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Trace Fossils as Indicators of Sedimentary Environments

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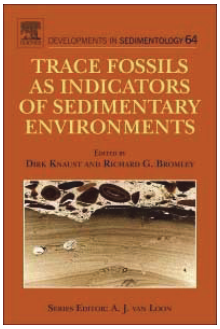
In the past century, especially in the beginning of the twenty-first century, ichnology underwent rapid growth and the potential of ichnological analysis was made manifest in a wide range of fields – palaeobiology, palaeoecology, biostratigraphy, evolutionary aspects, and sedimentology, among others. This important expansion is reflected in several symposium volumes, books and monographs published in recent years (i.e., Pemberton et al., 2001; Buatois et al., 2002; Hasiotis, 2002; Kowalewski and Kelley, 2002; Buatois and Mángano, 2003, 2011; Kelley et al., 2003; McIlroy, 2004; Webby et al., 2004; Wisshak, 2006; Bromley et al., 2007; Miller III, 2007; Seilacher, 2007; Gerard & Bromley, 2008; Wisshak and Tapanila, 2008; MacEachern et al., 2009). The panorama of applications of ichnology thus became highly useful in many disciplines, involving biologists, palaeontologists and sedimentologists. However, the latter group still resists the application of ichnology in basin analysis, which in most cases is conducted by ichnologists themselves. The relative lack of knowledge on the part of non-specialists leads them to underutilize trace fossils. This book strives to bridge the gap, focusing on the usefulness of ichnological research in basin analysis, and placing ichnology well in the reach of sedimentologists. However, this volume is by no means exclusively for sedimentologists and it may be considered as a reference for specialized ichnologists, and for non-specialist biologists or petroleum geologists, among others.



To this end the book is clearly differentiated in three parts. The first part (Part I, History, Concepts and Methods) offers a detailed update of several aspects of ichnology, from an overview of its history and relevant methodology, to a review of basic concepts such as ichnofacies and ichnofabrics. This extensive, yet precise introduction to ichnology will be of interest to expert and non-expert readers. The second section of the book (Parts II through V) presents detailed ichnological analysis of a number of depositional systems, including Continental and Glacial Systems (Part II), Shallow-Marine Siliciclastic Systems (Part III), Deep-Marine Siliciclastic Systems (Part IV), and Marine Carbonate Systems (Part V). This can be considered the core of the book, highlighting the importance of trace fossils in the field of basin analysis, and the usefulness of ichnology for interpreting sedimentary environments. Finally, the last section of the book (Part VI, Ichnology in Hydrocarbon-Reservoir and Aquifer Characterization) deals

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with the application of ichnological analysis to appraise hydrocarbon reservoirs and aquifers, mainly by examining the influence of trace fossils on porosity and permeability in sedimentary rocks and hence on fluid-flow properties.

Part I consists of ten chapters that focus on introductory topics. Chapter 1 – *A History of Ideas in Ichnology*. The first chapter presents a detailed historical overview of ichnology, tracing human interest in trace fossils from the Palaeolithic to modern times. In addition to describing the main developments and major protagonists over the years, many interesting facts and anecdotes are presented. Chapter 2 – *Ichnotaxonomy: Finding Patterns in a Welter of Information* introduces readers to the different types of trace-fossil classifications (stratinomic, biological, ethological and systematic), as well as to the steps involved in naming new trace fossils. Chapter 3 – *Trace-Fossil Systematics* provides a nomenclature key to organize ichnotaxa with respect to their ichnotaxobases, establishing a basic differentiation of three major groups of trace fossils: burrows, bioerosional trace fossils, and surface traces (trackways, imprints, and trails). This is a morphological classification at the ichnogenus level, based on significant morphological features such as orientation, branching, shape, or fill, among others, allowing even non-specialists to arrive at a preliminary determination. Several figures are included to illustrate the proposed classifications. Though not definitive, the classification scheme put forth by the author constitutes a sound starting point for a systematic trace-fossil foundation. In Chapter 4 – *The Ichnofacies Paradigm*, the paradigm is analysed in terms of the depositional parameters traditionally used for differentiation, with further emphasis placed on specific environmental factors such as temperature, oxygenation, salinity or sedimentation, mainly supported by neoichnological studies. Trace-fossil suites attributable to the different Seilacherian ichnofacies are illustrated, with good photographs from recent and fossil examples. Chapter 5 – *The Ichnofabric Concept* explores the concept of ichnofabric, not from a descriptive point of view, but focusing on its significance for fields as diverse as sedimentology, geochemistry, palaeoecology, taphonomy, and stratigraphy, with special attention to its potential use for exploration geologists and hydrogeologists in relation to sediment porosity and permeability. Several photographs of ichnofabrics in slabbed cores are provided. Chapter 6 – *Sequence Stratigraphy* looks into the applications of ichnology to genetic stratigraphy; after an introductory descriptive section, the focus shifts to several case studies. This can be considered as a revision of similar presentations from the same authors on this topic, in some cases using illustrations presented previously (for example, in chapter 7 of Miller III, 2007). Chapter 7 – *Ichnostratigraphy* offers a brief review of the utility of trace fossils in ichnostratigraphy (application of ichnology in biostratigraphy), analysed in depth in other recent books (i.e., Mángano and Buatois, 2011). Several examples are given for continental, marginal-marine, and marine (shallow and deep) environments. Chapter 8 – *Microbioerosion* consists of an overview of this comparatively young ichnological discipline. The methods used are described, from microscropy of petrographic thin sections to scanning electron microscopy of a cast obtained with the epoxy cast-embedding technique, and sophisticated microcomputed tomography. Moreover, microboring biota (cyanobacteria, chlorophytes, rhodophytes and fungi) and their traces are reviewed, along with their applicability for palaeoenvironmental analysis, mainly palaeobathymetry, palaeotemperature, palaeosalinity and trophic regime. Chapter 9 – *Methodology and Techniques* provides a run through the most appropriate and the most recent methods and techniques used in ichnology. A distinction is made regarding techniques and methods used in the field (outcrop observation, peels, moulds, casts, core samples, quantitative methods of bioturbation) and those used in the laboratory (sectioning, staining, peeling or advanced photography for enhancement of visibility, thin sections, optical microscopy, SEM, X-ray radiograph, or the more recent computer-aided tomography techniques). Well cores and borehole images are dealt with separately, as are statistical analysis and computer modelling. Finally, Chapter 10 – *Marine Invertebrate Neoichnology* is dedicated to neoichnology of siliciclastic, marginal-marine to marine depositional environments, with two clearly differentiated parts. The first presents the major invertebrate trace-making groups, primarily vermiform, and bivalves, crustaceans, echinoderms, cnidarians, sponges and sea anemones as secondary, along with their common traces. There are good drawings, photos and X-ray radiographs to illustrate different tracemakers and their traces. The second part explains the association between environmental and physico-chemical factors, stresses (e.g., salinity, grain size, oxygenation, turbidity), burrowing animals, and therefore their traces (e.g., diversity and density).

Part II consists of Chapters 11 to 14, which focus on the analysis of Continental and Glacial Systems, distinguishing between glacial, fluvial, lacustrine and aeolian environments. Characteristic ichnofacies are exemplified in ancient and recent environments. Chapter 11 – *Glacial Environments*. Although the ichnology of such settings is scarcely studied, this chapter describes trace-fossil assemblages from different glacial environments (e.g., terrestrial, glaciolacustrine and glaciomarine). Variations of trace fossils according to the evolution of glacial conditions are illustrated. Chapter 12 – *Fluvial Environments*. A detailed analysis of trace-fossil assemblages and ichnofacies of diverse fluvial subenvironments is presented. Ichnotaxa from fluvial environments are grouped in trace-fossil categories according to their morphology, and invertebrate and vertebrate ichnofacies from fluvial deposits are characterized. Examples of ichnofacies and ichnofabric in the palaeoenvironmental analysis of facies from different subenvironments (e.g., channel-belt, foodplain, and overbank, among others) are included. Chapter 13 – *Lacustrine Environments*. This chapter addresses the complexity of lacustrine environments, the interplay of abiotic and biotic factors, the influence of organisms and the consequent heterogeneity of trace-fossil assemblages. Application of ichnology in lacustrine environments is exemplified, according to a zonation scheme of subenvironments (from profundal to supralittoral zones) into different lake-type basins (overfilled, balanced-fill, and underfilled). Information on sedimentary processes, depositional settings, environmental conditions, hiatuses and architecture of the lake-basin is approached based on the analysis of biogenetic structures. Chapter 14 – *Eolian Environments*. Despite the scarcity of trace fossils in dune deposits, this information is essential for the interpretation of these environments due to the practical absence of body fossils. Here, examples from ancient coastal dunes and inland ergs are presented, with illustration of invertebrate and vertebrate trace fossils. The importance of ichnological data for palaeoclimatic studies is addressed. The application not only of ichnofacies but also of ichnofabrics holds great potential for characterizing aeolian environments.

Part III, consisting of Chapters 15 to 19, focuses on Shallow-Marine Siliciclastic Systems, establishing the characteristics of rocky shorelines, estuaries, deltas, tidal flats and subtidal sand bodies and shoreface environments. The degree of extension and detail varies from one environment to another. Chapter 15 – *Rocky Shorelines*. Rocky shores are essentially erosional, characterized by hard substrates and related to high-energy conditions, and usually found associated with regional unconformities. This chapter looks at macroscopic bioerosion structures, including bivalve, sponge, worm, echinoid and cirripede borings. Trace-fossil assemblages and ichnofacies are exemplified by several ancient case studies. Chapter 16 – *Estuaries*. The neo- and palaeoichnological approach is introduced in this chapter to evaluate the ichnological identification of estuaries, based on at least four significant conditions: the presence of brackish-water trace-fossil assemblages, the trace-fossil distribution linked to tidally influenced sedimentation, the occurrence of particular suites attributable to discontinuities of sequence-stratigraphic significance, and the existence of ichnological data associated with backstepping of sedimentary environments. Several recent and ancient case studies evidence the relationship between trace-fossil distributions and subenvironments within wave- and tide-dominated estuaries. Chapter 17 – *Deltas*. The assemblage or suite of trace-fossils in an ichnofabric or ichnofacies serves to refine subenvironments of marine deltas. Here the relationship between tracemakers and physico-chemical controls conforming deltaic environments is characterized, the main palaeoenvironmental controls on bioturbation being sedimentation rate, salinity, and hydrodynamic energy; and secondarily oxygenation, substrate consistency, turbidity, light, and temperature. Fluvial, tide, and wave-dominated deltaic ichnology are covered. Few illustrations are included. Chapter 18 – *Tidal Flats and Subtidal Sand Bodies*. A detailed study on macrotidal (tidal range > 4m) open-marine settings, in which tidal currents are the dominant sedimentary process, is presented in this chapter. An integrated ichnological and sedimentological model delineating supratidal, intertidal (mud, mixed, and sand flats), and shallow subtidal environments is proposed as an aid to characterizing dune fields, sand sheets, sand ridges, isolated dune patches, and tidal bars. The integrated models of the different subenvironments are well illustrated by explanatory diagrams and photographs from recent and, mainly, ancient examples. Controlling factors on benthic faunas in supratidal, intertidal and subtidal environments are considered according to the type of organism and associated biogenic structures. Ichnological data, with special attention to ichnofacies, are analysed in a sequence stratigraphic framework at the parasequence level. Chapter 19 – *Shorefaces*. This

chapter describes not only the shoreface environment and respective subenvironments, but also the adjacent ones, grouped into three depositional complexes: the offshore complex, the lower-middle shoreface complex, and the upper shoreface-foreshore-backshore complex. Sedimentological and ichnological features of these complexes are presented, and interpreted principally with regard to the dominant physical controlling processes (i.e., storms, fair-weather waves). Tidal effects on the shoreface are also analysed, with characterization of tidal-influenced and tidally modulated shorefaces depending on the tidal hydrodynamic conditions, based on sedimentological and ichnological criteria and illustrated by modern examples.

Part IV consists of Chapters 20 to 22 and focuses on Deep-Marine Siliciclastic Systems, i.e. slopes, deep-sea fans, and hemipelagic and pelagic basin plains, covering different aspects according to the environment in question. Chapter 20 – *Slopes* reviews slope environments through an integration of sedimentological and ichnological data, and features well photographed Cretaceous and Palaeogene cases from submarine canyons, intraslope minibasins, slope channels, and levee complexes. The physico-chemical parameters (e.g., current energy, sedimentation rate, slope instability, character of the substrate, oxygen, food availability, water turbidity) influencing distribution, diversity, and abundance of benthic organisms are presented. Moreover, a detailed characterization of the ichnofacies in bathyal settings is included, and the trace fossils typical of facies deposited on the slope are illustrated. Chapter 21 – *Deep-Sea Fans*. This chapter analyses deep-marine settings considerably affected by turbidite deposition. The main deep trace-fossil groups are outlined, with emphasis on the most common ethological categories and the differentiation between pre- and post-depositional trace fossils. Ichnofacies and ichnofabrics are considered to characterize subenvironments into deep-sea fans, the latter of special interest for reconstruction of the complex colonization history of a single layer in turbidite/hemipelagic sediments. An overview is presented on the trace fossils as indicators of ecological and physical sedimentary parameters, as well as respect to cyclicity and sequence stratigraphy, and mainly on evolutionary aspects. Chapter 22 – *Hemipelagic and Pelagic Basin Plains*. Ichnological and sedimentological features of hemipelagic and pelagic deposits are overviewed; ichnofabric analysis, with special mention to tiering of traces is indicated. There is a brief description of bioturbational sedimentary structures and post-depositional taxa. Application of ichnological data to decipher environmental conditions is analysed, focusing on the relationship between organic matter supply, sedimentation rate, and oxygenation. Modern and ancient examples are well illustrated. The importance of neoichnology for the characterization of tracemaker, their burrowing and general behaviour, and their relationship with environmental factors is addressed.

Part V includes Chapters 23 through 26 and highlights marine carbonate systems from the well-known shallow-marine carbonates, to the comparatively poorly characterized reefs and mounds, chalk and related deep-marine carbonates, and mixed siliciclastic/carbonate systems. Chapter 23 – *Shallow-Marine Carbonates*. Ichnology of shallow-marine carbonates, from marginal-marine (peritidal) to the shelf is considered, the bulk of this chapter being devoted to demonstrate the importance of ichnological analysis by the detailed presentation of ancient (Middle Ordovician and Middle Triassic) and recent examples, as comparative models. Criteria controlling the presence, distribution and quality of trace fossils include composition and distribution of benthic organisms as potential tracemakers, sediment types and their alteration, and the early-diagenetic history. Also described are the types of ichnofacies of interest for interpreting shallow-marine carbonate environments. Chapter 24 – *Reefs and Mounds* has a multiple focus: a) reef traces and tracemakers, with differentiation of macroborings and bioclaustartions, and the grazers; b) trends in reef ichnology over time, from fossil to modern reefs; and c) factors such as seawater temperature, sea level, sedimentation and water quality, among others, influencing the bioerosion of reefs. Chapter 25 – *Chalk and Related Deep-Marine Carbonates*. As indicated in the first sentence of the chapter, the focus is on “the ichnology of those marine carbonates that are composed mainly of the remains of calcareous nannoplankton, principally coccolithophores, that is carbonate ooze, chalk and nannofossil limestone”. The information is presented underlining the differences among all the ichnofacies involved, including ichnocoenosis and ichnofabrics, mainly illustrated by black/white schematic representations. Taken into account are the environmental parameters influencing ichnological data, such as oxygenation, bottom-current strength, sedimentation rate, substrate consistency, and even factors affecting the expression of trace fossils. Chapter 26 – *Mixed Siliciclastic/Carbonate Systems*. This chapter analyses the ichnology of mixed siliciclastic/carbonate systems,

with the accent almost exclusively on examples where admixture of clastic and carbonate sediment produces a unique ichnological signature. Most are Triassic examples, though some Permian and Eocene cases are discussed too, showing how spatial variability/lateral facies mixing resulted in unique relationships between trace-fossil assemblages, whereas temporal variability in the form of stratigraphic occurrence resulted in the vertical juxtaposition of trace-fossil assemblages and ichnofacies. Shell debris in clastic successions is presented as a significant element in the infaunal habitat and thus in trace-fossil assemblages.

Part VI of the book consists of two chapters revolving around a relatively novel application of ichnological analysis, of special interest for more industrial sectors – the impact of bioturbation on fluid-flow properties, in both hydrocarbon reservoirs and groundwater aquifers. Accordingly, Chapter 27 – *Porosity and Permeability in Bioturbated Sediments* presents an overview of the applications of ichnology to reservoir fluid flow. Permeability and porosity are analysed, explaining the various ways in which burrows may influence both properties (e.g. bioturbation intensity, burrow connectivity, burrow-surface area, and burrow architecture). Several cases worldwide are presented to exemplify a classification system for burrow-related permeability. In turn, Chapter 28 – *Carbonate Aquifers* shows ichnology to be a very useful tool for aquifer characterization, given the strong relationship between macroporosity and permeability related to ichnofabrics and groundwater flow in carbonate aquifers. Three case studies from the Pleistocene and Cretaceous are presented to uphold its use to improve the delineation of cyles, the mapping of cycles based on correlations of biogenically altered surfaces, the mapping of zones of preferential groundwater flow and palaeogroundwater flow, and our understanding of the origin of karst features related to ichnofabrics.

Altogether, this very interesting book, recommended for specialists and non-specialists in ichnology who undertake or approach basin analysis research. High-quality photographs, diagrams, sketches, and tables accompany the text, although in cases they come from previous publications. The fact that extension and detail vary from chapter to chapter is a minor point to be criticized, but this is hardly avoidable given the breadth of ichnological information derived from the major sedimentary environments considered here. The final result is a vast review in terms of the number of contributors (84), reviewers (36), pages (960), and chapters (28), providing extensive and significant information. This is the culmination of intense work by Dirk Knaust and Richard Bromley, and I congratulate both for their courage and for the quality of this integral volume.

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