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HANDBOOK OF
IRON METEORITES

VOLUME 1

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VOLUME 1

IRON METEORITES IN GENERAL

Tables, Appendices, References

VOLUME 2

IRON METEORITES

Abakan – Mejillones

VOLUME 3

IRON METEORITES

Merceditas – Zerhamra

Supplement

HANDBOOK OF
IRON METEORITES

Their History, Distribution, Composition and Structure

by

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Department of Metallurgy, Technical University, Lyngby, Denmark

VOLUME 1

IRON METEORITES IN GENERAL

Tables, Appendices, References

PUBLISHED FOR THE
CENTER FOR METEORITE STUDIES,
ARIZONA STATE UNIVERSITY
BY THE
UNIVERSITY OF CALIFORNIA PRESS
BERKELEY • LOS ANGELES • LONDON

Published with the partial support of the Carlsberg Foundation, Denmark.

University of California Press
Berkeley and Los Angeles, California

University of California Press, Ltd.
London, England

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ISBN 0-520-02934-8
Library of Congress Catalog Card Number: 74-27286

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Printed in the United States of America

To

Kirsti, Niels and Erik,

who lovingly

never lost their

patience.

To see a World in a Grain of Sand
And a Heaven in a Wild Flower,
Hold Infinity in the Palm of your Hand
and Eternity in an Hour.

– William Blake,
"Auguries of Innocence," *Poems*,
London, 1803

PREFACE

The Center for Meteorite Studies is pleased to have the opportunity to take an active part in the publication of this unique, important monograph on iron meteorites by Vagn Buchwald. Man's penetration of the frontiers of space has increased the world's thirst and need for additional information on these meteoritic messengers from time and space. Meteorites which have always fascinated the minds of scientists and laymen alike become all the more interesting when we are guided through their individual intricacies by a scientist who has spent a good part of his professional life studying them. Vagn Buchwald has travelled the world in order to inspect virtually all of the known iron meteorites which are described in detail in this work. As a part of his travels the Center for Meteorite Studies is proud to acknowledge the year he spent at Arizona State University as a Visiting Professor studying and teaching about the meteorites in the Nininger Meteorite Collection.

This set of books is the most comprehensive study of iron meteorites ever made, and most likely will be the most definitive and indispensable reference on them for decades to come. In the field of meteoritics, this work is rivaled, perhaps, only by E. Cohen's unfinished "Meteoritenkunde" started in the last century or O. C. Farrington's "Meteorites of North America" published in 1915. This publication is the culmination of an idea first developed I am sure, on the inspection of a few iron meteorites and then tenaciously followed up until all were studied and described.

As Vagn Buchwald has noted in his text, he owes thanks for his success to many who have helped him along the way. Foremost certainly as far as the Center for Meteorite Studies is concerned is Herbert G. Fales whose unflagging enthusiasm and support finally led to the start of this publication. In addition the support of The Carlsberg Foundation was critical in expediting the publication. The concern of Herbert G. Fales and The Carlsberg Foundation is to be commended.

George Boyd of the Center for Meteorite Studies performed the task of organizing the editing and production schedule and coordinating the efforts of all concerned. Peter Millman kindly reviewed much of the material in the first volume. Special thanks are due the staffs of the Bureau of Publications of Arizona State University for their detailed concern with the book design and the staff and editorial review committee of the University of California Press for their interest in producing and distributing the bound volumes.

Carleton B. Moore, Director
Center for Meteorite Studies
Arizona State University
Tempe, Arizona

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INTRODUCTION

The science of meteoritics comprises the study of meteors, meteorites and extraterrestrial dust. The study of meteors is mainly concerned with the recording and interpretation of high altitude objects that never fully penetrate our atmosphere, while the study of dust is a highly specialized branch that requires sophisticated sampling techniques for the collection and identification of the minute and controversial dust particles. The present work, on the other hand, deals mainly with the massive, tangible material. We will study the meteorite falls and finds and we will limit ourselves largely to the examination of such objects generally known as iron meteorites.

Individual iron meteorites have an importance comparable to that of individual botanical or zoological species. The phenomena of fall, shape, size, composition and structure are largely peculiar to each meteorite and for purposes of future reference should be carefully recorded. Only a small number of iron meteorites have been observed to fall and not very many of these attracted sufficient attention at the time of the fall to be fully described. An outstanding exception is Sikhote-Alin, which shed tons of fragments over Eastern Siberia in 1947 and resulted in a wealth of pertinent studies. However, many other falls and finds have received only scant attention, and the relevant publications are often to be found in rather inaccessible journals. Moreover, many iron meteorites were analyzed and described when they were found, perhaps a hundred years ago; and no later examinations have been carried out. Many meteorites have never been previously photographed. In my opinion, no meteorite has been adequately described until good photomacrographs and photomicrographs have also been published. Therefore, the figures and the explanations of the figures are an essential part of this handbook.

The collection of meteorites in the Mineralogical Museum of the University of Copenhagen is small by international standards, but it was during the reexamination and arranging of this collection in the early 1960s that I realized how antiquated and random the available information on iron meteorites was. When I found that it would be necessary to examine numerous meteorites that were not in the Danish collection, a rather heterogeneous pile of notes accumulated during visits to various museum collections in Europe, including the USSR. The initial metallurgical work was supplemented by a thorough study of synthetic iron-nickel-phosphorus alloys prepared for comparison.

The opportunity to concentrate on the present book came as a result of an appointment in 1967 as Visiting Professor at Arizona State University, Tempe, Arizona, under the auspices of the United States Educational Commission in Denmark (Fulbright Commission). After a year in Arizona, where I studied the Nininger Collection, I was generously invited to work as a postdoctoral research associate for two years with the Division of Meteorites at the Smithsonian Institution, Washington, D.C. In both places I was greatly encouraged to compile my data in the form of a manual, and no efforts were spared to make the iron meteorites in the respective collections available for a thorough examination. As a result, more than 1,100 large and small polished sections were newly prepared, identified and – in most cases – photomicrographed.

Previous Handbooks and Textbooks

I had felt the need for a readily available handbook of iron meteorites for a long time when finally, in 1967, I started systematic work on it. Again and again, I had, when discussing specific items within meteoritics, realized that much basic information was simply not available. I had also noted that much information, although already published, was much too difficult to relocate, or even worse, its existence was not even suspected by the research worker dearly in need of it. Since the days of Wülfing, Cohen and Farrington very little work had been done to compile the available data critically. Wülfing (1897) wrote a comprehensive *bibliography* of all meteorites known by the end of the nineteenth century. He also prepared a list of all known specimens then in collections and tried to estimate their relative value for purposes of exchange. His work was performed with excellent judgment and thoroughness and, therefore, his bibliography remains a valuable companion, particularly for historical studies.

Cohen undertook the task of *describing* all meteorites. His impressive Volumes 1 (1894) and 2 (1903d) treated the minerals, compositions and shapes systematically. Volume 3 (1905) described in great detail 96 iron meteorites comprising ataxites, hexahedrites and fine octahedrites. Volumes 4 and 5 were intended to complete the descriptions of the irons and to describe pallasites and stony meteorites, while Volume 6 would have contained astronomical information and fall observations. Unfortunately, Cohen had only finished the first three volumes when he died in 1905.

Cohen was very selective in his work; where Wülfing had compiled all references, however peripherically associated with the subject, Cohen confined himself to a critical review of the original papers and analyses to which he added his own descriptions and analytical results. His work is an important achievement and contains a wealth of original observations and ideas. The analyses he presented were unsurpassed for 50 years and are still very useful. In the unfortunately very rare supplement, Brezina & Cohen (1886-1906) published 190 photomacrographs of etched sections.

Farrington (1915) used a different approach, confining himself geographically to the North American meteorites. As opposed to Cohen, who had organized the meteorites systematically, Farrington chose to present them in alphabetical order. He reprinted part of *the original reports* on falls and finds and combined this with a few comments and a brief bibliography.

In 1944, S.H. Perry published his classical "The Metallography of Meteoric Iron." On the basis of about 300 eminent photomicrographs, prepared in the Department of Metallurgy, University of Michigan, he briefly described 98 iron meteorites – of which four were unknowingly duplicates. All his original photomicrographs were collected in five volumes (1944) and deposited in the U.S. National Museum. Additional volumes, VI through IX, appeared in the 1940s and 1950s. The volumes were not printed, but typewritten copies are still available for consultation at the Smithsonian Institution, University of Michigan, Field Museum of Natural History, American Museum of Natural History and British Museum (National History).

In recent years these important works have been supplemented by the extensive bibliography by Harrison Brown (1953), the "Catalogue of Meteorites" by Max Hey (1966), and the bibliographies edited by Yavnel (1965a; 1968a; 1971). The valuable textbooks by Nininger (1952a), Heide (1957), Krinov (1960a), Mason (1962a)and Wood (1968) must be mentioned, of course. However, none of these were specifically concerned with iron meteorites, and modern annotated bibliographies or handbooks have not appeared. This lack of general information is the more deplorable because interest in meteorites has increased considerably during the last 16 years since the launching of satellites and sputniks in 1957. A large number of outstanding papers on specific aspects have appeared, utilizing for example the powerful method of electron microprobe analysis whereby areas as small as one micron in diameter have been successfully analyzed. Other papers have dealt with refined methods for analyzing the elements with neutron activation techniques or have reported the unbelievably small concentrations of noble gases and their isotopes. These data make it possible for us to estimate, on the one hand, the ages of the meteorites, and on the other hand, to develop theories about the intensity of cosmic radiation in space, both near the Earth and at more distant points. The meteorites have thus acquired the important position as inexpensive space probes from which valuable information can be extracted by modern techniques.

About this book

In Volume 1 I have given a very brief survey of the various aspects of meteoritics, beginning with astronomic viewpoints and ending with a discussion of the problems associated with determining the age of a meteorite. The volume has eight appendices and a full list of references for all three volumes. Of particular interest is Appendix 1 in which all well-analyzed iron meteorites are systematically arranged, as opposed to the alphabetical arrangement in Volumes 2 and 3. Volume 1 contains 37 tables and over 200 photographs and drawings representing all typical iron meteorites. I hope that this volume alone may serve as a general introduction to the state of the art, so I have tried to make the text independent of the following volumes, although, of course, the bulk of the material was extracted from these volumes.

The material in Volumes 2 and 3 treats all known iron meteorites in considerable detail, supported by numerous tables and 2000 photographs, map sketches and diagrams. The material is basically descriptive. The emphasis is placed on presenting the data, critically revising older descriptions and offering suggestions regarding classification. Some interpretation of structure and chemistry is included, particularly concerning phosphides, sulfides, shock structures, heat-affected rim zones and hardness values, but otherwise it was felt that broader interpretation should be reserved for future work. The book is a description and definition of the individual meteorites, and, hopefully, it may serve as a reference work for physicists, chemists, geologists, mineralogists and metallurgists active in meteoritics but who have had little opportunity to see and examine larger sections of individual irons. From the general description given here, they will be able to continue and augment their work along various specific and often highly specialized lines, and they should be able to compare their data with data given here in order to establish general trends and laws.

The meteorites in Copenhagen, Washington and Tempe have formed the basis for my examinations. The University Collection in Copenhagen comprises 293 meteorites, of which 122 are iron meteorites and 24 stony irons. The collection of the Smithsonian Institution in Washington comprises about 1250 meteorites of which about 450 are iron meteorites, and 55 are stony irons. The meteorite collection of Arizona State University was started in 1960 by the purchase of about half of Dr. H.H. Nininger's collection. It has later been increased by gifts, purchases and exchanges and now comprises about 1000 falls and finds. Of these about 325 are iron meteorites and 40 stony irons.

Where these collections were found to be insufficient or to lack material for a certain iron meteorite completely, samples and information were obtained from other museums. It has thus been my privilege to work with most of the world's best collections. The samples which I have examined have been designated by their museum numbers under the individual descriptions for the benefit of future workers. At times the examinations unexpectedly took the character of detective work, because a rather large number of mis-identifications, mislabelings and unidentified specimens were found. Apparently samples of this kind are present in all collections, the actual number being approximately proportional to the size of the collection and to the number of smaller, private collections which have been incorporated. It was generally found that between 10 and 15% of the iron meteorites in a collection were mislabeled or belonged to a paired fall. Typical examples of these difficulties are treated under Durango, Kokstad and Saint Francois County, while Santa Rosa provided enough enigmas for a separate study (Buchwald & Wasson 1968).

During the work, a warm friendship with Dr. J.T. Wasson, University of California, Los Angeles, developed. It turned out to be of mutual benefit to examine the same specimens whenever possible. Considering the extreme rarity of material, it was very important to make the most of what was available. Therefore, samples were often prepared for non-destructive metallography and microphotography first and then sent, either in their entirety or in the form of hacksawed corners, to Dr. Wasson for an accurate determination of nickel, gallium, germanium and iridium. This form of cooperation in meteoritics is highly recommended because material is saved, and a complete identification of the specimen can be achieved. Moreover, it serves to exclude mislabeled or otherwise contradictory material at an early date, before too much time has been wasted on it.

After a considerable amount of thought, the meteorites were studied and arranged alphabetically in Volumes 2 and 3. However, in the appendix of Volume 1, the irons have been compiled on a classificational basis. I trust that this method has removed any bias from the descriptions and will make the book easier for the casual observer to use. Moreover, the classifications are apt to change in time, while the alphabet remains.

The names are in accordance with those adopted by Hey (1966), synomyms are only infrequently mentioned but will also be found in Hey. It is strongly recommended that in any publication on meteorites, the name forms adopted by Hey and his predecessor Prior (1923a) be applied, thus abstaining from introducing more modern name forms, even if these should be more correct from the standpoint of the native language, whether it be Polish, English or Japanese. The reader is here referred to a recent discussion of the problems associated with the naming of meteorites by Buchwald & Wasson (1972).

The handbook comprises 560 full descriptions and 100 short descriptions, covering a total of 660 individual masses and fragments. However, as explained elsewhere, so many paired falls and pseudometeorites were detected during the work that the book covers only 532 *different* iron meteorites. However, these are all that are presently recorded and available for examination. The individual manuscripts were prepared in alphabetical order in the years 1967 to 1972, inclusive. This may explain some omissions and missing references; however, I have tried hard to have all material updated at least to 1972. On occasion, after I had finished my description, a new publication appeared which treated the same problem. I was happy to see that the same results were usually achieved, so I have just had to add the new reference while proofreading. At the end of Volume 3 a *Supplement* will be found, giving information on meteorites examined after January 1973.

It has been my pleasure on a great many occasions to delve into the historical aspects of the meteoritic science. Sometimes it has absolutely been a must, since so many curious things evidently happened to old iron meteorites. In obscure and rather inaccessible journals and books I have found many important notes which helped me to solve particular problems. Likewise, in the accession protocols of the museums, in the archives and on old labels, often written in nineteenth century Gothic style, there was much information to be extracted. I do not have a historian's perspective and training, however, so I have rashly written as a metallurgist, without shame but in all humility. I hope that others will forgive narrowness and errors and will regard my documentation as a base on which future students will build the next story in their specific fields.

References to earlier work have been given as much as possible. However, for references to work earlier than 1900 the reader is asked to consult either of the previously mentioned Handbooks and Bibliographies, else this work would have been endless. I have been very selective when accepting chemical analyses, hoping to have excluded analyses which for one or other reason was unsatisfactory. In this, I have rarely discussed my choice but depended upon my structural studies, on some electron microprobe work and upon my intuition.

The descriptive part is thoroughly supported by photomacrographs and -micrographs. While most were prepared in my own laboratory, I never hesitated to ask for the loan of a good photograph from somebody else if it served to highlight a specific point. In particular, the Smithsonian Institution has contributed many photomacrographs of large polished and etched samples, and I am happy to express here my thanks to the photographic laboratory. In my opinion, good photographs are the best permanent records of the structure of iron meteorites. Almost as good are carefully drawn sketches such as I have often drawn them when working at the microscope. I had planned to include several of these, and also schematic drawings generalizing a specific theme, but time unfortunately did not permit me to fulfill this plan.

Acknowledgements

A Handbook like this could not have been produced without actively traveling to sites of meteoritic interest. I have liked my traveling, and I have enjoyed the field work which carried me to the Arctic desolation of Northern Greenland and exposed me to the merciless ultraviolet radiation at the high altitudes of the Atacama Desert. I have particularly liked visiting other laboratories and museums and to meet colleagues deeply engaged in meteoritic work. The Meteoritical Congresses in which I have participated since 1967 have been the most rewarding; during the associated meetings and field trips I have made acquaintance with almost all workers in Meteoritics. I should have liked Professor Heide and Dr. Buddhue, to whom I owe much, to have seen this work finished and regret that they are no more among us. I am grateful to them all, from my own first teachers in chemistry and metallurgy, to the students who in later years have enthusiastically worked along with me in solving specific problems.

Some who have helped deserve special mention for their devoted support.

I am greatly indebted to the curators of the Arizona State University collection, Dr. Carleton B. Moore and Mr. C.F. Lewis and to the curators of the Smithsonian Institution collection, Mr. R.S. Clarke Jr. and Dr. Brian Mason. Their advice during the three years I spent in the United States and their numerous written communications since, have significantly aided the preparation of the manual. For the keen and penetrating criticisms of parts of the original manuscript I am grateful to Dr. H. Voshage (Meteorite ages) and to Dr. Peter M. Millman (Astronomical sections).

I wish to record my deepest appreciation to the many scientists who so generously provided material from the collections and let me study their archives and files: Dr. Robert Hutchison, British Museum (Natural History), London; Professor H. Hintenberger and Dr. H. Wänke, Max-Planck-Institute für Chemie, Mainz; Dr. C. Frondel, Harvard University; Dr. Vincent Manson, American Museum of Natural History, New York; Dr. Edward Olsen, Field Museum of Natural History, Chicago; Dr. K. K. Turekian, Yale University; Drs. W. v.Engelhardt and W. Weisskirchner, Tübingen University; Professor J. Fabriès and Mme. Christophe Michel Lévy, Museum d'Histoire Naturelle, Paris; Professor G. Hoppe and Dr. G. Wappler, Humboldt University, Berlin; Dr. V. Kolomenskij, Mining Museum, Leningrad; Dr. L. G. Kvasha and Dr. E. Krinov, Academy of Sciences, Moscow; Dr. Gero Kurat, Naturhistorisches Museum, Vienna; and Dr. K. Tuček, Czechoslovakian National Museum, Prague.

While the collections mentioned above were studied repeatedly on extended visits, short visits were paid to the following collections: Amherst, Denver, Los Angeles, Mexico City, Philadelphia, Raleigh, San Francisco, Tucson; Frankfurt am Main, Heidelberg, Helsinki, Milano, Oslo, Stockholm, Torino, Utrecht, and Warsaw; Buenos Aires, La Plata, Rio de Janeiro, Santiago and Antofagasta; Pretoria, Johannesburg, Bloemfontein, East London, Port Elizabeth, Cape Town and Windhoek.

Without the technical assistance of the staff at the Smithsonian, particularly Mrs. Phyllis Brenner and Mr. Joe Nelen, little would have been accomplished. The experience of Dr. E.P. Henderson, the "grand old man" in iron meteorites, is also greatly appreciated.

I am indebted to Dr. and Mrs. H.H. Nininger, Sedona, for valuable criticism and for clarifying several points concerning the history of certain meteorites. I also thank Mr. Oscar C. Monnig, Fort Worth, and Mr. and Mrs. Herbert G. Fales, Phoenix, for good advice and encouragement. A special thanks is due to Mr. George A. Boyd, managing editor of Meteoritics, who, with an experienced hand helped to process the manuscript.

In the Smithsonian Library, Dr. Marquardt was always ready to hunt for a difficult original publication. In the map room of the British Museum much valuable information was also acquired. Major V.M. Lunddahl generously put the Map Archives of the Danish Geodetical Institute, Copenhagen, at my disposal.

From the staff of the Mineralogical Museum of the University of Copenhagen I have always received the best possible support. In particular, I am deeply indebted to the Director, professor Dr. A. Noe-Nygaard, to curator Dr. P. Graff-Petersen, and the now retired curator, Mrs. Sole Munck.

Without the continuing interest and support of the President of the Technical University of Denmark, Professor Dr. E. Knuth-Winterfeldt, and Professor Dr. E.W. Langer, Head of the Department of Metallurgy, Lyngby, this work would not have been possible. Help and advice from Professor Dr. H. Pauly and Mag. scient. H.K. Schönwandt, Institute of Crystallography, is also gratefully acknowledged. My patient colleagues at the Department of Metallurgy, who have discussed many pertinent problems with me and perhaps heard more of meteorites than cared for, also are heartily thanked. Mr. R. Norbach and Mrs. Laila Bjerregaard provided assistance at all stages of the electron-microprobe analyses while Mrs. Annelise Olsson prepared many of the photographs. The faithful technical assistance of Miss Polly Edwards through fifteen years' meteorite work is gratefully acknowledged. Finally, I wish to thank Mrs. Daphne Jensen, Copenhagen, and Mrs. Emily Kalled Lovell, Tempe, who helped to transform the handwritten notes into a readable English manuscript.

Grants from "Statens Teknisk-Videnskabelige Fond" (Denmark) secured laboratory assistance on two occasions during 1965-66 and 1971-72. The Rask-Ørsted Foundation (Denmark) and the Technical University of Denmark provided financial support for typewriting and translating the manuscript. A Fulbright scholarship enabled me to travel to the United States, and grants from NASA and the National Research Council secured my tenure as a postdoctoral research associate with the institutions in Tempe and Washington. Grants from the Carlsberg Foundation, Denmark, and Arizona State University, Tempe, covered the expenses in editing and composing the three volumes. For this financial support I am deeply grateful.

When all this has been said, it remains to mention again three persons who never hesitated a moment in their enthusiastic support of this project. Were it not for Professor A. Noe-Nygaard, Dr. Carleton B. Moore and Mr. Herbert G. Fales the present work would not have reached the final stage. I owe them much and thank them with all my heart.

Copenhagen, September 1973

V. F. Buchwald