# Traces of Catastrophe

A Handbook of Shock-Metamorphic Effects in Terrestrial Meteorite Impact Structures

Bevan M. French

# Traces of Catastrophe

## A Handbook of Shock-Metamorphic Effects in Terrestrial Meteorite Impact Structures

**Bevan M. French**

Research Collaborator
Department of Mineral Sciences, MRC-119
Smithsonian Institution
Washington DC 20560

LPI Contribution No. 954

This volume may be cited as

French B. M. (1998) *Traces of Catastrophe: A Handbook of Shock-Metamorphic Effects in Terrestrial Meteorite Impact Structures.* LPI Contribution No. 954, Lunar and Planetary Institute, Houston. 120 pp.

This volume is distributed by

ORDER DEPARTMENT
Lunar and Planetary Institute
3600 Bay Area Boulevard
Houston TX 77058-1113, USA
Phone: 281-486-2172
Fax: 281-486-2186
E-mail: order@lpi.usra.edu

*Mail order requestors will be invoiced for the cost of shipping and handling.*

**Cover Art.** "One Minute After the End of the Cretaceous." This artist's view shows the ancestral Gulf of Mexico near the present Yucatán peninsula as it was 65 m.y. ago, just after the impact of an asteroid or comet about 10 km in diameter began to form the huge Chixculub (Mexico) impact structure. In only a minute after the impact, a transient crater about 100 km across has been excavated, cutting through the surface ocean water, the underlying carbonate sediments, and the deep-seated crystalline crustal rocks. The edge of the growing transient crater is marked by a curtain of material that is being ejected into the atmosphere. Earth's Moon appears as a small dot above and to the left of the ejecta curtain. Painting by William K. Hartmann; used by permission of the artist.

*Dedicated to*

*Ralph B. Baldwin*

*Robert S. Dietz*

*Eugene M. Shoemaker*

*Who were so far ahead*
*Of all the rest of us.*

# Contents

# Preface

Meteorite impacts are getting plenty of respect these days. The public regards them as the established destroyer of dinosaurs and as the possible destroyer of civilization. The large planetary science community sees impacts as the process that helped form the solar system and is still modifying planets more than 4 b.y. later. Increasing numbers of geoscientists are coming to appreciate the importance of meteorite impact events and the extent of their influence on the geological and biological history of Earth.

However, despite the growing importance of meteorite impact phenomena in terrestrial geology, the topic is still not widely addressed in general geoscience textbooks and references. (Some exceptions are *Dence and Robertson,* 1989; *Philpotts,* 1990, Chapter 14-9; *Melosh,* 1992; and *Hibbard,* 1995, Chapter 24.) The geoscientist seeking instruction and information about impacts therefore faces a body of literature that, although large, is both specialized and scattered: isolated review articles (e.g., *Grieve,* 1991; *Grieve and Pesonen,* 1992; *Grieve and Pilkington,* 1996); older volumes on shock waves and cratering mechanics (*Roddy et al.,* 1977; *Melosh,* 1989) and shock metamorphism (*French and Short,* 1968); collections of papers in special issues of various journals (*Hörz,* 1971; *Nicolaysen and Reimold,* 1990; *Pesonen and Henkel,* 1992; *Glikson,* 1996b); and several good histories and memoirs (*Hoyt,* 1987; *Mark,* 1987; *Alvarez,* 1997). The linking of meteorite impacts to at least one extinction event (*Alvarez et al.,* 1980) has brought impact processes into the geological mainstream, and this trend is reflected by the appearance of several Special Papers of the Geological Society of America, each one a collection of technical papers involving extinctions (*Silver and Schultz,* 1982; *Sharpton and Ward,* 1990; *Ryder et al.,* 1996) and planetary cratering (*Dressler et al.,* 1994; *Koeberl and Anderson,* 1996a). More recently, several books have given serious consideration to large impact events in the present (*Spencer and Mitton,* 1995) and to the hazards associated with possible impact events in the future (*Chapman and Morrison,* 1989; *Gehrels,* 1994).

It is therefore surprising and unfortunate that no complete and systematic introductory textbook for geoscientists has yet appeared. With this book, I have attempted to fill this gap and provide for geoscientists a detailed introduction and overview of impact processes, crater formation, and shock metamorphism. The book is not intended for a general reader, nor is it aimed primarily at specialists actually working in impact geology. It is intended for geoscientists of all kinds: students who want to learn about the importance of meteorite impact; professors who want to add impact information to their geoscience courses; and professional geologists who may unexpectedly encounter an impact structure in the next field area or in the next drill core.

The book therefore emphasizes terrestrial impact structures, field geology, and particularly the recognition and petrographic study of shock-metamorphic effects in terrestrial rocks. As a result, I have deliberately left out or summarized only briefly many important and exciting aspects of impact geology: shock-wave physics, cratering mechanics, cratering on other planets, ejecta formation and deposits, extinction mechanisms, geochemical and geophysical studies of impact structures, and tektites. However, I have included literature references to get the interested reader started on further exploration in these fields.

Although this book could be used as a textbook, albeit a very focused one, I view it as a combination of sourcebook, laboratory manual, and reference for working geologists. The chapters are designed to be read independently, depending on the background and needs of the reader. Nonspecialists or readers interested in general information can explore the early chapters (Chapters 1 and 2). Geoscientists with backgrounds in structural geology, mineralogy, and petrology may prefer to go directly to the detailed information on cratering mechanics (Chapter 3), shock-metamorphic features (Chapter 4), impactites (Chapter 5), impact melts (Chapter 6), or the detection and identification of new impact structures (Chapter 7). With this presentation, some introductory material is repeated in different chapters, but I hope the arrangement will be useful for a wide range of readers interested in various aspects of impact.

In any field of science, the fine details of terminology are complicated and often controversial. Impact geology is no exception. I have tried to keep things simple, even at the loss of some precision. For example, I use **meteorite** as a general term for any extraterrestrial object, regardless of size, composition, or source, that is large enough to strike Earth's surface and to make a crater. More specific terms **(asteroid, comet, projectile,** etc.) are reserved for more specific contexts. Similarly, I use **impact crater** and **impact structure** more or less interchangeably, despite the actual differences that exist between them Finally, I have kept the classification of **impactites** (breccias, impact melts, etc.) as simple as possible. I hope this approach will help communicate information to all kinds of readers and will also prepare specialists to explore the details as needed.

I owe a great deal to many colleagues, who responded both promptly and generously to my many requests for samples, photographs, literature references, and other material needed for this book. I am especially grateful to those who supplied photographs, particularly Richard Grieve, Glenn Izett, and Dieter Stöffler. The reader will also note my extensive reliance on Jay Melosh's textbook (*Melosh,* 1989), which, after nearly a decade, still remains an essential sourcebook on the theoretical aspects of cratering mechanics and shock metamorphism. I am equally indebted to other colleagues who reviewed the various versions of the changing manuscript, and whose criticisms and comments produced major improvements: Burkhard Dressler, Richard Grieve, Fred Hörz, Christian Koeberl, Bruce Marsh, Anthony Philpotts, Virgil Sharpton, Richard Wunderman, and Mary-Hill French. Any errors, misstatements, and other flaws that managed to survive are entirely my own.

I am also grateful to the staff at the Lunar and Planetary Institute, especially Mary Cloud, for their continued interest in this undertaking, for their patience while it was slowly taking shape, and for their usual speed and editorial excellence in the final production. I thank Debra Rueb and Mary Ann Hager for providing graphics and other resources from the LPI library, and Stephen L. Hokanson and Reneé Dotson for their editorial and digital publishing expertise. William K. Hartmann generously provided one of his striking paintings for use on the cover. Finally, I am grateful for the continued support of the Smithsonian Institution, which allowed me to continue working on this book as a Research Collaborator in the Department of Mineral Sciences since 1994.

The field of impact geology continues to expand in scope and importance, as the statistically minded reader can see from the bibliography; the number and variety of articles on the subject published in just the last five years is impressive. Even though approximately 150 terrestrial impact structures are known, several hundred remain to be discovered and studied, perhaps as genuine exercises for students. Beyond the identification of new impact structures, we are just beginning to explore the role of impacts in major geological processes: the actual mechanisms by which extinctions are produced, the recognition of distal ejecta deposits in the geological record, and the role of large impacts in shaping the Precambrian Earth. I hope this book will help in the explorations to come.

*Bevan M. French*
*Chevy Chase, Maryland*
*September 1998*

# A Note on Style

Metric and standard international (SI) units are used throughout. Length units are meters (m), millimeters (mm), centimeters (cm), decimeters (dm), kilometers (km), and micrometers (μm). In planetary discussions, the astronomical unit (AU) is also used; 1 AU = $150 \times 10^6$ km. Mass units are grams (g), milligrams (mg), kilograms (kg), and micrograms (μg). Larger masses are given in tons (T, 1 T = $10^6$ kg), kilotons (kT, or $10^3$ T), and megatons (MT, or $10^6$ T).

Ages of stratigraphic units or times of geologic events are given in kilo-annum (ka, $10^3$ years before present), Mega-annum (Ma, $10^6$ years before present), and Giga-annum (Ga, $10^9$ years before present). ("Present" in this sense refers to 1950 A.D.) Length units of time used are billion years (b.y.), million years (m.y.), years (yr), minutes (min), and seconds (s).

Energies are given in joules (J). Pressures are in gigapascals (GPa); 1 GPa = 10 kilobars (kbar); 100 GPa = 1 Megabar (Mbar). Other miscellaneous abbreviations used are diameter (D) and Cretaceous-Tertiary (K/T).

Technical terms are highlighted where they are first defined in the text. Terms directly related to cratering and shock metamorphism are shown in **boldface**; other technical terms are shown in *italics*.