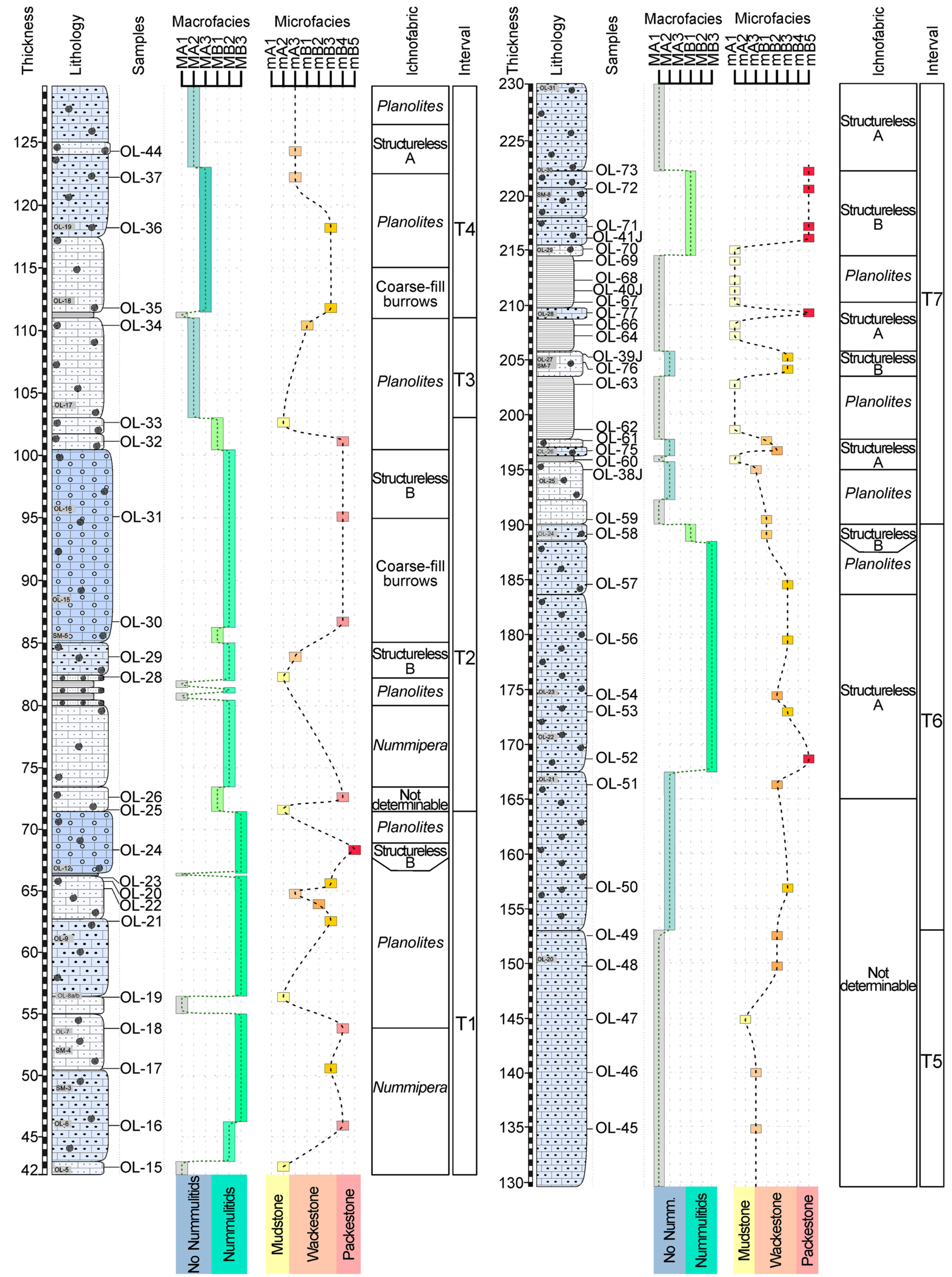
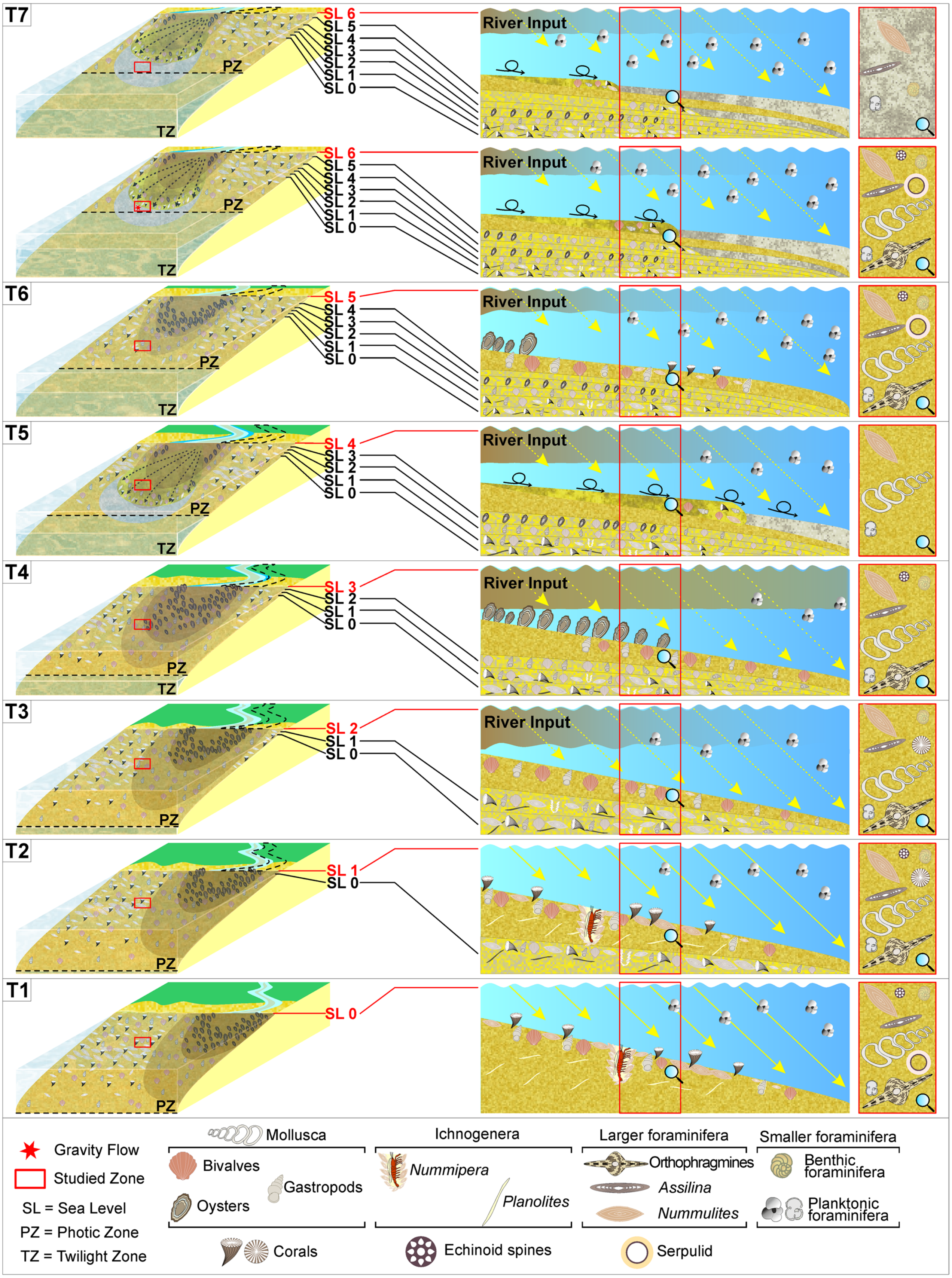


**Fig. 7** Correlation of the micro- and macrofacies displaying the ichnofabric characteristics in each paleoenvironmental interval


T7
T6
T5
T4
T3
T2
T1
SL 6
SL 5
SL 4
SL 3
SL 2
SL 1
SL 0
PZ
TZ
River Input
Mollusca
Bivalves
Gastropods
Oysters
Ichnogenera
Nummipera
Planolites
Larger foraminifera
Orthophragmines
Assilina
Nummulites
Smaller foraminifera
Benthic foraminifera
Planktonic foraminifera
Gravity Flow
Studied Zone
SL = Sea Level
PZ = Photic Zone
TZ = Twilight Zone
Corals
Echinoid spines
Serpulid

◂**Fig. 8** Paleoenvironmental evolution of the carbonate ramp at the Olivetta San Michele section, showing the benthic and planktonic communities in the different intervals of time (from T1 to T7) during the Bartonian

of west-central Argentina (Toscano et al. 2018). The ichnofabrics in this interval represent a pre-depositional suite of trace fossils, i.e., the burrows formed prior to event deposition (Uchman and Wetzel 2012). The top of this interval is characterized by *Planolites* IF, which reflects increasing sedimentation rates and commonly indicates fluctuations in oxygen and nutrient contents. The inferred water depth of T4 might still fit at a similar level as previously proposed (interval T4; Figs. 7, 8).

The interval T5 is characterized by the sudden disappearance of all body and trace fossils; the only occurrences seen in the thin sections consist of rare small LBF tests and mollusk fragments. This nearly barren condition is difficult to explain, as organisms should be thriving both on and beneath the seafloor in shallow-water settings. Enhanced sedimentation as well as hypoxic conditions in bottom waters should not be considered because such intervals enhance the preservation of pelagic and planktonic fauna that settles to the seafloor in the absence of scavengers and bioturbators (e.g., Savrda and Bottjer 1991; Wilby et al. 2004; Smith and McGowan 2008). Thus, a possible explanation could be linked to intense hydrodynamic conditions at the seafloor with still enhanced turbidity in the top layers of the water column; this might strongly affect the benthic community, removing all eventually available taxa from that portion of the seafloor. We assume that the river's frontal position favored an increased supply of terrigenous material, displacing all taxa out of the area and causing a barren scenario (interval T5; Figs. 7, 8). Possible variation in salinity produced by riverine supply may be considered a stressful factor for the biota, as recorded in this interval (e.g., Tomanek 2014).

This scenario changes completely in interval T6, where both micro- and macrofauna (diverse LBF taxa, gastropods, corals, SBF, and PF) are recorded again in the sedimentary succession. LBF tests are commonly dispersed in the matrix, but sporadically they are accumulated in irregular patterns, as is typical for the effects of sediment bioturbation. In a few cases, iso-oriented tests may indicate a mild seafloor current and the traction carpet effect (Racey 2001; Gingras et al. 2011, 2015; Kövecsi et al. 2022). Such evidence fits with an active deltaic system where hyperpycnal flows may have similar impacts on seafloors rich in nummulitic tests or may be the consequence of subtidal currents that have similar effects (interval T6; Figs. 7, 8). The sea floor must have been again favorable for a new development of the fauna, but the water depth must have become much deeper within the photic zone, which in this scenario could have been placed at 50 to 60 m of water depth, as evidenced by the presence of thin and flat *Assilina* without other LBF (Hottinger 1983; Coletti et al. 2021).

The interval T7 is characterized by an alternation of calcisiltite, biocalcisiltite, calcarenite, and biocalcarenite beds with several marly horizons. Biocalcisiltite and biocalcarenite beds have erosive basal contacts and are rich in LBF tests, mostly broken or abraded, thus making them almost nummulithoclastic deposits, here interpreted as high-energy transportation events. These events displaced LBF tests, coming from the more proximal portion of the ramp, into a much deeper setting (interval T7; Figs. 7, 8). The marly sediments are rich in pelagic and planktonic organisms and are therefore interpreted as background sedimentation in deeper and calmer depositional settings.

Trace fossils that are produced very close to the sediment surface tend to be preserved only when they are partly scoured and cast (Uchman and Wetzel 2012); therefore, the absence of the 'coarse-fill burrows' IF suggests that gravity flows were weaker and therefore more distal. Consequently, they might have had not enough energy to preserve shallow-tier burrows, thus confirming the deepening trend suggested by body fossils and sedimentological features (Ferrando et al. 2021) (interval T7; Figs. 7, 8).

The presence of repeated gravity flows may have been favored by global climatic and environmental variations that are well known through the MECO (Zachos et al. 2001): in fact, the sudden increase in temperature could have enhanced precipitations and the hydrological cycle with consequences on the terrigenous flow, as seen already in different basins of the NW Tethys (Held and Soden 2006; Chou et al. 2013; Marvel and Bonfils 2013; Baatsen et al. 2020). This climate variation is known to have caused an alternation between arid and humid conditions, which seems typical of the MECO (e.g., Turkey: Rego et al. 2018; Spain: Peris Cabré et al. 2023; Tunisia: Messaoud et al. 2023; Italy: Gandolfi et al. 2023; Briguglio et al. 2024). In shallow-marine settings, the prolonged warming of the atmosphere and ocean system triggered sediment production despite the underlying transgressive phase, thus registering variations in terrigenous supply along the Provençal Domain (Giammarino et al. 2009; Dallagiovanna et al. 2012a, b). The MECO event coincides with the drowning of the Eocene ramp, which is a regional event in NW Tethys that correlates with the Franco-Italian Maritime Alps and eastern Switzerland sections (Sayer 1995; Sinclair et al. 1998; Allen et al. 2001; Varrone and Clari 2003; Gandolfi et al. 2023). The rapid subsidence of the basin is not only the most important factor that favored the regional drowning ramp, but also the increase in nutrient supply might reduce the productivity of the carbonate ramp because of the renewal of terrigenous input into the distal part of the basin (Hallock and Schlager 1986; Sayer 1995).

## Conclusions

The studied sedimentary succession of Olivetta SM is characteristic of a carbonate ramp that formed during the middle Eocene (Bartonian) in the western Tethys, representing a transgressive phase of the basin in the Provençal Domain.

The lower part of the Olivetta SM section is dominated by photosymbiont-bearing organisms that indicate high irradiation and low turbidity in the water column with minimal disturbance by the deltaic system. Gradually, the increase in the terrigenous input firstly favored the proliferation of the filter feeders, then produced a barren interval. Toward the top of the section, the MECO event is registered and can be recognized as an alternation of gravity flows, with a higher diversity of organisms (including LBF) and silty marls, which are barren of macrofossils but rich in foraminifera, especially planktonic.

The retrieved data have shown with high resolution how environmental changes had a direct impact on the benthic community of the NW Tethys: the constant enhancement of riverine inputs that supplied nutrients increased water turbidity and reduced the penetration of solar radiation. These factors, coupled with the general transgressive trend, led to the complete collapse of the benthic carbonate producers. The MECO event in shallow-water sediments does not imply a significant increase in temperature as it does in deeper settings, but it still had a major impact on the benthic community as it triggered precipitations and thus increased the sedimentation rate.

We recognize that identifying global climatic events in shallow-water deposits seems much harder than in deeper settings; only a combination of different field data may shed light on the event occurrence and its effect on the biota. Microfacies analysis, outcrop scale observation, and ichnofabric distribution have proven to be robust enough to accurately describe the effect of MECO on the biota in a shallow-water depositional scenario. This opens new research goals and perspectives because shallow-water settings are those more affected by the ongoing climatic perturbation, and more data are needed from the fossil record during climatic analogs, especially in the Cenozoic.

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**Data availability** The authors declare that the data supporting the findings of this study are available within this paper.

## Declarations

**Conflict of interest** The authors have no competing interests to declare that are relevant to the content of the article and did not receive support from any organization for the submitted work.



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