **186**: 19–26. https://doi.org/10.1016/j.sedgeo.2005.12.002

Mazumder, R., van Loon, A.J., Malviya, V.P., Arima, M., Ogawa, Y., 2016. Soft-sediment deformation structures in the Mio-Pliocene Misaki Formation within alternating deep sea clays and volcanic ashes (Miura Peninsula, Japan). Sedimentary Geology, **344**: 323–335. https://doi.org/10.1016/j.sedgeo.2016.02.010

McCalpin, J.P., 2009. Paleoseismology, International Geophysics Series. Elsevier Publishing.

Megartsi, M., 1985. Le volcanisme mio-plio-quaternaire de l'Oranie nord occidentale (géologie, pétrologie, géodynamique). Ph.D. Thesis, Université des Sciences et de la Technologie Houari Boumediene, Algerie.

Miyata, T., 1990. Slump strain indicative of paleoslope in Cretaceous Izumi sedimentary basin along Median tectonic line, southwest, Japan. Geology, **18**: 392–394. https://doi.org/10.1130/0091-7613(1990)018%3C0392:SSIOPI%3E2.3.CO

Mohindra, R., Thakur, V.C., 1998. Historic large earthquake-induced soft sediment deformation features in the Sub-Himalayan Doon Valley. Geological Magazine, **135**: 269–281. http://dx.doi.org/10.1017/S0016756898008413.

Montenat, C., Barrier, P., Ott d'Estevou, P., Hibsch, C., 2007. Seismites: an attempt at critical analysis and classification. Sedimentary Geology, **196**: 5–30. https://doi.org/10.1016/j.sedgeo.2006.08.004

Moretti, M., 2000. Soft-sediment deformation structures interpreted as seismites in Middle-Late Pleistocene aeolian deposits (Apulian foreland, southern Italy). Sedimentary Geology, **135**: 167–179. https://doi.org/10.1016/S0037-0738(00)00070-1

Moretti, M., Ronchi, A., 2011. Liquefaction features interpreted as seismites in the Pleistocene fluvio-lacustrine deposits of the Neuquén Basin (Northern Patagonia). Sedimentary Geology, **235**: 200–209. https://doi.org/10.1016/j.sedgeo.2010.09.014

Moretti, M., Soria, J.M., Alfaro, P., Walsh, N., 2001. Asymmetrical soft-sediment deformation structures triggered by rapid sedimentation in turbiditic deposits (Late Miocene, Guadix Basin, Southern Spain). Facies, **44**: 283–294. https://doi.org/10.1007/BF02668179

Mulder, T., Philippe, R., Faugeres, J.C., Gerard, J., 2011. Reply to the discussion by Roger Higgs on "Hummocky cross-stratification-like structures in deep-sea turbidites: Upper Cretaceous Basque basins (Western Pyrenees, France)" by Mulder et al. Sedimentology, **56**: 997–1015.

Naimi, M.N., Vinn, O., Cherif, A., 2021. Bioerosion in Ostrea lamellosa shells from the Messinian of the Tafna Basin (NW Algeria). Carnets de Geolgie, Madrid, **21**: 127–135. https://doi.org/10.2110/carnets.2021.2105

Obermeier, S.F., Olson, S.M., Green, R.A., 2005. Field occurrences of liquefaction-induced features: a primer for engineering geologic analysis of paleoseismic shaking. Engineering Geology, **76**: 209–234. https://doi.org/10.1016/j.enggeo.2004.07.009

Obermeier, S.F., 2009. Using liquefaction-induced and other soft-sediment features for paleoseismic analysis. International Geophysics, **95**: 497–564. https://doi.org/10.1016/S0074-6142(09)95007-0

Odonne, F., Callot, P., Debroas, E.J., Sempere, T., Hoareau, G., Maillard, A., 2011. Soft-sediment deformation from submarine sliding: favourable conditions and triggering mechanisms in examples from the Eocene Sobrarbe delta (Ainsa, Spanish Pyrenees) and the mid-Cretaceous Ayabacas Formation (Andes of Peru). Sedimentary Geology, **235**: 234–248. https://doi.org/10.1016/j.sedgeo.2010.09.013

Oliveira, C.M.M., Hodgson, D.M., Flint, S.S., 2011. Distribution of soft-sediment deformation structures in clinoform successions of the Permian Ecca Group, Karoo Basin, South Africa. Sedimentary Geology, **235**: 314–330. https://doi.org/10.1016/j.sedgeo.2010.09.011

Owen, G., 1987. Deformation processes in unconsolidated sands. Geological Society Special Publication, **29**: 11–24. https://doi.org/10.1144/GSL.SP.1987.029.01.02

Owen, G., 1995. Soft sediment deformation in upper Proterozoic Torridonian sandstones (Applecross Formation) at Torridon, northwest Scotland. Journal of Sedimentary Research, **65**: 495–504. https://doi.org/10.1306/D4268108-2B26-11D7-8648000102C1865D

Owen, G., 1996. Experimental soft-sediment deformation: structures formed by the liquefaction of unconsolidated sands and some ancient examples. Sedimentology, **43**: 279–293. https://doi.org/10.1046/j.1365-3091.1996.d01-5.x

Owen, G., 2003. Load structures: gravity-driven sediment mobilization in the shallow subsurface. Geological Society Special Publications, **216**: 21–34. https://doi.org/10.1144/GSL.SP.2003.216.01.03

Owen, G., Moretti, M., 2011. Identifying triggers for liquefaction induced soft-sediment deformation in sands. Sedimentary Geology, **235**: 141–147. https://doi.org/10.1016/j.sedgeo.2010.10.003

Owen, G., Moretti, M., Alfaro, P., 2011. Recognizing triggers for soft-sediment deformation: current understanding and future directions. Sedimentary Geology, **235**: 133–342. https://doi.org/10.1016/j.sedgeo.2010.12.010

Pisarska-Jamroży, M., 2006. Transitional deposits between the end moraine and outwash plain in the Pomeranian glaciomarginal zone of NW Poland: a missing component of ice contact sedimentary models. Boreas, **35:** 126–141. https://doi.org/10.1111/j.1502-3885.2006.tb01117.x

Pisarska-Jamroży, M., 2008. Zonation of glaciomarginal environment inferred from Pleistocene deposits of Mysliborz Lakeland, NW Poland. Geografiska Annaler: Series A, Physical Geography, **90**: 237–249. https://doi.org/10.1111/j.1468-0459.2008.342.x

Pisarska-Jamroży, M., 2013. Varves and megavarves in the Eberswalde Valley (NE Germany) – a key for the interpretation of glaciolimnic processes. Sedimentary Geology, **291**: 84–96. https://doi.org/10.1016/j.sedgeo.2013.03.018

Pisarska-Jamroży, M., Weckwerth, P., 2013. Soft-sediment deformation structures in a Pleistocene glaciolacustrine delta and their implications for the recognition of subenvironments in delta deposits. Sedimentology, **60**: 637–665. https://doi.org/10.1111/j.1365-3091.2012.01354.x

Pisarska-Jamroży, M., Woźniak, P.P., 2019. Debris flow and glacioisostatic-induced soft-sediment deformation structures in a Pleistocene glaciolacustrine fan: the southern Baltic Sea coast, Poland. Geomorphology, **326**: 225–238. https://doi.org/10.1016/j.geomorph.2018.01.015

Pisarska-Jamroży, M., Zieliński, T., 2012. Specific erosional and depositional processes in a Pleistocene subglacial tunnel in the Wielkopolska region, Poland. Geografiska Annaler: Series A, Physical Geography, **94**: 429–443. https://doi.org/10.1111/j.1468-0459.2012.00466.x

Pisarska-Jamroży, M., Belzyt, S., Börner, A., Hoffmann, G., Hüneke, H., Kenzler., M., Van Loon, A.T., 2018. Evidence from seismites for glacio-isostatically induced crustal faulting in front of an advancing land-ice mass (Rügen Island, SW Baltic Sea). Tectonophysics, **745**: 338–348. https://doi.org/10.1016/j.tecto.2018.08.004

Pisarska-Jamroży, M., Belzyt, S., Bitinas, A., Jusienė, A., Woronko, B., 2019a. Seismic shocks, periglacial conditions and glacitectonics as causes of the deformation of a Pleistocene meandering river succession in central Lithuania. Baltica, **32**: 63–77. https://doi.org/10.5200/baltica.2019.1.6

Pisarska-Jamroży, M., Van Loon, A.J., Mleczak, M., Roman, M., 2019b. Enigmatic gravity-flow deposits at Ujście (western Poland), triggered by earthquakes (as evidenced by seismites) caused by Saalian glacioisostatic crustal rebound. Geomorphology, (326): 239–251. https://doi.org/10.1016/j.geomorph.2018.01.010

Rana, N., Prakash Sati, S., Sundriyal, Y., Juyal, N., 2016. Genesis and implication of soft sediment deformation structures in high energy fluvial deposits of the Alaknanda valley, Garhwal Himalaya, India. Sedimentary Geology, **344**: 263–276. https://doi.org/10.1016/j.sedgeo.2016.06.012

Rodríguez-Pascua, M.A., Calvo, J.P., De Vicente, G., Gómez-Gras., D., 2000. Soft-sediment deformation structures interpreted as seismites in lacustrine sediments of the Prebetic

Zone, SE Spain, and their potential use as indicators of earthquake magnitudes during the Late Miocene. Sedimentary Geology, **135**: 117–135. https://doi.org/10.1016/S0037-0738(00)00067-1

Ross, J.A., Peakall, J., Keevil, G.M., 2013. Subaqueous sand extrusion dynamics. Journal of the Geological Society, **170**, 593–602. https://doi.org/10.1144/jgs2012-124

Rossetti, D.F., 1999. Soft-sediment deformation structures in late Albian to Cenomanian deposits, São Luís Basin, northern Brazil: evidence for palaeoseismicity. Sedimentology, **46**: 1065–1081. https://doi.org/10.1046/j.1365-3091.1999.00265.x

Roy, S.K., Banerjee, S., 2016. Soft sediment deformation structures in the Andaman Flysch Group, Andaman Basin: evidence for Paleogene seismic activity in the Island Arc. Beri Sedimentology, **35**: 55–64. https://doi.org/10.51835/bsed.2016.35.1.103

Seilacher, A., 1969. Fault-graded beds interpreted as seismites. Sedimentology, **13**: 155–159. https://doi.org/10.1111/j.1365-3091.1969.tb01125.x

Shanmugam, G., 2016. The seismite problem. Journal of Palaeogeography, **5**: 318–362. https://doi.org/10.1016/j.jop.2016.06.002

Singh, S., Jain, A.K., 2007. Liquefaction and fluidization of lacustrine deposits from Lahaul-Spiti and Ladakh Himalaya: Geological evidences of paleoseismicity along active fault zone. Sedimentary Geology, **196**: 47–57. https://doi.org/10.1016/j.sedgeo.2006.06.005

Topal, S., Özkul, M., 2014. Soft-Sediment deformation Structures interpreted as Seismites in the Kolankaya Formation, Denizli Basin (SW Turkey). The Scientific World Journal, 2014. https://doi.org/10.1155/2014/352654

Umair, A., Syed Ahmad, A., 2018. Seismically induced soft-sediment deformation structures in an active seismogenic setting: The Plio-Pleistocene Karewa deposits, Kashmir Basin (NW Himalaya). Journal of Structural Geology, **115**: 28–46. https://doi.org/10.1016/j.jsg.2018.07.005

Valente, A., Slaczka, A., Cavuoto, G., 2014. Soft-sediment deformation structures in seismically affected deep-sea Miocene turbidite. Geologos, **20**: 67–78. https://doi.org/10.2478/logos-2014-0009

Vandekerkhove, E., Van Daele, M., Praet, N., Cnudde, V., Haeussler, P.J., De Batist, M., 2020. Flood-triggered versus earthquake-triggered turbidites: a sedimentological study in clastic lake sediments (Eklutna Lake, Alaska). Sedimentology, **67**: 364–389. https://doi.org/10.1111/sed.12646

Van Loon, A.J., 2009. Soft-sediment deformation structures in siliciclastic sediments: an overview. Geologos, **15**: 3–55.

Van Loon, A.J., Pisarska-Jamrozy, M., Nartiss, N., Krievans, M., Soms, J., 2016. Seismites resulting from high-frequency, high-magnitude earthquakes in Latvia caused by Late Glacial glacio-isostatic uplift. Journal of Palaeogeography, **5**: 363–380. https://doi.org/10.1016/j.jop.2016.05.002

Vanneste, K., Meghraoui, M., Camelbeeck, T., 1999. Late Quaternary earthquake-related soft-sediment deformation along the Belgian portion of the Feldbiss Fault, Lower Rhine Graben system. Tectonophysics, **309**: 57–79. https://doi.org/10.1016/S0040-1951(99)00132-8

Waldron, J.W.F., Gagnon, J.F., 2011. Recognizing soft sediment structures in deformed rocks of orogens. Journal of Structural Geology, **33**: 271–279. https://doi.org/10.1016/j.jsg.2010.06.015

Woźniak, P.P., Pisarska-Jamroży, M., 2016. Rzucewo-soft-sediment deformation structures in glaciolimnic sediments-different trigger mechanisms. Quaternary geology of north-central Poland: from the Baltic coast to the LGM limit. University of Gdańsk: 53–67.

Woźniak, P.P., Pisarska-Jamroży, M., 2018. Debris flows with soft-sediment clasts in a Pleistocene glaciolacustrine fan (Gdańsk Bay, Poland). Catena, **165**: 178–191. https://doi.org/10.1016/j.catena.2018.01.022

Woźniak, P.P., Belzyt, S., Pisarska-Jamroży, M., Woronko, B., Lamsters, K., Nartišs, M., Bitinas, A., 2021. Liquefaction and re-liquefaction of sediments induced by uneven loading and glacigenic earthquakes: Implications of results from the Latvian Baltic Sea coast. Sedimentary Geology, **421**: 105944. https://doi.org/10.1016/j.sedgeo.2021.105944

Yang, R.C., Van Loon, A.J., 2016. Early Cretaceous slumps and turbidite with peculiar soft-sediment deformation structures on Lingshan Island (Qingdao, China) indicating a tensional tectonic regime. Journal of Asian Earth Sciences, **129**: 206–219. https://doi.org/10.1016/j.jseaes.2016.08.014