Atlas of Trace Fossils in Well Core

Dirk Knaust

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Appearance, Taxonomy and Interpretation

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Cover image: Sectioned well-core sample of a cross-bedded sandstone with mud drapes and floating granulae, comprising the cross section of a large spreite burrow assigned to *Teichichnus zigzag*. Middle Jurassic (Bathonian) Tarbert Formation (tidally influenced delta front), Oseberg Sør Field, Norwegian North Sea (well 30/9-4S, ca. 3347.2 m). Image width ca. 9 cm. Photograph taken by the author.

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For my son and daughter,
Per Ragnar and Solveig Alida

Foreword

It is not easy to tell which of the graduate students will become masters in their field. When I met Dirk Knaust in 1997 at the Fourth International Ichnofabric Workshop on San Salvador, he was just another graduate student, obviously very intelligent, but there were others with longer strings of publications. But as the years progressed, Dirk's work in ichnology accelerated, and it became clear that he is a perfectionist whose body of work is ripening at last. Building on his doctoral study of the Muschelkalk, he expanded his range to the North Sea and many other regions, and as we all know, the best ichnologist is the one who has seen the most trace fossils. In his maturity, he has produced a series of papers revising *Asteriacites, Rhizocorallium, Balanoglossites, Pholeus, Oichnus*, and other ichnogenera (Knaust 2002, 2008, 2013; Wisshak et al. 2015; Knaust and Neumann 2016), brought the world's attention to extraordinarily preserved tracemakers in the Muschelkalk (Knaust 2010a, b), and elucidated the connection between bioturbation and reservoir quality (Knaust 2009a, b; Knaust et al. 2014).

Dirk's most important effort in recent years has been, together with Richard G. Bromley, to organize and edit *Trace Fossils as Indicators of Sedimentary Environments*, a thick volume that brings ichnology to sedimentologists and other geologists—and sedimentology back to ichnologists (Knaust and Bromley 2012). He carried an advance copy of the book to Ichnia 2012, where it was a big hit among ichnologists on the long drives between field trip stops on the Avalon Peninsula of Newfoundland. The copy passed slowly from hand to hand to the rear of the bus and back to the front again. I think he must have sold to forty people on the bus within a few hours.

Currently, Dirk is at work with me on leading a revision of the trace-fossil volume of the *Treatise on Invertebrate Paleontology*. As he pointed out in a keynote address at Ichnia 2016, the number of named invertebrate ichnogenera has more than doubled since Walter Häntzschel's last revision in 1975. After Bertling et al. (2006) reached a consensus on which criteria were best for differentiating ichnotaxa, Dirk applied these ichnotaxobases systematically to the entire corpus of invertebrate trace fossils, using them to define categories within a key (Knaust 2012)—an effort that required consulting the diagnoses and major revisions of every ichnogenus. He reasoned that ichnogenera falling within the same category are potential synonyms, and indeed some have been found by this method. The key is effectively a massive test of the consensus criteria, generating predictions that might otherwise not be investigated. It is also a way to guide ichnologists toward a viable classification of trace fossils that utilizes ichnofamilies within the context of tracemaker behavior and paleoenvironments. In a recent paper, Dirk erected a new ichnofamily, the Siphonichnidae, to accommodate bivalvian activity as diverse as those recorded in *Parahaentzschelinia, Scalichnus*, and *Hillichnus* (Knaust 2015). He has also drawn attention to the meiobenthos as significant agents of bioturbation, even identifying fossil tracemakers in some cases (Knaust 2010a, b).

The book at hand, *Atlas of Trace Fossils in Well Core—Appearance, Taxonomy and Interpretation*, was developed over a period of years from the series of in-house workshops that Dirk has led from 2011 onwards. It is clear that this work comes from long gestation of ideas and presentation. It includes two sections: First, a brief introduction acquaints the reader with the fundamentals of ichnology, with special regard to their use in petroleum geology.

Second, in the main part of the book, 39 genera of trace fossils and associated features are discussed individually. For each ichnogenus, sections are given on their morphology, fill and size, ichnotaxonomy, substrate, appearance in core, similar trace fossils, producers, ethology (behavior), depositional environment, ichnofacies, age, and finally reservoir quality, accompanied by a generous number of illustrations. The treatment is condensed but draws on a very broad knowledge of the literature as well as extensive personal experience. Many of the illustrations are new; others are borrowed from the best in the literature. For many ichnogenera, the criteria for identification of the major ichnospecies are given, and close attention is paid to possible tracemakers and their behavior. Is such detail necessary? Not for every project, but the studies that pay attention to ichnospecies do yield finer details about depositional environments than those which identify trace fossils only to ichnogenus, or ignore ichnotaxonomy altogether.

The trace fossils that have been chosen for treatment in this volume include all the ichnogenera that are ordinarily found in cores, whether taken for academic or economic purposes, plus ichnogenera that are common in geological contexts with which Dirk is familiar. The result is that here is not only the most up-to-date compendium of information on trace fossils in cores, but also an advancement of science on trace fossils such as *Phoebichnus* that many ichnologists have not recognized in their own material.

Anyone who wishes to use trace fossils in core or outcrop can benefit from reading this book, but those who want information on how trace fossils determine the porosity and permeability of rocks will find it particularly useful (Knaust 2014). Dirk gives specific information about the properties that each ichnogenus may lend reservoir rocks, whether aiding or hindering the flow of pore fluids.

Need I remind readers that what controls petroleum flow also applies to groundwater? Hydrogeologists and environmental geologists may be pleasantly surprised to find that they can better understand the properties of aquifers and aquitards by reference to ichnology. This is a barely touched area of science, but one that will becoming increasingly important as water tables fall and engineering projects respond to environmental changes. The permeability of the limestone underlying Miami, for instance, is determined partly by its trace fossils. It will not be surprising if the stratigraphic distribution of trace fossils turns out to determine the fate of different areas of Florida as sea level rises.

You have in your hands an authoritative book, one that will have an influence for years to come throughout the field of invertebrate ichnology as well as aspects of sedimentology, petroleum geology, and environmental geology. It has built on decades of work by the ichnological community and Knaust's own, and is a fitting companion for the scientist who works with trace fossils.

July 2016

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Preface

This book provides the reader with a blend of high-quality photographs, figures, and accompanied text for the identification of trace fossils in well core and outcrop. Ichnological data are becoming more and more crucial in sedimentological and paleoenvironmental interpretation, not only in the exploration and exploitation of hydrocarbon but also in the characterization of aquifers and in scientific drilling. Key features include the identification and interpretation of trace fossils in core and outcrop, integrated sedimentological–ichnological core logging, and hydrocarbon reservoir characterization. It has been prepared for an audience in the fields of sedimentology, paleontology, and petroleum geoscience from academia (graduate students and professionals) and industry (reservoir geologists).

After an introduction to the study of trace fossils in well core and an outlining of ichnological basics, principles and concepts, this book offers a detailed description and interpretation of 39 commonly occurring ichnogenera together with recurrently associated features such as diffuse bioturbate texture, plant roots and their traces, borings and pseudo-trace fossils. The trace fossils are highlighted by their expression in well core, illustrated with numerous original photographs and supplemented with carefully selected schematic drawings from the literature. This unique information is complemented by examples of trace fossils in outcrop, as well as relevant key figures from existing work.

Each chapter is treated in a consistent manner, stating the ichnogenus name and author in the title, followed by sections on morphology, fill and size; ichnotaxonomy; substrate; appearance in core; similar trace fossils; producers; ethology; depositional environment; ichnofacies; age as well as reservoir quality. This book is rounded off with an extensive list of references for further reading. The material for the book originated from the author's continuous work with trace fossils, chiefly in core, over the last two decades.

The well-core examples selected for this book mainly originate from the Norwegian Continental Shelf, which has been subject to extensive exploration and exploitation for oil and gas over the last half-century, although data from other regions of the world have been added. Based on this, siliciclastic rocks are overrepresented as compared to carbonates, and the majority of material comes from Mesozoic strata; however, all major paleoenvironments are covered. The presented trace fossils and associated features are thus just examples of possible occurrences in core, and other regions or stratigraphical units may return other interesting ichnological data. It is my hope that this book will promote further studies in this field.

Many colleagues and friends have shared their ideas over the last years, as well as specimens and literature; these include, in alphabetical order:

Andrea Baucon (Milano), Zain Belaústegui (Barcelona), Markus Bertling (Münster), Richard G. Bromley (Copenhagen), Luis A. Buatois (Saskatoon), Richard H.T. Callow (Stavanger), Kevin J. Cunningham (Miami), H. Allen Curran (Northampton), Andrei V. Dronov (Moscow), Allan A. Ekdale (Salt Lake City), Christian C. Emig (Marseille), Christian Gaillard (Lyon), Jorge F. Genise (Buenos Aires), Jean Gérard (Madrid), Jordi de Gibert (Barcelona, deceased), Murray K. Gingras (Edmonton), Roland Goldring (Reading, deceased), Murray R. Gregory (Auckland), Hans Hagdorn (Ingelfingen), Geir Helgesen (Stavanger), William Helland-Hansen (Bergen), Günther Hertweck (Wilhelmshaven), Sören Jensen

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Several ideas originated during the International Congresses on Ichnology and International Ichnofabric Workshops and also during in-house core workshops, special projects, and teaching trace-fossil analysis. Statoil ASA, in particular Sture Leiknes (Bergen), Frode Hadler-Jacobsen (Trondheim), Kjell Sunde (Bergen), and Ole Jacob Martinsen (Bergen), is thanked for providing me with the opportunity to study trace fossils in so many cores and to enable the publication of selected parts of this knowledge. This book has greatly benefited from the thorough reviews provided by Andrew K. Rindsberg (Livingston) and Andreas Wetzel (Basel), whose timely suggestions are much appreciated.

Stavanger, Norway Dirk Knaust
August 2016

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About the Author

Dirk Knaust is Specialist in Sedimentology in Statoil's Research and Technology unit in Stavanger, Norway. After working as a geologist in an underground mine and graduating in Germany with a Ph.D. in Geology (Carbonate Sedimentology, Stratigraphy, and Paleontology in the Triassic), in 1997 he followed an offer from the Norwegian oil and gas industry working in Exploration and Field Development. Since then, he has been frequently exposed to a vast amount of well core for investigation. The author has studied various aspects of trace fossils and ichnology, which is documented in about 60 publications in scientific journals and edited volumes. He is co-editor of the book *Trace Fossils as Indicators of Sedimentary Environments* (Elsevier) and associate editor of the journal *Ichnos*, amongst others. Dirk is leading author of a revised version of the *Trace Fossils* volume to be published in the *Treatise of Invertebrate Paleontology*.

The author inspecting dinosaur footprints on a Jurassic carbonate mud flat in Portugal