

CAMBRIDGE PLANETARY SCIENCE

METEORITES

A Petrologic, Chemical and Isotopic Synthesis

A detailed microscopic image of a meteorite's internal structure, showing a complex network of interlocking mineral grains. The grains are primarily yellow and orange, with some white and light blue areas. The overall texture is highly crystalline and intricate, typical of a meteorite's internal structure.

Robert Hutchison

METEORITES

A Petrologic, Chemical and Isotopic Synthesis

ROBERT HUTCHISON

The Natural History Museum, London



CAMBRIDGE UNIVERSITY PRESS
Cambridge, New York, Melbourne, Madrid, Cape Town, Singapore, São Paulo

Cambridge University Press
The Edinburgh Building, Cambridge CB2 2RU, UK

Published in the United States of America by Cambridge University Press, New York

www.cambridge.org
Information on this title: www.cambridge.org/9780521470100

© R. Hutchison 2004

This publication is in copyright. Subject to statutory exception
and to the provisions of relevant collective licensing agreements,
no reproduction of any part may take place without
the written permission of Cambridge University Press.

First published 2004
This digitally printed first paperback version, with corrections, 2006

A catalogue record for this publication is available from the British Library

Library of Congress Cataloguing in Publication data

Hutchison, Robert, 1938–
Meteorites: a petrologic, chemical and isotopic synthesis / Robert Hutchison.
p. cm. – (Cambridge planetary science series; 2)
Includes bibliographical references and index.
ISBN 0 521 47010 2
1. Meteorites. I. Title. II. Series.
QB755.H89 2004 523.5'1 – dc22 2003062625

ISBN-13 978-0-521-47010-0 hardback
ISBN-10 0-521-47010-2 hardback

ISBN-13 978-0-521-03539-2 paperback
ISBN-10 0-521-03539-2 paperback

Contents

| | |
|--|----------------|
| <i>Preface</i> | <i>page xi</i> |
| <i>Acknowledgements</i> | <i>xiii</i> |
| 1 Introduction | 1 |
| 1.1 The flux of extraterrestrial material | 1 |
| 1.2 Kinds of meteoritic material | 4 |
| 1.3 Sources of meteorites | 10 |
| 1.4 Meteorite recovery: falls, finds and “super-finds” | 11 |
| 1.5 How to recognize a meteorite | 13 |
| 1.6 Meteorite names | 15 |
| 1.7 Meteorite literature | 16 |
| Select bibliography | 17 |
| 2 The chondrites: chemistry and classification | 18 |
| 2.1 Historical overview | 18 |
| 2.2 Chondrite classes and groups: chemical signatures | 24 |
| 2.3 Cosmochemical classification of the elements | 34 |
| 2.4 Geochemical classification of the elements | 37 |
| 2.5 Primary variations: oxygen isotopic ratios | 38 |
| 2.6 Secondary variations: petrologic types | 40 |
| 2.7 Tertiary variations: shock facies and stages | 42 |
| 2.8 Terrestrial weathering of meteorite finds | 45 |
| 2.9 Classification: status and prospects | 47 |
| 2.10 Summary | 51 |
| Select bibliography | 52 |
| 3 The components of chondrites | 53 |
| 3.1 Introduction | 54 |
| 3.2 Chondrules | 55 |
| 3.3 Refractory calcium-aluminum-rich inclusions – CAIs | 75 |

| | | |
|-----|--|-----|
| 3.4 | Other high-temperature materials in chondrites | 84 |
| 3.5 | Low-temperature components in chondrites – matrix | 85 |
| 3.6 | Other low-temperature material in chondrites | 92 |
| 3.7 | Oxygen isotopic ratios of chondrules, CAIs and matrix | 92 |
| 3.8 | Summary | 95 |
| | Select bibliography | 95 |
| 4 | Petrography of the chondrites I: carbonaceous chondrites | 96 |
| 4.1 | General introduction | 96 |
| 4.2 | The carbonaceous chondrite groups | 97 |
| 4.3 | Ungrouped carbonaceous chondrites | 121 |
| 4.4 | Summary | 123 |
| | Select bibliography | 125 |
| 5 | Petrography of the chondrites II: non-carbonaceous chondrites | 127 |
| 5.1 | Introduction | 127 |
| 5.2 | The ordinary chondrites and R group | 128 |
| 5.3 | Enstatite chondrites | 142 |
| 5.4 | Ungrouped non-carbonaceous chondrites | 146 |
| 5.5 | Summary | 150 |
| | Select bibliography | 150 |
| 6 | Time in the evolution of chondrites | 152 |
| 6.1 | Introduction | 153 |
| 6.2 | Stages in chondrite history | 153 |
| 6.3 | Stages 7 to 10: Cosmic ray exposure (CRE) ages and terrestrial ages | 154 |
| 6.4 | Systems based on primordial radionuclides | 155 |
| 6.5 | Gas-retention ages (stages 5 to 7) | 158 |
| 6.6 | Formation and metamorphic ages (stages 2 to 5) | 162 |
| 6.7 | Early Solar System chronology | 179 |
| 6.8 | Timing of nucleosynthesis: formation intervals | 183 |
| 6.9 | Summary: early chondrite history | 185 |
| | Select bibliography | 187 |
| 7 | Origin of chondrites and their components | 188 |
| 7.1 | Introduction | 189 |
| 7.2 | Origin of the chondrite groups | 193 |
| 7.3 | Origin of chondrules | 219 |
| 7.4 | Origin of calcium-aluminum-rich inclusions (CAIs) | 229 |
| 7.5 | Summary | 239 |
| | Select bibliography | 241 |
| 8 | Differentiated meteorites I: primitive achondrites, ureilites and aubrites | 243 |
| 8.1 | Introduction | 243 |

| | | |
|------|---|-----|
| 8.2 | Achondrites | 245 |
| 8.3 | Primitive achondrites | 248 |
| 8.4 | Acapulcoites and lodranites | 249 |
| 8.5 | Winonaites and chondritic silicates in IAB iron meteorites | 253 |
| 8.6 | Brachinites (olivine achondrites) | 256 |
| 8.7 | Ureilites (olivine-pyroxene achondrites) | 257 |
| 8.8 | Aubrites (enstatite achondrites) | 267 |
| 8.9 | Chemical compositions of primitive achondrites, ureilites and aubrites | 273 |
| 8.10 | Summary | 274 |
| | Select bibliography | 275 |
| 9 | Differentiated meteorites II: asteroidal, lunar and Martian basaltic meteorites | 277 |
| 9.1 | Introduction | 278 |
| 9.2 | Howardites, eucrites and diogenites (HEDs) | 280 |
| 9.3 | Angrites: silica undersaturated Ca-rich basaltic achondrites | 291 |
| 9.4 | Summary: products of asteroidal volcanism | 295 |
| 9.5 | Lunar meteorites | 296 |
| 9.6 | Martian (SNC) meteorites | 305 |
| | Select bibliography | 319 |
| 10 | Differentiated meteorites III: iron and stony iron meteorites | 321 |
| 10.1 | Introduction | 322 |
| 10.2 | The Fe-Ni system and the structure of iron meteorites | 324 |
| 10.3 | Chemical classification of iron meteorites | 331 |
| 10.4 | Properties of the iron meteorite groups | 338 |
| 10.5 | Stony iron meteorites | 345 |
| 10.6 | Ungrouped iron and stony iron meteorites | 355 |
| 10.7 | Summary | 362 |
| | Select bibliography | 363 |
| 11 | Parent body processes and petrogenetic associations | 364 |
| 11.1 | Introduction | 365 |
| 11.2 | Early history of asteroids | 366 |
| 11.3 | The HED-IIIAB iron-MGP-mesosiderite association | 378 |
| 11.4 | Metamorphism in chondrite parent bodies | 399 |
| 11.5 | Petrogenetic associations | 414 |
| 11.6 | Summary | 418 |
| | Select bibliography | 419 |
| 12 | Origin of Solar System planets: a meteoriticist's view | 420 |
| 12.1 | Introduction | 421 |
| 12.2 | Protosolar matter | 422 |
| 12.3 | Trapped noble gases in chondrites | 427 |

| | | |
|------|---|-----|
| 12.4 | Composition and form of protosolar matter | 433 |
| 12.5 | Timing and evidence of early hypervelocity impact | 434 |
| 12.6 | Possible origins of a protojupiter | 438 |
| 12.7 | Consequences for the probability of life-supporting planets | 441 |
| 12.8 | Summary | 442 |
| | Select bibliography | 442 |
| | <i>Glossary</i> | 443 |
| | <i>Bibliography</i> | 450 |
| | <i>Index of meteorite names</i> | 478 |
| | <i>General index</i> | 482 |