TERRESTRIAL IMPACT STRUCTURES: The TanDEM-X Atlas. Vol.1 and 2.

Manfred Gottwald, Thomas Kenkmann, Wolf Uwe Reimold

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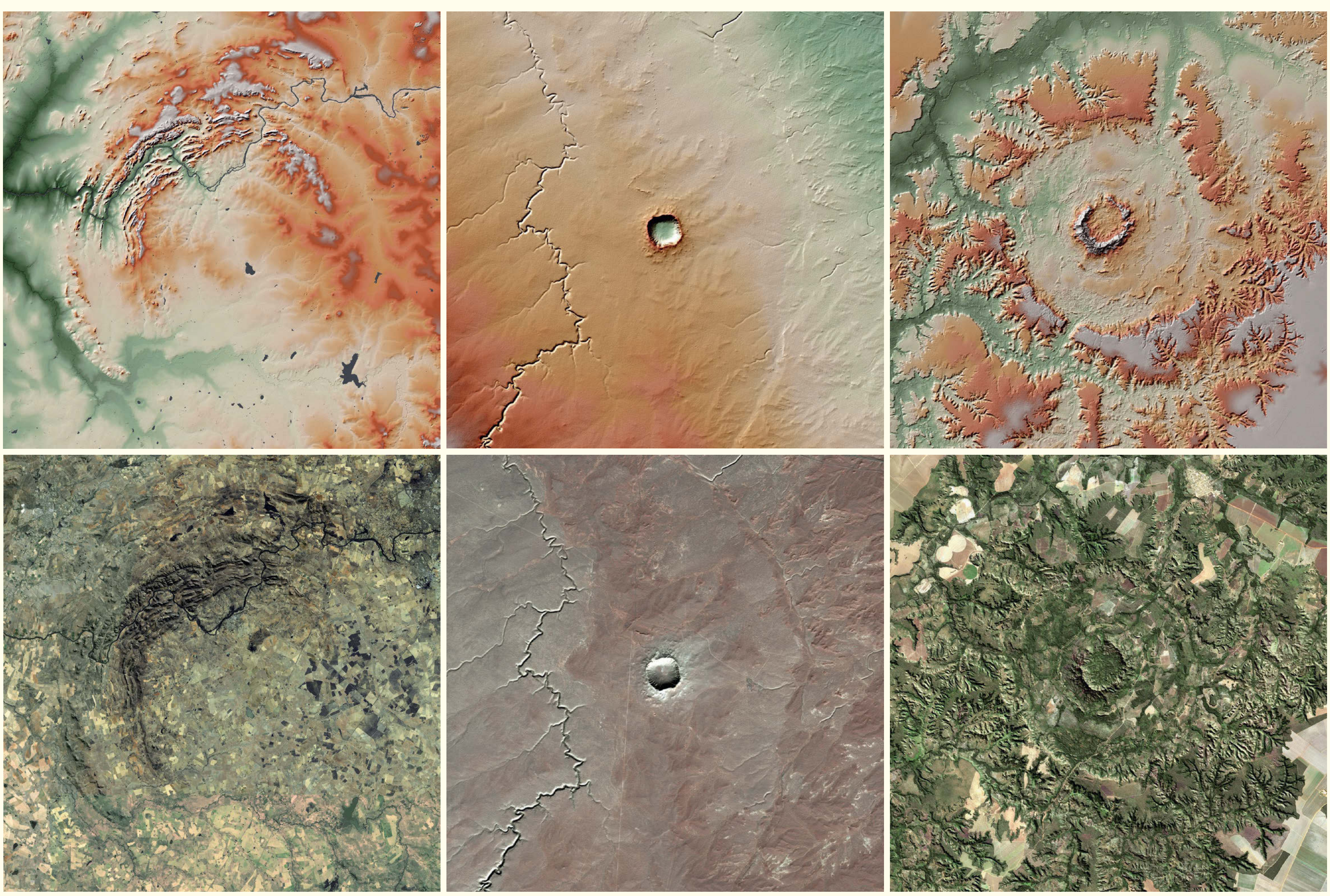
Africa, North/Central America, South America

M. Gottwald, T. Kenkmann and W. U. Reimold



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front cover
Vredefort Dome, Meteor Crater, Serra da Cangalha (from left to right).
Top row: TanDEM-X topographic maps; bottom row Sentinel-2 RGB images,
fused with the TanDEM-X digital elevation model.

back cover
Top: Meteor Crater (photo: T. Kenkmann);
bottom: B.P. structure (photo: W. U. Reimold).

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Preface

The idea for this atlas was born already several years ago. Then, a precise topographic atlas presenting terrestrial impact craters, the scars of the impacts of solid bodies onto the Earth's surface, had not been established yet. This was astonishing, as such impacts had long been considered as the "most fundamental process on the surfaces of the terrestrial planets", as the late Eugene Shoemaker, one of the pioneers of impact geology, had put it. But when the first digital elevation data had been processed from the early phase of the TanDEM-X mission, they immediately showed their great potential for mapping applications. We were particularly excited, because the objective of this space-borne undertaking of generating a precise high-resolution digital elevation model for the entire solid surface of Earth would allow, for the first time, to map the morphology of all terrestrial impact structures with a topographic expression, in detail. What had been the limiting factor of the existing datasets for such an exercise in the past – no global coverage, data gaps, or data artefacts – would no longer hamper the cartographic work. Only very small impact craters below the resolution of the TanDEM-X data would escape recognition in the TanDEM-X maps.

Patience, however, was required before the final TanDEM-X Digital Elevation Model (DEM) was released and access to the data for science applications was granted. In the meantime, we had investigated the workflow to present the topography of an impact structure and its environs by using Raw DEM scenes. Because our intention was not to merely publish a sequence of high-quality maps, our atlas concept foresaw to additionally provide short and concise, illustrated text sections for each impact structure. As two of us, Thomas Kenkmann and Wolf Uwe Reimold, have throughout their careers as impact geologists confirmed the impact origin of a considerable number of structures and participated in the studies of many more, these so-called "fact sheets" also reflect personal experience. Clearly this is the reason why these texts sometimes differ in style – this is indeed intended. What is more, the fact sheets also reflect the varied degrees of detailed study that different impact structures have permitted to date.

The individual texts also provide information about the location of a structure and how to access it. For those structures in very remote parts of the globe, the access notes can, however, be limited. A list of selected references completes each text. These are the main references that were used by the authors of the individual fact sheets – who are acknowledged at the top of each structure's first page. These references are also intended to provide the layperson with a strategic entry into the literature pertaining to any of these impact structures.

The atlas consists of three parts: introductory chapters, the physical maps with corresponding texts for all impact structures covered herein, and an annexure with supplementary information. The first introductory chapter briefly explains why interplanetary space is filled with small bodies and why they sometimes approach Earth's orbit. Chapter 2 goes a bit deeper into the principles of hypervelocity impact. It explains crater formation, shock metamorphism, and specific impact-related lithologies. This chapter introduces impact related concepts that are addressed in more detail in the subsequent impact structure-related fact sheets. The third chapter describes the terrestrial impact crater record. A short account on its completeness – or rather lack thereof – is followed by its status at the time of the manuscript deadline as of February 2020. As the last two years have been very productive in identifying previously unknown impact structures, we have thrived towards a status that is as complete as possible. Our atlas, however, has a differentiated view on some alleged impact structures. Where we feel that the evidence for an impact origin is still incomplete or ambiguous, we treat these structures separately, even though other impact data bases may list these cases as confirmed – without further analysis of the evidence.

The remaining introductory chapters explain the remote sensing principles behind data acquisition and processing, together with how the physical maps were generated. Chapter 4 illustrates radar remote sensing, particularly the concept of Synthetic Aperture Radar (SAR) that allows high-resolution space-borne imaging in the microwave spectral domain. While SAR yields 2D imagery, it is a pre-condition for SAR interferometry, which exploits elevation and therefore delivers a 3D view. This concept has been successfully implemented in the TanDEM-X mission, which is the topic of chapter 5. This section not only summarizes the characteristics of both radar satellites, but it also explains how the challenging task of interferometric data takes was pursued with subsequent data processing. Chapter 6 explains how the maps were produced. This demanded a stepwise approach with observation of various requirements, such as map projection, illumination, and dealing with the presence of water bodies.

With chapter 7 the map-oriented part of the atlas – by far the major portion of our book – begins: Africa, North/Central America and South America are covered in Part 1, Asia, Australia and Europe in Part 2. All impact structures on a continent are listed alphabetically. Each section comprises a one-page physical map together with the illustrated fact sheet. Those structures where confirmation as impact structures has remained ambiguous or incomplete appear separately at the end of each continent chapter.

An annex with the complete list of selected references, a glossary, a geologic timescale, and lists of acronyms and abbreviations completes the atlas.

For whom, which readership, was this atlas compiled? Our atlas is intended to provide the professional expert with a reference book summarizing the terrestrial impact crater record as of February 2020 in a complete and coherent, as well as concise manner. For the interested layman our book can be a source of impact cratering information at different levels – basic in the introductory chapters and more specific in the fact sheets. The maps together with the indication how to access an individual impact site may even trigger visits to some of the more conveniently located structures.

In this atlas our knowledge and expertise from different research areas – impact geology, a bit of astronomy, and remote sensing – has been combined. Thomas Kenkmann and Wolf Uwe Reimold assembled the fact sheets for the currently confirmed impact structures. Their ongoing work in the past years even helped to add several new impact structures to the terrestrial impact record – and to the atlas content. We believe that this work provides a status that is as up-to-date as possible. During their field work, they obtained a large repository of imagery, some of which is shared here in the book. Manfred Gottwald dealt with the remote sensing related tasks, formulated the introductory chapters, and took care of the graphic artwork. This included the processing of the TanDEM-X digital elevation data, the production of the physical maps, and, where appropriate, the fusion of the TanDEM-X data with Sentinel-2 data.

What we present in this atlas about the terrestrial impact structure record – its content and parameterization – reflects the status that, as we feel, provides a complete and consistent view as of February 2020. For several impacts, however, different results can be found in literature. As the study of impact structures is an ongoing and vivid research topic, for these structures only future work will reveal the final truth.

Considerable effort has been put into the making of this reference work. We hope that our result will provide assistance to many, and enjoyment as well. It may be a reference volume for years to come.

Manfred Gottwald, Garching bei München
Thomas Kenkmann, Albert-Ludwigs-Universität, Freiburg
Wolf Uwe Reimold, University of Brasília, Brasília
February 2020

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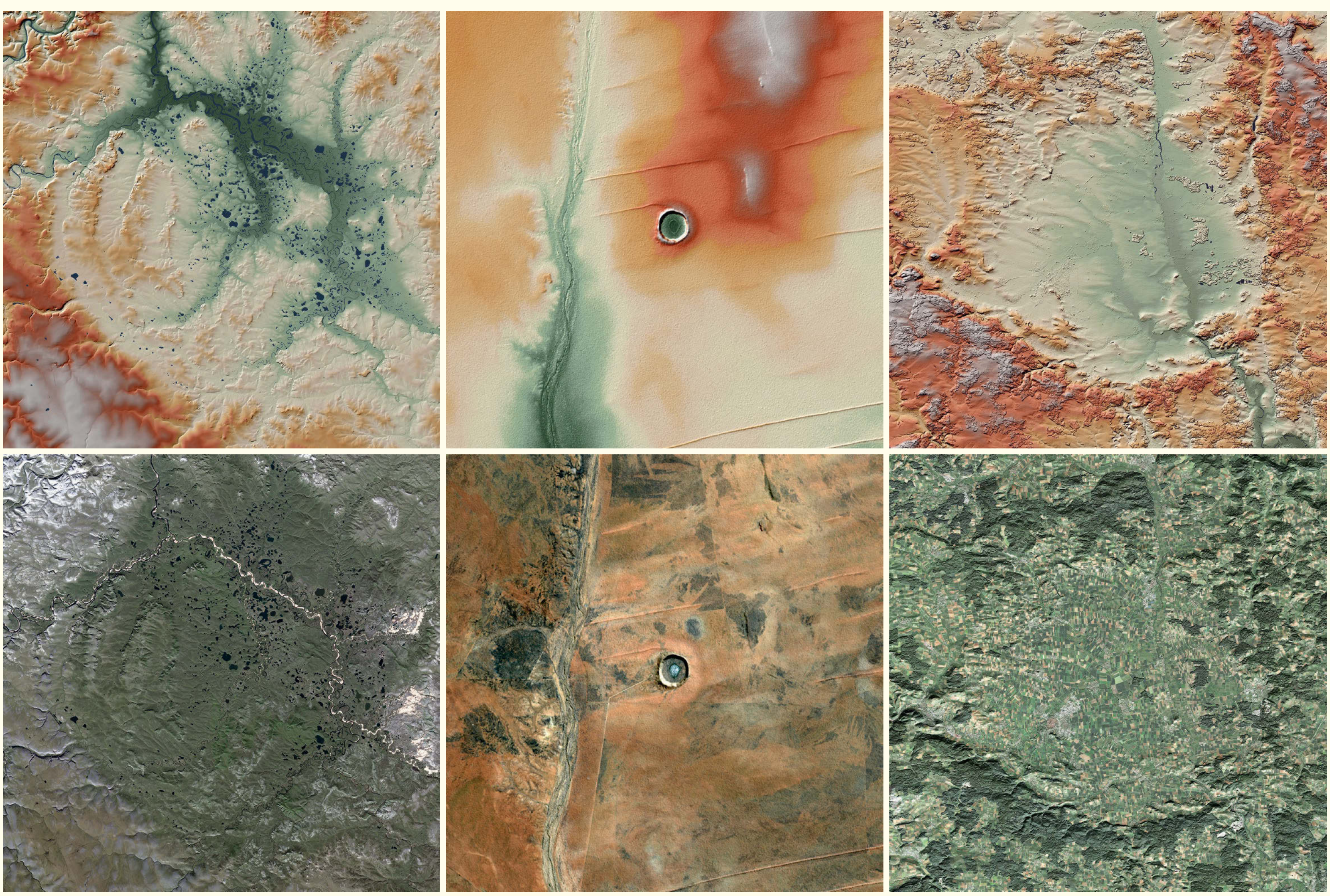
Asia, Australia, Europe

M. Gottwald, T. Kenkmann and W. U. Reimold



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Popigai, Wolfe Creek, Ries Crater (from left to right).
Top row: TanDEM-X topographic maps; bottom row Sentinel-2 RGB images,
fused with theTanDEM-X digital elevation model.

back cover
Top: El'gygytgyn (photo: U. Raschke);
bottom: Kara-Kul (copyright: J.-L. Dauvergne, provided by S. Bouley).

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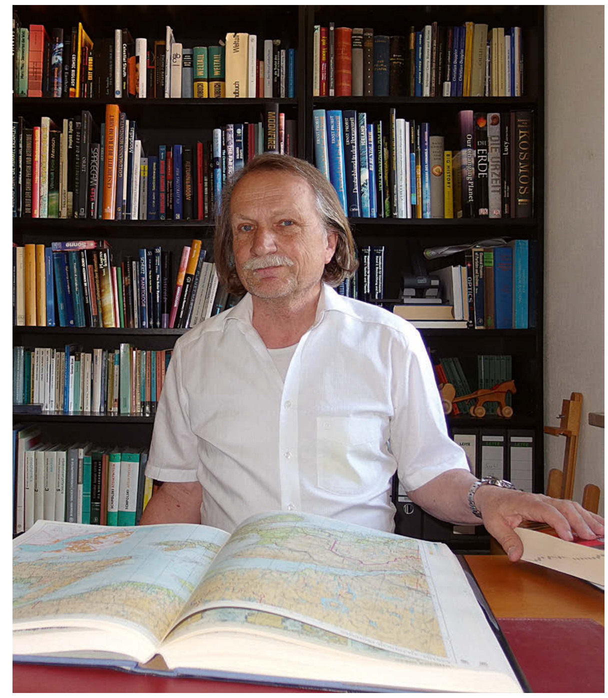
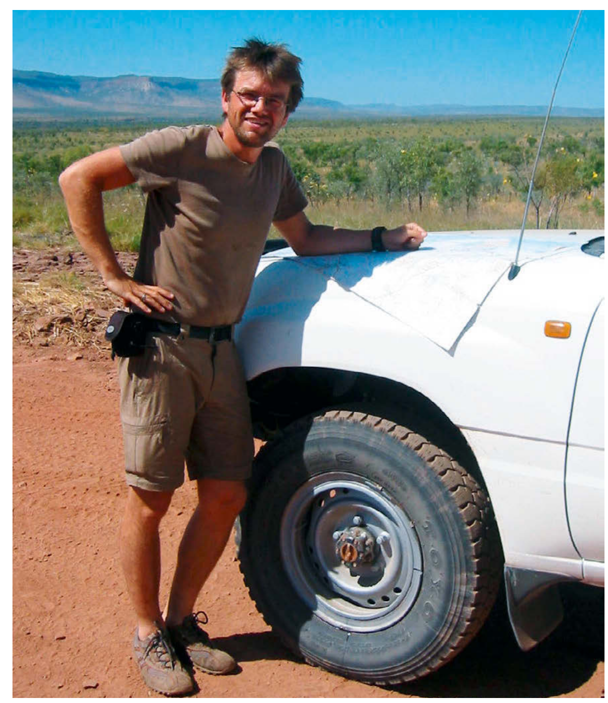
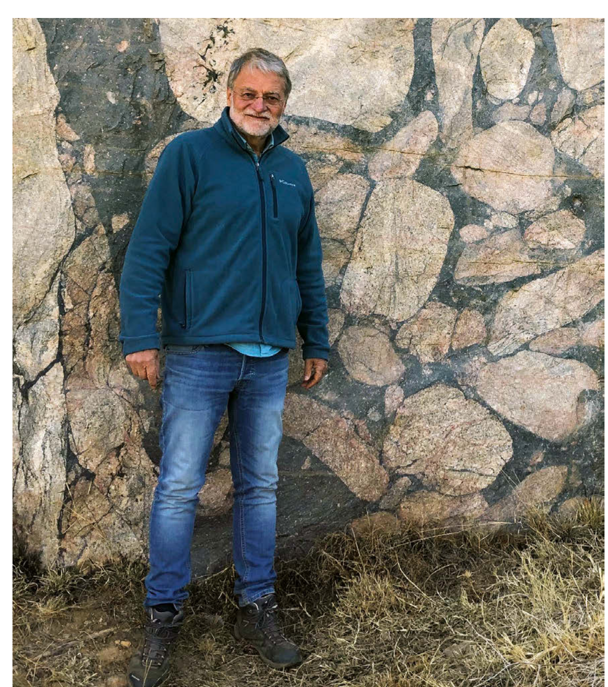
Manfred Gottwald was educated in astronomy and physics at the Ludwig-Maximilians-Universität in Munich. After his Ph.D. in 1983 he worked in high-energy astrophysics for the European Space Agency and the Max-Planck Institute for Extraterrestrial Physics, studying objects far out in our galaxy and beyond. When he joined the German Aerospace Center at Oberpfaffenhofen, our solar system and Earth became the scientific topics of choice. At the Earth Observation Center he was involved in many space-borne missions investigating our atmosphere, our cryosphere and the terrestrial surface. Particularly challenging was his responsibility for the atmospheric science instrument SCIAMACHY on the European ENVISAT platform. Since the International Polar Year 2007/2008 he coordinated the national Earth Observation missions in support of polar science under the auspices of the World Meteorological Organization. This familiarized him with the TanDEM-X radar mission, whose high-resolution digital elevation model allowed Manfred to engage in impact craters, a field where astronomy meets geology. His books, papers and talks, both for scientific communities and the interested public, cover the entire universe, from its distant edge right to the surface of our home planet.



Thomas Kenkmann studied geology and paleontology at the University of Cologne and completed his dissertation in 1997 at the Freie Universität Berlin. Since 2010 he has been Professor of Geology and Structural Geology at the University of Freiburg, Germany. Thomas Kenkmann and his working group are investigating the structure and deformation inventory of impact craters on Earth and other planetary bodies at scales ranging from satellite imagery to micrometers. Thomas is a passionate field geologist, who has studied more than 40 terrestrial impact craters worldwide, and mapped many of them geologically, among them Upheaval Dome in the United States, Jebel Waqf as Suwwan in Jordan, Serra da Cangalha in Brazil, and Matt Wilson, and Gosses Bluff in Australia. He is responsible for a number of crater discoveries and confirmations such as Saqqar in Saudi Arabia, the Douglas crater strewn field in the United States, or Ramgarh in India. He is also experimentalist and initiated and coordinated a multidisciplinary consortium to understand meteorite impact into various rock types by conducting shock and cratering experiments. He has published a multitude of refereed scientific articles in journals and books and edited several special issues and a book on impact craters. In 2012, Thomas Kenkmann won the State Teaching Award of the Ministry of Education, Research and Art of the Federal State of Baden-Württemberg, Germany. Thomas Kenkmann received the Barringer Medal and Award of the Meteoritical Society in 2018 for his key contributions to the areas of impact crater research.



Wolf Uwe Reimold holds M.Sc. (1977) and Ph.D. (1980) degrees in Mineralogy from the University of Münster (Germany). Post-doctoral research at NASA Johnson Space Center in Houston (USA) was followed by research positions and then a Professorship in Mineralogy at the University of the Witwatersrand (Johannesburg, South Africa, 1984–2005). Uwe's main research interests have been multidisciplinary Impact Crater and Shock Metamorphism studies, besides some Economic Geology and Regional Geology exploits in southern Africa and Ethiopia. Impact research was mainly focused on structures in Africa, Europe, and North America, including a major contribution to the understanding of the Vredefort impact structure in South Africa. Other main research targets were Bosumtwi (Ghana), Roter Kamm (Namibia), and various structures in Scandinavia, and in recent years in Brazil. In 2006, Uwe transferred to Humboldt University and the Museum für Naturkunde in Berlin, where he served as Professor of Mineralogy and Petrography, and Head of the Evolution and Geosciences Division of the Museum. In 2018 Uwe took retirement in Berlin, and a new position as Professor Titular at the Institute of Geosciences at the University of Brasília, Brasil. Uwe Reimold was President of the Geological Society of South Africa (2002), and their De Beers Alex L. Du Toit Lecturer in 2006. He was honored for his Impact Cratering Research with the Barringer Medal and Award by The Meteoritical Society in 2009. Uwe Reimold's distinguished scientific output includes authorship of more than 350 refereed scientific articles and chapters in books, as well as author- or editorship of a dozen scientific and popular scientific books.



Impact cratering is one of the fundamental processes in the solar system and, with all certainty, beyond. This process played a major role when the planets and their moons began to form from the protoplanetary disk, and throughout planetary evolution since then. On Earth, impacts of certain size even affected the evolution of life.

Lunar and interplanetary spaceflight over the past 50 years has provided us with detailed maps of the old, impact-crater covered surfaces of our Solar System neighbors. For Earth, the global impact crater record only represents a fraction of the bombardment that our planet has had to endure. Tectonic activity, erosion and weathering, and post-impact burial under sedimentary covers have erased most of the terrestrial impact history. Many of the remaining recognized crater structures have either been modified almost beyond recognition, or are buried entirely.

Mapping what is left of the terrestrial impact record from a satellite platform in low-earth orbit is often obscured by dense clouds and dust-laden air layers in our atmosphere; or even the lack of solar illumination prevents us to see the bare ground. Remote sensing methods developed in the past decades have given us tools, however, to tackle the challenge of mapping the Earth's surface with high precision.

Between 2010 and 2016 the German TanDEM-X radar X-band mission, operated and managed by DLR, the German Aerospace Center, generated the first global space-borne terrestrial digital elevation model of high resolution, based on Synthetic Aperture Radar interferometric measurements. We have used these data and produced the first topographic atlas of all currently confirmed terrestrial impact structures. This book provides the readership with the basic principles of impact cratering, of radar remote sensing, and of the TanDEM-X mission. It addresses the updated terrestrial impact crater record with more than 200 high-resolution maps, supplemented by geological descriptions and a plethora of field photographs for most structures. Thus, our atlas provides a comprehensive overview of the impact crater record for each continent.

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