

2.1 Terminology and Definitions

Ichnology is the study of traces produced by organisms (animals, plants and microbes) on or within a substrate. It deals with all aspects related to modern (neoichnology) and fossil traces (paleoichnology), bioturbation and bioerosion, and is interdisciplinary in combining sedimentological, paleontological, biological and ecological methods (Bromley 1996). It complements and constrains sedimentological interpretations and serves as a powerful tool in reservoir characterization.

The subjects of paleoichnology are *trace fossils* (also called ichnofossils), which are fossilized structures produced in substrates ranging from unlithified sediment to sedimentary rock or organic matter (including shell, bone, wood and peat) by the activity of organisms. Traces of organisms can be grouped into categories, depending on the type of substrate and manner of origin (Fig. 2.1):

- **Burrows:** Most common trace-fossil category, comprising galleries, tunnels, shafts, chambers, etc., excavated by animals within an unconsolidated substrate.
- **Bioerosion trace fossils:** If the excavation takes place in a consolidated and lithified substrate, the resulting trace is a bioerosional trace fossil such as a boring or a scratch.
- **Trails:** Trails are surface features, in which the producer leaves a continuous path behind it while moving.
- **Trackways:** In contrast to trails, trackways are discontinuous paths which originate from walking animals. Individual imprints of the trackway are called tracks.
- **Plant-root traces:** Most traces are related to the activity of animals, although plants can also leave their traces by means of their roots.

There are many other categories of traces with less importance for the purpose of this book, of which coprolites (i.e. fossil feces) are probably the most important. An overview of accepted groups of traces is given by Bertling et al. (2006).

Bioturbation is the process by which the primary structure and properties of a sediment are modified by the activity of organisms living within it, which may result in sediment mixing (Bromley 1996). The latter expression is often loosely applied to the product of this process, which is better defined by the term bioturbate texture (Frey 1973). *Bioerosion*, in contrast, comprises processes of mechanical or biochemical destruction of hard substrates by organisms. From a sedimentological point of view, bioturbation, bioerosion, biodeposition and biostratification structures can be grouped together as *biogenic sedimentary structures* (Frey 1973).

Ichnofacies as concept was established by Seilacher (1967) based on his and others, earlier work. Trace-fossil communities (ichnocoenoses) were linked to an overall ocean profile, mainly related to the behavioral response of the tracemakers to a bathymetric gradient in food supply. Ichnofacies represents a powerful tool when working on a larger scale (e.g. basin scale) and screening new areas, where a rough interpretation of the paleoenvironment in terms of broad facies belts can be given. The ichnofacies concept has been continuously updated, refined and extended into the continental realm. Current overviews and discussions are provided by Buatois and Mángano (2011), MacEachern et al. (2012) and Melchor et al. (2012, for continental ichnofacies).

The *ichnofabric* concept regards all aspects of the texture and internal structure of a sediment that result from bioturbation at all scales (Ekdale and Bromley 1983, 1991; Bromley

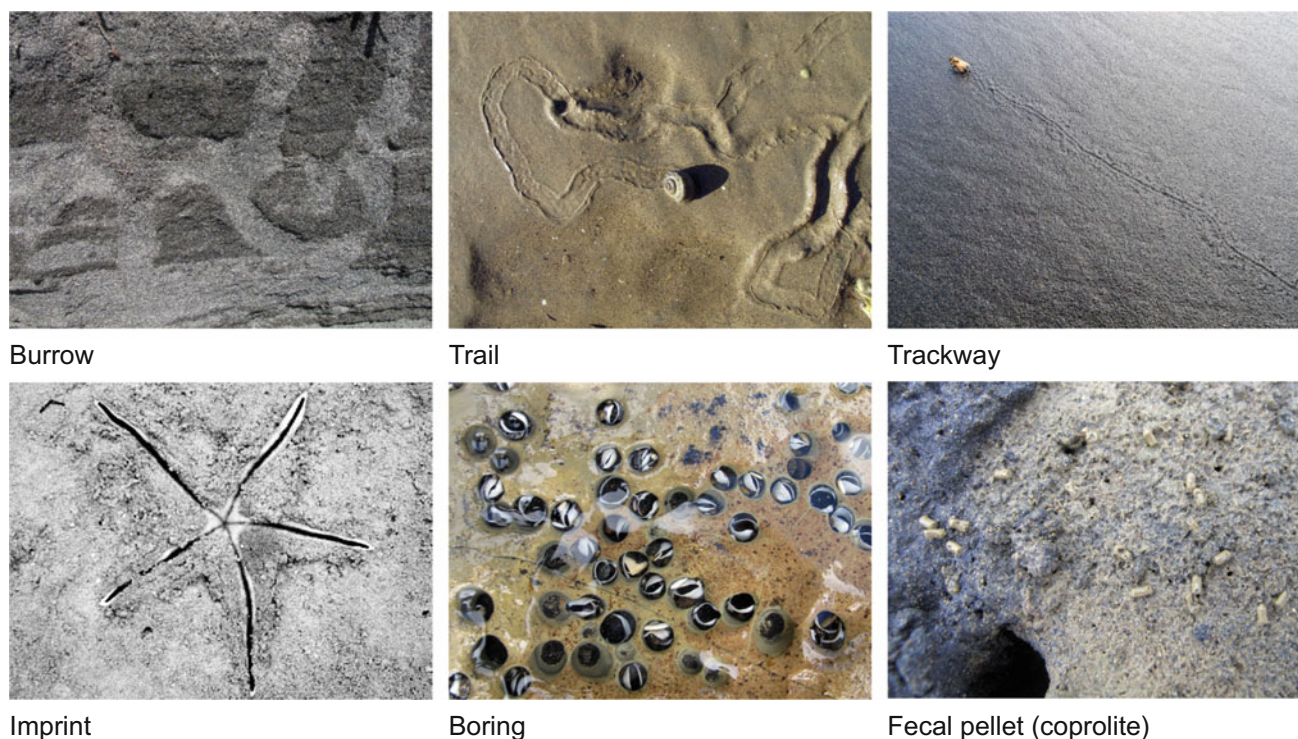


Fig. 2.1 Major categories of traces that may become trace fossils if fossilized. Bedding-surface views except for burrow (*upper left*), which is vertical section. Imprint image courtesy of H. Allen Curran (Northampton)

and Ekdale 1986). It has been developed on sectioned rock faces, where different cross-cutting relations can be related to successive colonization or tiering, and changing degree of bioturbation can be analyzed. Compared with the ichnofacies concept, which puts emphasis on the recognition of recurrent ichnocoenoses and facies belts, the purpose of the ichnofabric concept is mainly the analysis of different stages contained in a particular piece of bioturbated rock. Therefore it is a valuable tool in the detailed interpretation of rock samples from core (Taylor et al. 2003; Ekdale et al. 2012).

2.2 Some Principles

The study of trace fossils is related to various challenges of which the following are highlighted.

- *One type of organism can produce many different traces:* For example, given a particular insect which is able digging a burrow into the substrate, leaving a trackway on the surface due to locomotion, or an imprint while resting, scraping hard substrate (such as wood) while feeding, building chambers while breeding, and leaving their excrement in form of fecal pellets. Other examples include many species of crustaceans and molluscs, able to produce different traces and burrows with contrasting characteristics (Fig. 2.2, see also Fig. 5.85).
- *Many different organisms can produce the same trace:* Simple vertical shafts without branching (e.g. *Skolithos*) would be a good example, because they can be produced by many different organisms such as priapulids, holothurians, polychaetes, phoronids, crustaceans, anthozoans, insects, spiders and even plant roots (Fig. 2.3).
- *The tracemaker is rarely known:* Particularly true for many trace fossils, the tracemaker is only preserved under rare circumstances (e.g. exceptionally preserved fossils or fossilagerstätten, Fig. 2.4; see also Figs. 5.103 and 5.133). In most cases, the producer can be inferred at a higher taxonomic rank with some uncertainty, for instance by analyzing particular features of the trace (e.g. architecture, scratches and fecal pellets) or reconstruction of its functional morphology.

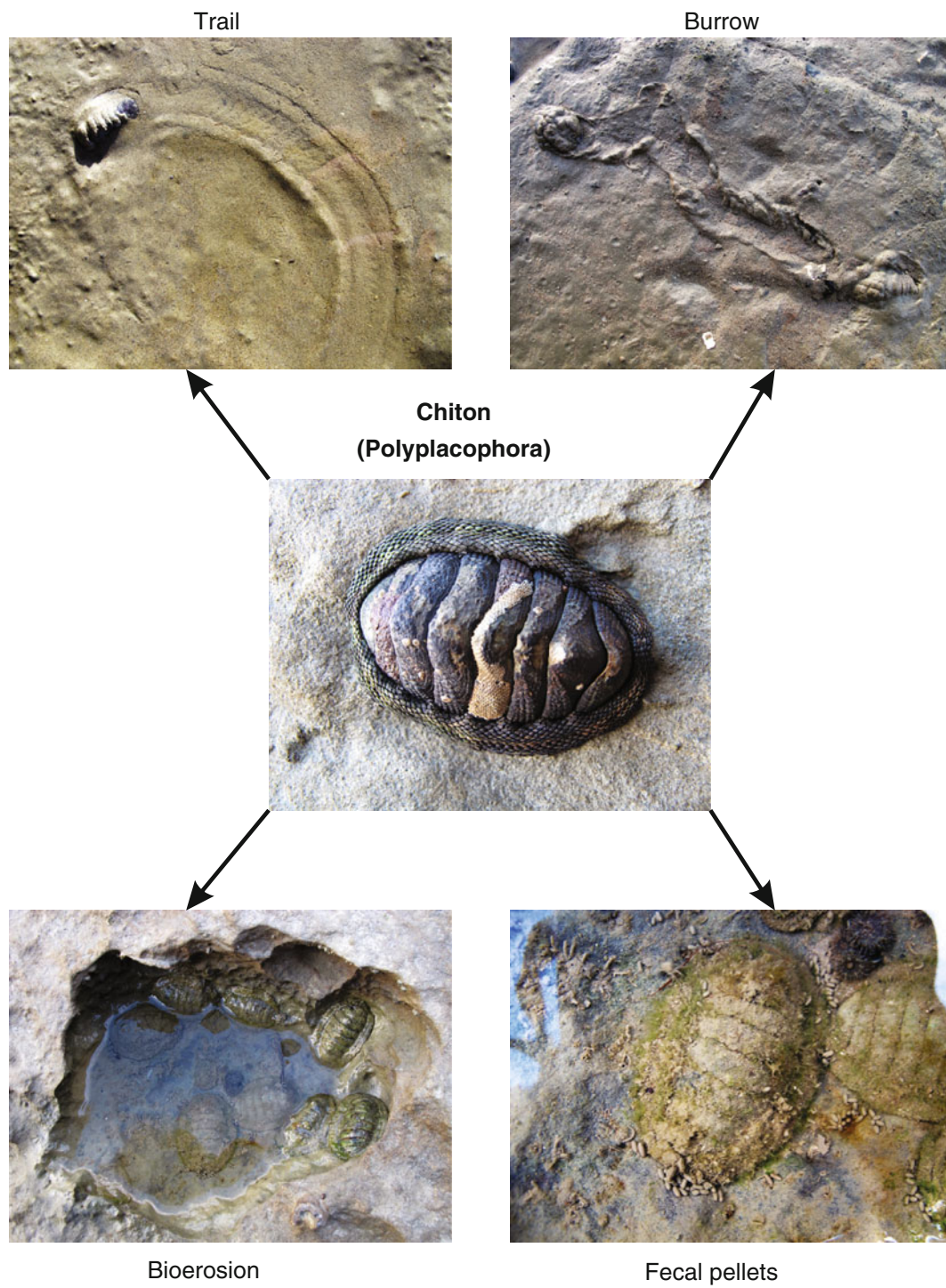


Fig. 2.2 Various traces produced by chiton (Polyplacophora)

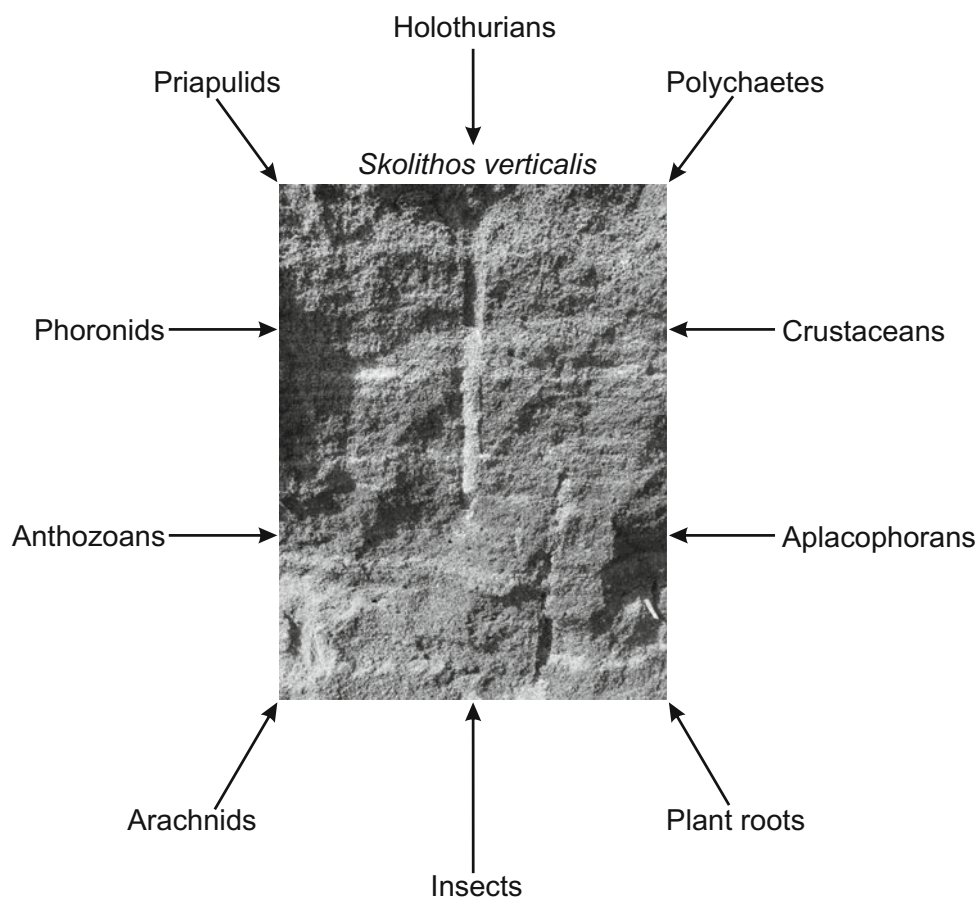


Fig. 2.3 *Skolithos*, a very simple trace, can potentially be produced by a wide range of organisms of different phyla and environments

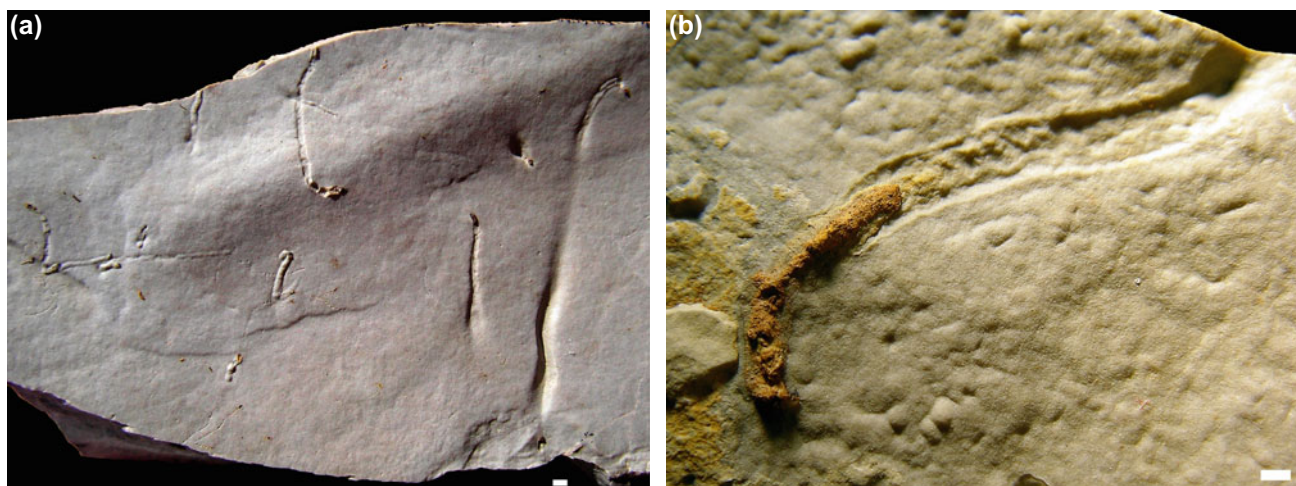


Fig. 2.4 Examples of trace fossils (mainly trails and shallow burrows) that preserve their producers at the termination of the trace. The very fine-grained (micritic) sediment and favored taphonomic and diagenetic circumstances (e.g. microbial growth, lowered oxygenation) prevented a total loss of the organic material and promoted exceptional fossil preservation, which allows a determination of higher taxonomic categories. Middle Triassic (Anisian-Ladinian) Meissner Formation (Muschelkalk), Thuringia, Germany. Scale bars = 1 mm. For details

see Knaust (2007, 2010, 2015). **a** Bedding surface with many trails and burrows, most of which preserve their producers in form of weathered sulfide aggregates (e.g. arthropods, nemerteans, nematodes) or calcite crystals (e.g. involutinidae foraminifers, turbellarian platyhelminthes). **b** Undulating bedding surface with pustules due to microbial modification with a trail occurring together with its supposed nemertean (ribbon worm) producer which is preserved as limonite aggregate. Note the slightly sinuous fecal string

Rhizocorallium commune

softground
deposit-feeding
Cruziana Ichnofacies

*Rhizocorallium jenense*

firmground
suspension-feeding
Glossifungites Ichnofacies



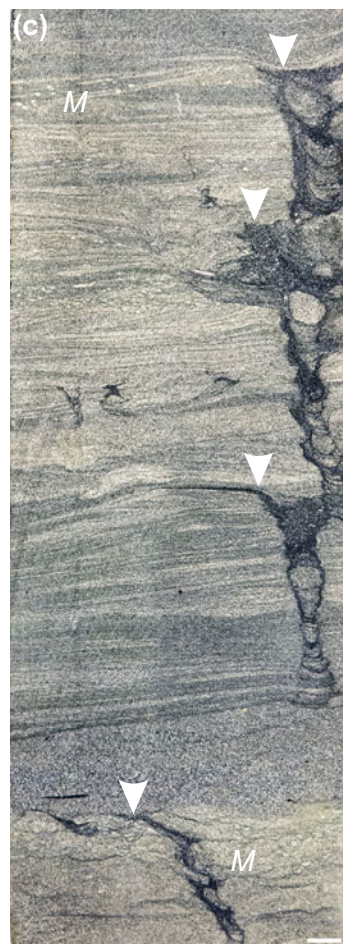
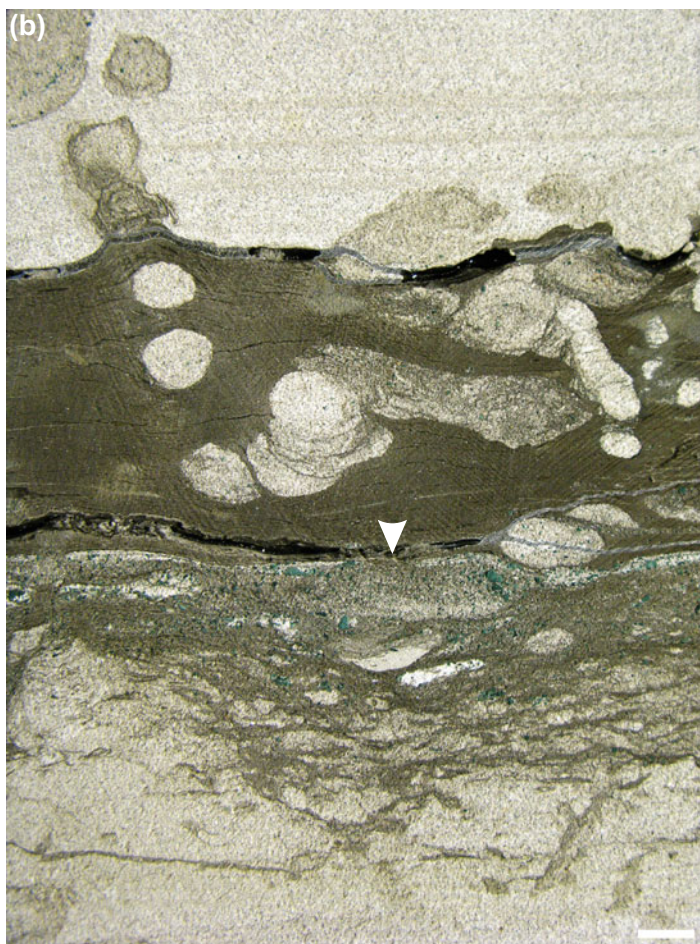
Fig. 2.5 The only two valid ichnospecies of *Rhizocorallium*, with different morphological features mainly due to contrasting substrate conditions. *Scale bars* = 1 cm. **a** *R. commune* produced in softground, a wide horizontal burrow with actively created spreite, fecal pellets and occasional branching. **b** *R. jenense* produced in firmground, a narrow

pouch-shaped and inclined burrow with passive fill and a dense pattern of scratches on the margin of burrow. After Knaust (2013), republished with permission of Elsevier; permission conveyed through Copyright Clearance Center, Inc. See also Fig. 5.117

- *The same trace becomes preserved differently in various substrates:* Different categories of substrate (e.g. softground, firmground and hardground) preserve the traces of the same producer in different ways. The ichnogenus *Rhizocorallium* is only one example (Fig. 2.5), where a probable polychaete makes extensive horizontal spreite burrows with occasional branching and active fill (*R. commune*, probably resulting from deposit feeding), while in firmground the burrows are shorter and inclined, unbranched and open or passively filled (*R. jenense*, probably resulting from suspension feeding).
- *Compound, composite and complex trace fossils:* Trace-fossil architecture can be complicated by the interaction of different tracemakers, or producers with contrasting behavior. Compound trace fossils are those comprising intergradational forms of ichnotaxonically different parts, such as *Thalassinoides*-*Ophiomorpha*-

Spongeliomorpha (Fig. 5.85). Composite trace fossils originate from the interpenetration of ichnotaxonically different parts, which can be identified as such by their cross-cutting relationship. Complex trace fossils are morphologically complex structures, including compound trace fossils, which are characterized by their high degree of organization, for instance *Zoophycos* and *Hillichnus*.

- *Multiple colonization phases and surfaces, tiers and cross-cutting relationship lead to complex ichnofabrics:* Traces are rarely single, and interaction among different generations of traces with contrasting features is the norm (Fig. 2.6). This can result in partly or completely bioturbated substrate, which may preserve discrete traces on top of a diffuse (bioturbated) background. Interaction of benthic communities may also lead to reburrowing of existing burrows by subsequent producers.



◀ **Fig. 2.6** Ichnofabrics with multiple colonization surfaces in outcrop and in core. *Scale bars* = 5 cm (**a**) and 1 cm (**b**, **c**). **a** Outcrop photograph of a limestone bedding plane showing hardground features with dense occurrence of *Gastrochaenolites* isp., produced by boring bivalves (in places preserved) in a shallow-marine environment. A second colonization of the same surface is documented by a network of calichified root traces, which belong to the overlying eolian sandstone. This surface is a regional angular unconformity between Cretaceous platform carbonates and Pliocene to Pleistocene eolian dune deposits (brownish patches of sand). Cliff section south of Taghazout, western Morocco. **b** Parts of two sandy turbidite layers interbedded with hemipelagic mudstone in vertical core section. The top surface of the lower turbidite served as a colonization surface (*arrow head*), which resulted in a mixed layer with incorporated green clay minerals beneath

it due to repeated bioturbation. The mudstone layer above it contains large burrows actively filled with sand (*Thalassinoides* and *Ophiomorpha*) as part of deep-tier burrowing through the overlying sand (turbidite). Upper Cretaceous (Maastrichtian) Springar Formation (deepmarine), Norwegian Sea (well 6604/10-1, ca. 3647.5 m). **c** Ripple-laminated fine-grained sandstone with intervals containing *Macaronichnus segregatis* (*M*) in vertical core section. The displayed sandstone shows multiple colonization surfaces (*arrow heads*) from which the muddy spreite burrows *Teichichnus zigzag* penetrate the underlying sediment, indicating rapid deposition (sandy tidal-flat deposit). The succession is interrupted by a medium-grained sandstone layer in its lower part, probably a storm deposit (tempestite). Middle Jurassic (Bathonian) Tarbert Formation (sandy tidal flat), Oseberg Sør Field, Norwegian North Sea (well 30/9-F-26, ca. 4466.8 m)

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