Key evidence for distal turbiditic- and bottom-current interactions from tubular turbidite infills

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ABSTRACT

Infilling of trace fossils can serve as a proxy for sediment otherwise missing from basin deposits. The Petra Tou Romiou section (southern Cyprus) includes calcilutite/calcarenite material that represents deep-marine deposits of Eocene age. Lateral and vertical variation indicates pelagic, gravitational, and bottom-current processes simultaneously influencing sedimentation. Detailed ichnological analysis resolved interactions between these deep-marine sedimentary processes in this distal marine setting. Calcarenite turbiditic beds occur as well-preserved and continuous tabular beds that disappear laterally. In some cases, trace fossils infilled with calcarenitic material are termed *tubular turbidites*. These structures correspond to actively filled *Planolites* formed in softground conditions and infilled by calcarenitic sediment interpreted as the record of missing turbiditic deposits when calcarenite turbiditic beds disappeared due to erosion. The variable preservation of calcarenite turbidite beds along with the presences of *tubular turbidites* indicate rapid erosion following turbidite deposition and post-depositional reworking of turbidites by bottom-currents. A refined interpretation of *tubular turbidites* can help constrain sedimentary processes that form deep-marine deposits and as such, has considerable paleoceanographic and economic implications.

Keywords: Trace fossils, *Planolites* infill, turbidites, contourites, Petra Tou Romiou, Cyprus

1. Introduction

Deep-marine settings consist of deposits influenced by three main sedimentary processes including pelagic (vertical settling of pelagic particles in the water column), gravitational (downslope density currents; turbid flows of predominantly terrigenous sediments), and bottom current (mainly alongslope flow of bottom currents) (e.g., Rebesco et al., 2014). End-member deposits in these settings may arise from a single, predominant process, while more varied deposits can form due to the interaction of processes (e.g., Pickering and Hiscott, 2016). Gravitational currents and overflows, together with barotropic currents, giant eddies, deep-sea storms, vortices, internal waves, internal tides, or tsunamis, among other processes, can all affect the seafloor in deep-water environments (see Fig. 13 in Rebesco et al., 2014). Over the last decade, studies of different continental margins have described how these processes in combination can result in mixed / hybrid sedimentary systems (Gong et al., 2018; Sansom, 2018; Normandeau et al., 2019). Differentiation of gravitational and bottom-current processes remains a challenge however. Without clearly delineated examples, these systems are difficult to interpret in terms of standard turbiditic and contourite facies models (Shanmugam, 2002; Rebesco et al., 2014).

Ichnological analysis is a useful tool for identifying and characterizing pelagic, gravitational, and bottom current deposits (Wetzel et al., 2008; Rodríguez-Tovar and Hernández-Molina, 2018; Rodríguez-Tovar et al., 2019a). Infilling of trace fossils can provide key evidence of sediment lost from shallow- to deep-marine environments (i.e., Wetzel, 2015). In some cases, the sedimentary record is preserved exclusively by burrow infill. Fill was emplaced deep within the surrounding sediment and can thereby elude mixing by bioturbation or later erosion. Both actively and passively filled burrows can store sediment not otherwise preserved. Three different cases have been proposed based on type of infilling material and depositional processes: *tubular tempestites* (Wanless et al., 1988; Gingras et al., 2007; Leonowicz, 2016); *tubular tidalites* (Gingras and MacEachern, 2012; Wetzel et al., 2014; Gingras and Zonneveld, 2015; Rodríguez-Tovar et al., 2019b), and *tubular turbidites* (Hubbard et al., 2012). These latter deposits were described by Hubbard et al. (2012) as follows: "sand-filled burrows (in some instances) record the passage of coarse-grained material through an erosional conduit such as a submarine canyon or channel, without deposition of a coarse lag," wherein "the only evidence of coarse-grained sediment in the system may be recorded within the burrow fills". In this interpretation, *tubular turbidite* means passively filled firmground burrows in the bathyal realm, belonging to the *Glossifungites* ichnofacies, and indicating sediment bypass.

This contribution describes a new type of *tubular turbidites* associated to actively infilled *Planolites* produced in softgrounds and reflecting varying degrees of post-depositional erosion by bottom-current activity, from the Eocene Lefkara Formation of the Petra Tou Romiou section (southern Cyprus, Eastern Mediterranean Sea: Fig. 1). The Lefkara *tubular turbidites* consist of actively filled softground burrows and associate with calcarenite sediments subjected to different degrees of erosion. As such, these features provide key evidence of turbiditic- and bottom-current interactions which can ultimately inform sedimentary interpretations, paleoclimatic research, and petroleum exploration.

2. Geological setting and the studied section

The Petra Tou Romiou section is located in an outcrop at the southern part of Cyprus, Eastern Mediterranean Sea (34º39’27.4’’N, 32º38’55.5’’E). It includes both the Lefkara and Pakhna formations, which are part of the Circum Troodos Massif sedimentary succession (Edwards et al., 2010) (Fig. 1). The research is conducted at the Lefkara Formation (late Palaeocene to Oligocene), which consists primarily of chalky limestones and marls with intercalated bedded and nodular cherts (Edwards et al., 2010). This carbonate-dominated succession formed by pelagic and hemipelagic sediment accumulation temporarily influenced by weak bottom-currents and punctuated by distal turbidity flows (Stow et al., 2002). The depositional setting of this deep-marine record developed along the lower continental slope during the Eocene. The Parkhna Formation, overlying the Lefkara Formation disconformably in most areas, consists of chalks, marly chalks, bioturbated silty marls to siltstones, calcarenites and conglomerates, deposited during the Miocene (Eaton and Robertson, 1993).

The lower part of the studied Lefkara Formation belongs to the Chalk Unit, consisting of regular alternation of calcilutites and calcarenite beds (Fig. 2). Whitish calcilutites consisting of globigerinid wackestones (sparse biomicrites) reach thicknesses of a meter to several meters and represent the primary lithology (Fig. 2). These whitish calcilutites can exhibit decimetre-scale banding marked by subtle color changes. Thin, interbedded calcarenites (thicknesses < 5 cm) consist of globigerinid wackestones-packstones and show transitional relationships with the whitish calcilutites. In some cases, thicker interbedeed calcarenites (5-8 cm) exhibit faint wavy lamination (calnwl in Fig. 3A-D). A second type of calcarenite beds show a sharp base and exhibit pronounced normal grading. These beds shift from parallel- and cross-laminated to bioturbated fabrics (Fig. 3D). Some of the more coarse-grained beds from this facies show good lateral continuity (caln in Fig. 3) while others may thin out and even disappear laterally (caln-d in Fig. 3). This transition leaves a subtle pressure dissolution seam (Figs. 3C). In some cases, a vertical calcilutite-calcarenite-calcilutite succession consisting of whitish calcilutites, well-developed calcarenite beds, whitish calcarenites with faint wavy lamination and then whitish calcilutites is observed (Fig. 3).

3. Methods

During five field campaigns (2014 to 2018) *The Drifters Research Group* (RHUL) and the *Ichnology & Palaeoenvironment Research Group* (UGR) have been studying Eocene to early Miocene succession from Lefkara and Pakhna formations (Cyprus). Detailed sedimentological and ichnological analysis of the Lefkara Formation focussed especially on the transition between calcilutites and well-defined (sharp based) calcarenite beds identified as turbidites. Stratigraphic and sedimentological observation documented stratigraphic architecture, contacts between sedimentary facies, and lateral variation in calcarenite beds.

Outcrop observations of ichnological features included analysis of shape, configuration, orientation, length, width, and diameter of burrows, burrow margins, and especially sediment fill within trace fossils. We also analysed relationships between trace fossil assemblages and both the whitish calcilutite and sharp based calcarenite facies types. Select samples were collected for further imaging and petrographic analysis in laboratory.

4. Ichnological analysis

Ichnological analysis of calcilutite intervals distinguished two trace fossil assemblages according to infill material (Figs. 4, 5).

The first is a light trace fossil assemblage with calcilutite infill primarily resembling the host sediment and consisting of dominant *Chondrites* and *Planolites*, and frequent *Thalasinoides* and *Zoophycos*. This assemblage occurs extensively throughout the calcilutite interval and was previously described by Miguez-Salas and Rodríguez-Tovar (2018; Fig. 4). *Chondrites* is observed in variably oriented vertical cross sections with oval or circular spots with burrow diameters of 1-2 mm-wide (smaller forms) and 2-3 mm-wide (larger forms). *Planolites* are registered as horizontal straight to gently curved flattened cylinders, and elliptical spots in cross sections, unlined, showing diameters from 0.3 to 1.5 cm. *Thalassinoides* is mainly observed in vertical cross sections as unlined cylindrical or subcylindrical horizontal forms, with diameters ranging from 2 to 7 cm. *Zoophycos* is registered only in vertical cross sections as horizontal to sub-horizontal spreiten structures, with widths between less than 10 cm to almost 30 cm.

The second type is a conspicuous trace fossil assemblage primarily comprised of horizontal and slightly oblique bioturbation structures with calcarenite infill similar to the calcarenite beds. These fossils occur exclusively in upper part of the calcilutite intervals and below calcarenite beds (Fig. 5). In the second type, the trace fossils are linear, cylindrical, had a smooth tubular morphology, are subcircular in cross-section, and are sometimes preserved as a full-relief exichnion, 8 mm in diameter. The longest observed length up to 5 cm. The traces are simple, mainly horizontal or slightly inclined and without branching. These features allow assignation to *Planolites*, and differentiation respect to larger and branched structures as *Thalassinoides*. Discrete calcarenite infilled trace fossils showed clear but variable relationships with overlying sharp based calcarenites. These in turn allowed for differentiation of three cases (Fig. 5):

i) Conspicuous calcarenite infilled trace fossils derived from a well-preserved calcarenite bed, which occurred in contact with or at a short remove from the fossils (Fig. 5A, B). Penetration depths of up to 4 cm indicate a clear relationship between calcarenite beds and the trace fossil.

ii) Conspicuous calcarenite infilled trace fossils into the calcilutite interval, and underlying a discontinuous calcarenite bed/horizon (Fig. 5C, D) or a pressure dissolution seam (Fig. 5E), at a stratigraphic distance of 1 to 5 cm.

iii) Conspicuous calcarenite infilled within trace fossils penetrating calcilutite intervals showing no evidence of calcarenite bed/horizon or pressure dissolution seam (Fig. 5F).

This second type (*Planolites* with calcarenite infill material) is the focus of the conducted research.

5. Discussion

Facies, facies association, and microfacies analysis allowed general interpretation of depositional processes influencing the Lefkara Formation at the Petra Tou Romiou section (Cyprus). The ichnological assemblage of the calcilutite facies consists of traces with calcilutite infill (*Chondrites*, *Planolites*, *Thalasinoides*, and *Zoophycos*) which are typical of the *Zoophycos* ichnofacies (Miguez-Salas and Rodríguez-Tovar, 2018). Together, these indicate pelagic conditions. Calcarenite beds with faint wavy lamination comprise bigradational sequences similar to those defined by Gontier et al. (1984) wherein gradational boundaries relate to bottom-current processes. Well-developed calcarenite beds with sharp, erosive basal surfaces, normal grading, and parallel to low-angle cross lamination have been interpreted as fine-grained turbidites based on their semblance to fined-grained distal turbiditic deposits described in the literature (e.g., Stow and Shanmugan, 1980; Pickering and Hiscott, 2016; Hüneke et al., submitted). End member deposits exhibit both lateral and vertical variation in fine-grained turbidite beds overlapped by whitish calcarenites with faint wavy lamination. These indicate varying degrees of interaction between depositional and erosional processes typical of deep-sea environments. Distal turbidites were reworked after deposition under the control of the bottom-current activity.

Calcarenite infill trace fossils associates exclusively with *Planolites* in the upper part of the calcilutite intervals, just below the calcarenite beds. *Planolites* is typically interpreted as an actively filled (burrow fill directly emplaced by the burrower; Bromley, 1996) fodinichnion produced by eurybathic vagile "worm"-like deposit-feeders in softgrounds (e.g., Osgood, 1970; Pemberton and Frey, 1982; Fillion and Pickerill, 1990; Keighley and Pickerill, 1995). *Planolites* represent the activity of trace makers mainly in shallow tiers, up to 1 cm below the boundary surface (i.e., Rodríguez-Tovar and Uchman, 2004), but has been also assigned to midtier levels (Buatois et al., 2011), in any case being a characteristic component of softgrounds (Knaust, 2017). The presence of softground *Planolites* actively infilled by turbiditic calcarenite material indicates rapid bioturbation immediately after turbidite deposition in softground conditions. *Planolites* observed storing turbiditic material, in absence of the calcarenite turbiditic bed above, are herein interpreted as "*tubular turbidites*". This represents a refined definition of *tubular turbidites* because the original description (Hubbard et al., 2012) interpreted them as related to turbiditic processes without deposition of the coarse lag, wherein firmground traces passively infilled by coarse-grained sediment during bypass (Fig. 6). The example described here includes coarse lag, which indicates that bypass is not a necessary preservational factor.

The variable relationship between calcarenite infilled *Planolites* and the overlying sharp based calcarenites (cases i to iii) allows for more precise interpretation of distal turbiditic- and bottom-current interactions (Figs. 5 and 7):

a) A well-preserved calcarenite bed in contact with or at a short distance from clear calcarenite-filled *Planolites* (Fig. 5A, B, and Fig. 7) represents complete preservation of the original turbidite (case i above) without significant erosion. Subsequent bottom-current processes do not rework turbiditic deposits probably due to an interval without deposition (or scarce pelagic deposition) between turbiditic deposition and subsequent bottom-current reworking. This favors lithification (firmgrounds) and turbidite preservation.

b) A thin calcarenite bed/horizon (Fig. 5C, D) or a pressure dissolution seam (case ii, Fig. 5E) underlain by conspicuous *Planolites* (*tubular turbidites*) represents rapid, post-depositional erosion of the softground turbidite by subsequent bottom-current reworking (Fig. 7). Bottom currents are interpreted as relatively weak and achieve total or limited erosion.

c) Exclusive presence of conspicuous *Planolites* (*tubular turbidites*) into the calcilutitic interval without a calcarenite bed/horizon or a pressure dissolution seam (case iii; Fig. 5F) represents total post-depositional erosion of the softground turbidite by subsequent bottom-current reworking. Pervasive, strong bottom currents leave only the *tubular turbidites* behind (Fig. 7).

6. Conclusions

Facies and microfacies analysis of Eocene calcilutite/calcarenite units of the Petra Tou Romiou section (southern Cyprus) record the complex history of a deep-marine depositional system. The section exhibits vertical gradation from whitish calcilutites, well-developed calcarenite beds, and whitish calcarenites with faint, wavy lamination to whitish calcilutites. These patterns indicate varying interactions between gravitational processes, bottom-currents, and pelagic sedimentation. In the absence of abundant sedimentary structures or other depositional indicators, detailed ichnological analysis can reveal complex turbiditic and bottom-current interactions.

Calcarenite infilled *Planolites* located in the upper part of the calcilutite intervals occur below a well-developed calcarenite bed. In some cases these are interpreted as a new type of *tubular turbidite* which indicates rapid bioturbation in softground immediately following turbidite deposition, and then erosion of the turbiditic bed. Calcarenite beds varied from well-preserved to absent. This variable preservation of fine-grained turbidites as well as its varying relationship with calcarenite infilled *Planolites* are interpreted as reflecting varying degrees of post-depositional erosion by bottom-current activity.

These newly constrained features can improve characterization of depositional and post-depositional processes. The presence of *tubular turbidites* indicates complex interactions between gravitational and bottom-current processes and constrains interpretations of economically and geologically significant mixed/hybrid depositional systems.

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References

Bromley, R., 1996. Trace Fossils: Biology, taphonomy and applications. Chapman & Hall, 361 pp.

Buatois, L.A., Saccavino, L.L., Zavala, C., 2011. Ichnologic signatures of hyperpycnal flow deposits in Cretaceous river-dominated deltas, Austral Basin, southern Argentina. In: Slatt, R.M., Zavala, C. (Eds.), Sediment transfer from shelf to deep water—Revisiting the delivery system. AAPG Studies in Geology 61, pp. 153–170.

Constantinou, G., 1995. Geological Map of Cyprus, Scale 1/250.000. Geological Survey of Cyprus, Nicosia.

Eaton, S., Robertson, A., 1993. The Miocene Pakhna Formation, southern Cyprus and its relationship to the Neogene tectonic evolution of the Eastern Mediterranean. Sedimentary Geology 86, 273–296.

Edwards, S., Hudson-Edwards, K., Cann, J., Malpas, J., Xenophontos, C., 2010. Classic Geology in Europe 7: Cyprus. Terra Publishing, Dunedin Academic Press Ltd., 271 pp.

Fillion, D., Pickerill, R.K., 1990. Ichnology of the Upper Cambrian? to Lower Ordovician Bell Island and Wabana groups of eastern Newfoundland, Canada. Palaeontographica Canadiana 7, 1–119.

Gingras, M.K., Bann, K.L., MacEachern, J.A., Waldron, J., Pemberton, S.G., 2007. A Conceptual Framework for the Application of Trace Fossils. In: MacEachern, J.A., Bann, K.L., Gingras, M.K., Pemberton, S.G. (Eds.), Applied Ichnology. SEPM Society for Sedimentary Geology 52, pp. 1–25.

Gingras, M.K., MacEachern, J.A., 2012. Tidal ichnology of shallow-water clastic settings. In: Davis, Jr., Dalrymple, R.W. (Eds.), Principles of Tidal Sedimentology. Springer, pp. 57–77.

Gingras, M.K., Zonneveld, J.-H., 2015. Tubular tidalites: A biogenic sedimentary structure indicative of tidally influenced sedimentation. Journal of Sedimentary Research 85, 845–854.

Gong, C., Wang, Y., Rebesco, M., Salon, S., Steel, R.J. 2018. How do turbidity flows interact with contour currents in unidirectionally migrating deep-water channels? Geology 46, 551–554.

Gonthier, E., Faugères, J.-C., Stow, D.A.V., 1984. Contourite facies of the Faro Drift, Gulf of Cadiz. In: Stow, D.A.V., Piper, D.J.W. (Eds.), Fine Grained Sediments, Deepwater Processes and Facies. Geological Society, London, Special Publication 15, pp. 275–291.

Hubbard, S.M., MacEachern, J.A., Bann, K.L., 2012. Slopes. In: Knaust, D., Bromley, R. (Eds.), Trace fossils as indicators of sedimentary environments. Developments in Sedimentology 64, Elsevier, pp. 607–642.

Keighley, D.G., Pickerill, R.K., 1995. The ichnotaxa *Palaeophycus* and *Planolites*: historical perspectives and recommendations. Ichnos 3, 301–309.

Knaust, D., 2017. Atlas of trace fossils in well core. Appearance, Taxonomy and Interpretation. Springer, 209 pp.

Leonowicz, P., 2016. Tubular tempestites from Jurassic mudstones of southern Poland. Geological Quarterly 60, 385–394.

Miguez-Salas, O., Rodríguez-Tovar, F.J., 2019. Stable deep-sea macrobenthic trace maker associations in disturbed environments from the Eocene Lefkara Formation, Cyprus. Geobios 52, 37–45.

Normandeau, A., Campbell, D.C., Cartigny, M.J.B., 2019. The influence of turbidity currents and contour currents on the distribution of deep-water sediment waves offshore eastern Canada. Sedimentology, doi: 10.1111/sed.12557

Osgood, R.G., 1970. Trace fossils of the Cincinnati area. Palaeontographica Americana 6, 193–235.

Palamakumbura, R.N., Robertson, A.H.F., 2018. Pliocene–Pleistocene sedimentary–tectonic development of the Mesaoria (Mesarya) Basin in an incipient, diachronous collisional setting: facies evidence from the north of Cyprus. Geological Magazine 155, 997–1022.

Pemberton, S.G., Frey, R.W., 1982. Trace fossil nomenclature and the *Planolites*-*Palaeophycus* dilemma. Journal of Paleontology 56, 843–881.

Pickering, K.T., Hiscott, R.N., 2016. Deep Marine Systems: Processes, Deposits, Environments, tectonics and Sedimentation. American Geophysical Union and Wiley, 637 pp.

Rebesco, M., Hernández-Molina, F.J., Van Rooij, D., Wåhlin, A., 2014. Contourites and associated sediments controlled by deep-water circulation processes: state of the art and future considerations. Marine Geology 352, 111–154.

Rodríguez-Tovar, F.J., Uchman, A., 2004. Trace fossils after the K-T boundary event from the Agost section, SE Spain. Geological Magazine 141, 429–440.

Rodríguez-Tovar, F.J., Hernández-Molina, F.J., 2018. Ichnological analysis of contourites: Past, present and future. Earth-Science Reviews 182, 28–41.

Rodríguez-Tovar, F.J., Hernández-Molina, F.J., Hüneke, H., Llave, E., Stow, D., 2019a. Contourite facies model: Improving contourite characterization based on the ichnological analysis. Sedimentary Geology 384, 60–69.

Rodríguez-Tovar, F.J., Mayoral, E., Santos, A., Dorador, J., Wetzel, A., 2019b. Crowded tubular tidalites in Miocene shelf sandstones of southern Iberia. Palaeogeography, Palaeoclimatology, Palaeoecology 521, 1–9.

Sansom, P., 2018. Hybrid turbidite-contourite systems of the Tanzanian margin. Petroleum Geoscience, doi:1100 https://doi.org/10.1144/petgeo2018-044

Shanmugam, G., 2002. Ten turbidite myths. Earth-Science Reviews 58, 311–341.

Stow, D.A.V., Shanmugam, G., 1980. Sequence of structures in fine-grained turbidites: Comparison of recent deep-sea and ancient flysch sediments. Sedimentary Geology 25, 23–42.

Stow, D.A.V., Kahler, G., Reeder, M., 2002. Fossil contourites: Type example from an Oligocene palaeoslope system, Cyprus. In: Stow, D.A.V., Pudsey, C.J., Howe, J.A., Faugères, J.-C., Viana, A.R. (Eds.), Deep-Water Contourite Systems: Modern Drifts and Ancient Series, Seismic and Sedimentary Characteristics. Geological Society of London Memoir 22, pp. 443–455.

Wanless, H.R., Tedesco, L.P., Tyrrell, K.M., 1988. Production of subtidal tubular and surficial tempestites by Hurricane Kate, Caicos Platform, British West Indies. Journal of Sedimentary Petrology 58, 739–750.

Wetzel, A., 2015. Burrows storing an otherwise lost sedimentary record. In: McIlroy, D. (Ed.), ICHNOLOGY: Papers from ICHNIA III. Geological Association of Canada, Miscellaneous Publication 9, pp. 211–224.

Wetzel, A., Carmona, N., Ponce, J.J., 2014. Tidal signature recorded in burrow fill. Sedimentology 61, 1198–1240.

Wetzel, A., Werner, F., Stow, D.A.V., 2008. Bioturbation and biogenic sedimentary structures in contourites. In: Rebesco, M., Camerlenghi, A. (Eds.), Contourites. Developments in Sedimentology 60. pp. 183–202.

Figure captions

Figure 1. Location and geological map of the Petra Tou Romiou section (southern Cyprus) (modified from Constantinou, 1995; Palamakumbura and Robertson, 2018).

Figure 2. General lithological column of the Petra Tou Romiou section with detailed of the studied Chalk Unit showing regular alternation of calcilutites and calcarenite beds, including outcrop photograph.

Figure 3. Detailed field photographs of the vertical calcilutite-calcarenite-calcilutite succession showing different facies. These include whitish calcilutites (calu), well-developed calcarenite beds (caln: continuous, caln-d; discontinuous), whitish calcarenites with faint wavy lamination (calnwl), and whitish calcilutites. Note the horizontal lamination in the well-developed calcarenite bed shown in panel D.

Figure 4. Trace fossils observed in calcilutite intervals below a well-developed, continuous calcarenite bed (black arrow). These include a light-colored trace fossil assemblage with calcilutite infill similar to the host sediment (light green arrows; *Ch*: *Chondrites*, *Pl*: *Planolites*, *Th*: *Thalasinoides*, and *Zo*: *Zoophycos*) and a trace fossil assemblage consisting of calcarenite infill similar to the calcarenite beds (yellow arrows; *Pl*: *Planolites*).

Figure 5. Field photographs of differentiated cases (i to iii) showing varying relationships between conspicuous calcarenite filled traces and overlying sharp based calcarenites. Case i (**A, B):** Conspicuous calcarenite filled trace fossils (blue arrows) in contact with (**B**) or at a short distance from (**A**) a well-developed, continuous calcarenite bed (black arrow; caln). Case ii (**C, D, E**) Conspicuous calcarenite filled trace fossils (blue arrows) at a short distance from a discontinuous calcarenite horizon (**C, D**, caln-d) or pressure dissolution seam (**E**, red arrow; pds). Note calcilutite infilled trace fossils (yellow arrows) in D. Case iii (**F**): Conspicuous calcarenite filled trace fossils (blue arrows) bioturbating the calcilutite interval (calu) lacking evidence of a calcarenite bed/horizon or a pressure dissolution seam.

Figure 6. Sketch summarizing tubular turbidites models (bypass vs erosion). Above: *Tubular turbidites* – bypass model (Hubbard et al., 2012): A) Firm ground *Thalassinoides* previous to turbiditic event in fine-grained pelagic sediment, B) Passive infilling of *Thalassinoides* by coarser-grained sediment during turbiditic event, C) Tubular turbidites (*Thalassinoides*) after bypass of turbiditic event, D) Deposition of fine-grained pelagic sediment. Below: *Tubular turbidites* – erosion model: A) Fine-grained pelagic sediment, B) Coarse-grained turbiditic event, C) Bioturbation of active infilling *Planolites* in softground coarse-grained turbiditic sediment, D) *Tubular turbidites* (*Planolites*) after erosion of coarse-grained turbiditic sediment and deposition of fine-grained pelagic sediment.

Figure 7. Sketch summarizing different cases of turbiditic and bottom-current interactions (cases i to iii), according to the magnitude of post-depositional erosion of turbiditic calcarenite material by bottom-current activity. Note the variable relationship between pelagic calcilutites, well-developed calcarenite beds, and whitish calcarenites with faint wavy lamination, and the relationship with conspicuous traces with calcarenite infill. Note: Fig. 3 caption describes facies types.

Figure 1

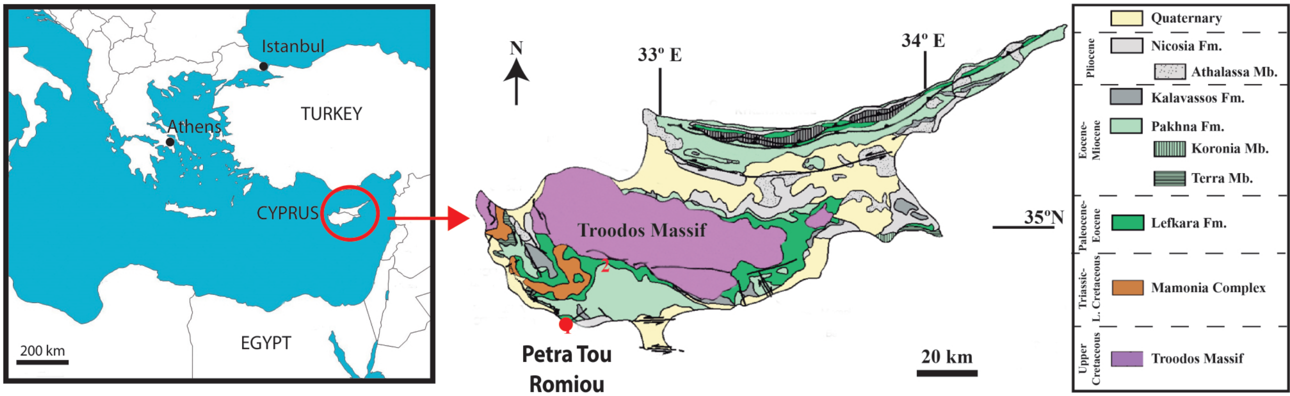
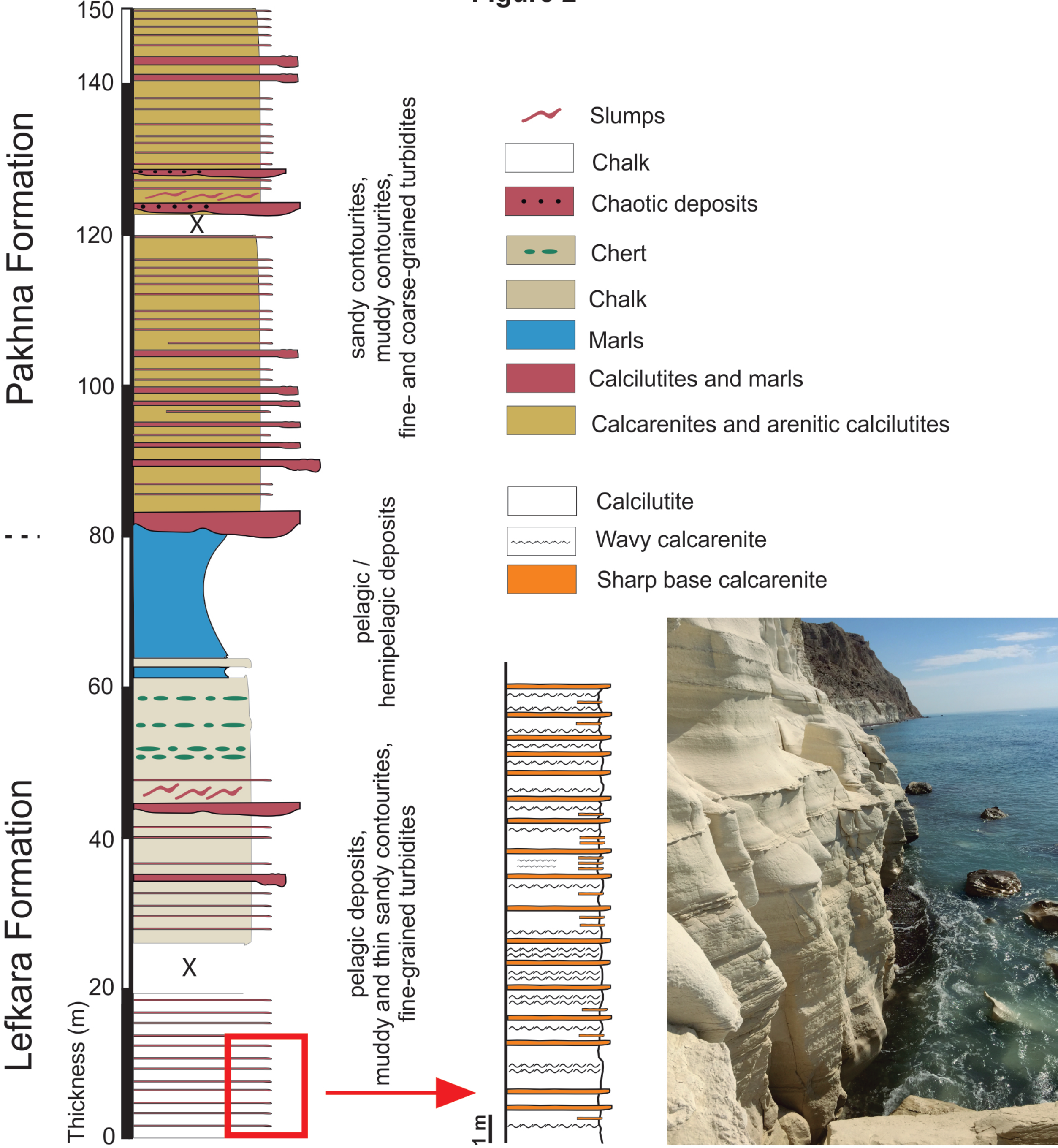

Istanbul
TURKEY
Athens
CYPRUS
EGYPT
200 km
N
33º E
34º E
35ºN
Troodos Massif
Petra Tou Romiou
20 km
Quaternary
Pliocene
Nicosia Fm.
Athalassa Mb.
Eocene-Miocene
Kalavassos Fm.
Pakhna Fm.
Koronia Mb.
Terra Mb.
Paleocene-Eocene
Lefkara Fm.
Triassic-L. Cretaceous
Mamonia Complex
Upper Cretaceous
Troodos Massif

Figure 2



Pakhna Formation
Lefkara Formation
Thickness (m)
150
140
120
100
80
60
40
20
0
X
X
sandy contourites, muddy contourites, fine- and coarse-grained turbidites
pelagic / hemipelagic deposits
pelagic deposits, muddy and thin sandy contourites, fine-grained turbidites
Slumps
Chalk
Chaotic deposits
Chert
Chalk
Marls
Calcilutites and marls
Calcarenites and arenitic calcilutites
Calcilutite
Wavy calcarenite
Sharp base calcarenite
1 m

Figure 3

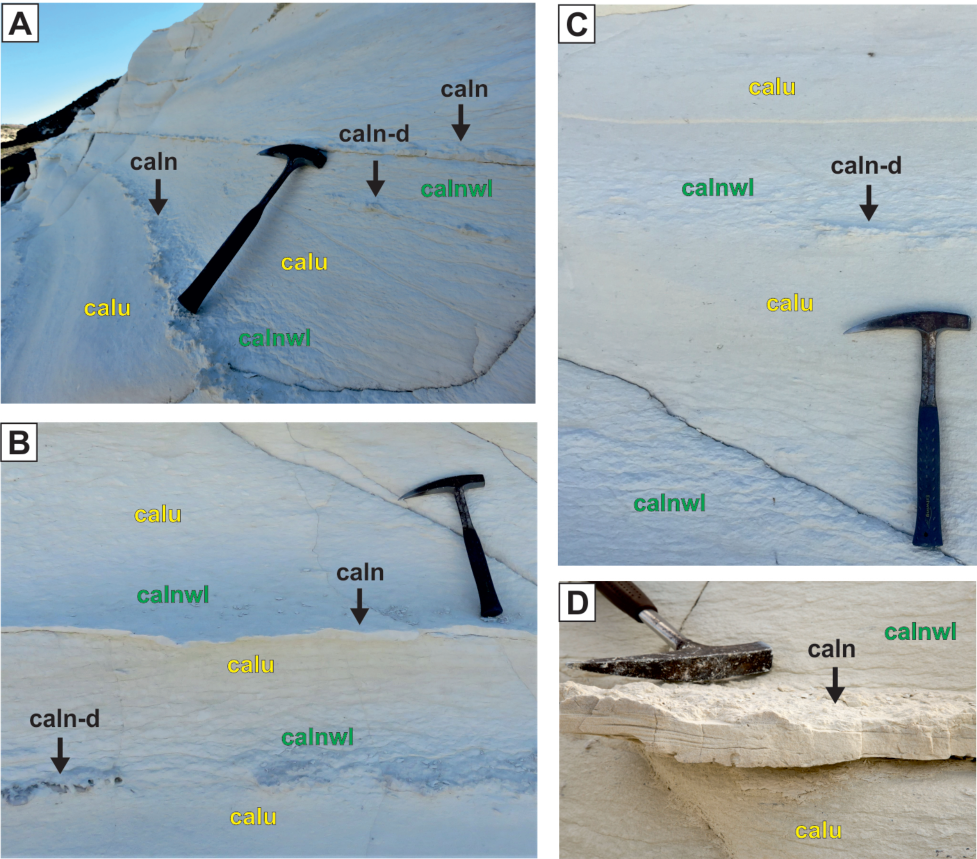

A
caln
caln-d
caln
calnwl
calu
calu
calnwl
B
calu
calnwl
caln
calu
caln-d
calnwl
calu
C
calu
calnwl
caln-d
calu
calnwl
D
calnwl
caln
calu

Figure 4

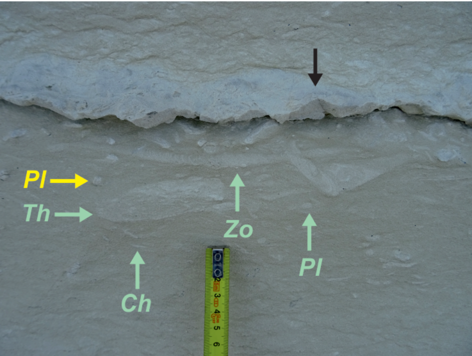


Figure 5

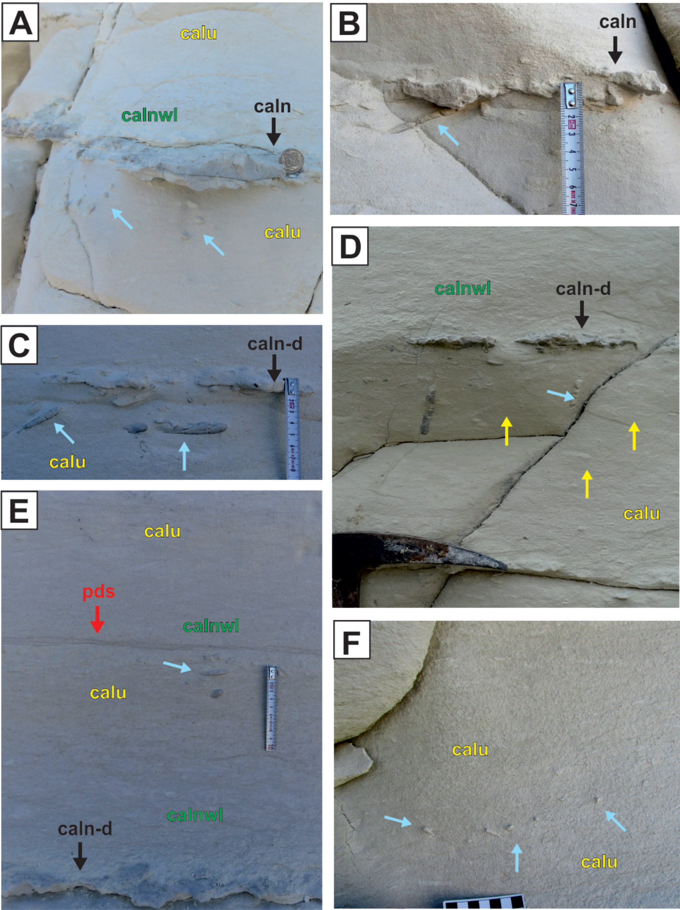
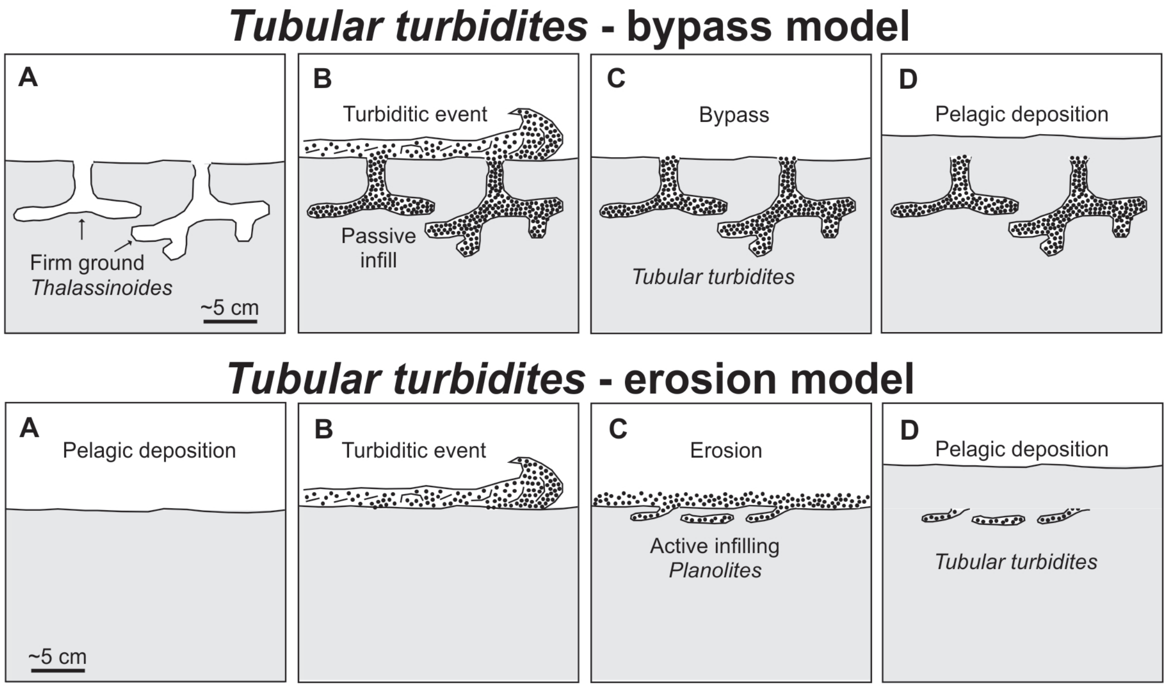
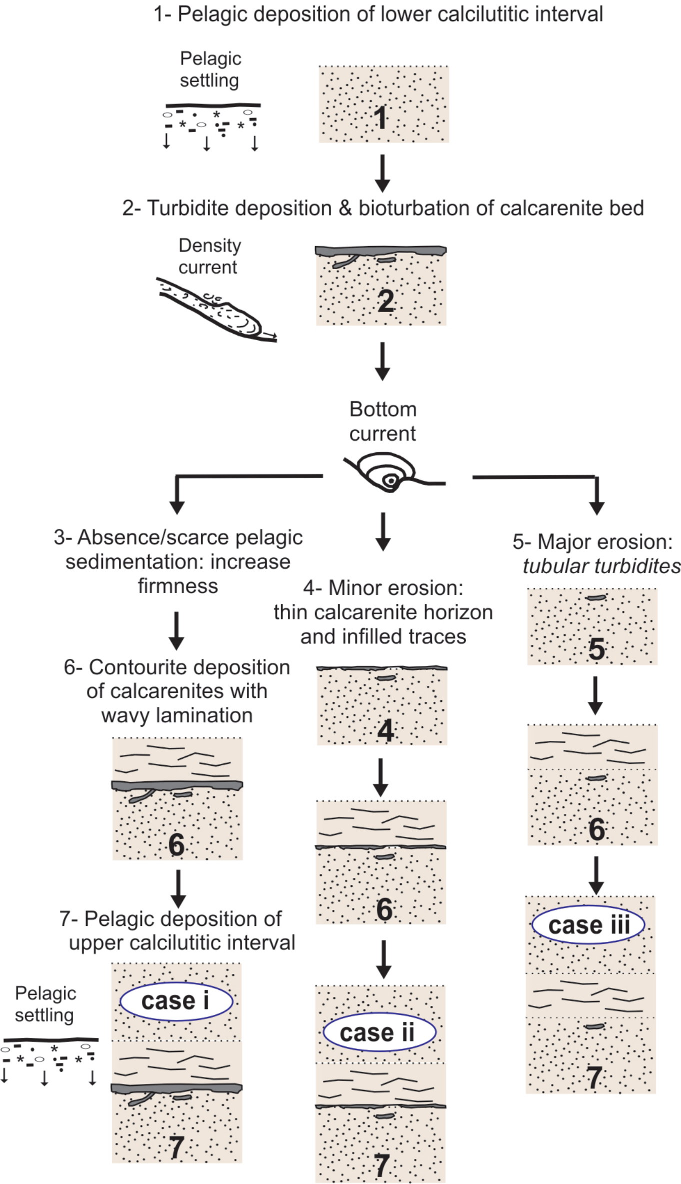

A
calu
calnwl
caln
calu
B
caln
C
caln-d
calu
D
calnwl
caln-d
calu
E
calu
pds
calnwl
calu
calnwl
caln-d
F
calu
calu

Figure 6



Tubular turbidites - bypass model
A
Firm ground
Thalassinoides
~5 cm
B
Turbiditic event
Passive
infill
C
Bypass
Tubular turbidites
D
Pelagic deposition
Tubular turbidites - erosion model
A
Pelagic deposition
~5 cm
B
Turbiditic event
C
Erosion
Active infilling
Planolites
D
Pelagic deposition
Tubular turbidites

Figure 7


1- Pelagic deposition of lower calcilutitic interval
Pelagic settling
1
2- Turbidite deposition & bioturbation of calcarenite bed
Density current
2
Bottom current
3- Absence/scarce pelagic sedimentation: increase firmness
4- Minor erosion: thin calcarenite horizon and infilled traces
5- Major erosion: *tubular turbidites*
5
4
6- Contourite deposition of calcarenites with wavy lamination
6
6
6
7- Pelagic deposition of upper calcilutitic interval
Pelagic settling
case i
case ii
case iii
7
7
7