
ORE MICROSCOPY AND ORE PETROGRAPHY

Second Edition

JAMES R. CRAIG

Department of Geological Sciences
Virginia Polytechnic Institute and State University
Blacksburg, Virginia

DAVID J. VAUGHAN

Department of Geology
The University of Manchester
Manchester, U.K.



A Wiley-Interscience Publication

JOHN WILEY & SONS, INC.

New York / Chichester / Brisbane / Toronto / Singapore

This text is printed on acid-free paper.

Copyright © 1994 by John Wiley & Sons, Inc.

All rights reserved. Published simultaneously in Canada.

Reproduction or translation of any part of this work beyond that permitted by Section 107 or 108 of the 1976 United States Copyright Act without the permission of the copyright owner is unlawful. Requests for permission or further information should be addressed to the Permissions Department, John Wiley & Sons, Inc., 605 Third Avenue, New York, NY 10158-0012.

This publication is designed to provide accurate and authoritative information in regard to the subject matter covered. It is sold with the understanding that the publisher is not engaged in rendering professional services. If legal, accounting, medical, psychological, or any other expert assistance is required, the services of a competent professional person should be sought.

Library of Congress Cataloging in Publication Data:

Craig, James R., 1940-

Ore microscopy and ore petrography / James R. Craig, David J. Vaughan. — 2nd ed.

p. cm.

Includes bibliographical references and indexes.

ISBN 0-471-55175-9 (acid-free)

1. Ores. 2. Thin sections (Geology) I. Vaughan, David J., 1946-

II. Title.

QE390.C7 1994

549'.12—dc20

94-2395

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

CONTENTS

PREFACE TO THE SECOND EDITION	xi
PREFACE TO THE FIRST EDITION	xiii
1 THE ORE MICROSCOPE	1
1.1 Introduction / 1	
1.2 Components of the Ore Microscope / 2	
1.3 Accessories / 13	
References / 15	
2 THE PREPARATION OF SAMPLES FOR ORE MICROSCOPY	17
2.1 Introduction / 17	
2.2 Preparation of Polished Sections / 18	
2.3 Grinding and Polishing Equipment / 27	
2.4 Preparation of Grain Mounts and Mounts for Specialist Analytical Methods / 30	
2.5 Preparation of Polished (and Doubly Polished) Thin Sections / 31	
2.6 Electrolyte Polishing and Etching Techniques / 34	
2.7 How to Achieve High-Quality Polished Surfaces / 34	
References / 37	

3	MINERAL IDENTIFICATION—QUALITATIVE METHODS	39
3.1	Introduction / 39	
3.2	Qualitative Optical Properties / 40	
3.3	Qualitative Examination of Hardness / 45	
3.4	Structural and Morphological Properties / 48	
3.5	Other Aids to Identification (Phase Equilibria, Mineral Assemblages, Characteristic Textures, and Ancillary Techniques) / 52	
3.6	Concluding Statement / 53	
	References / 53	
	Bibliography / 54	
4	REFLECTED LIGHT OPTICS	55
4.1	Introduction / 55	
4.2	Reflection of Linearly (or "Plane") Polarized Light / 61	
4.3	Reflection Between Crossed Polars / 69	
4.4	Concluding Remarks / 76	
	References / 77	
5	QUANTITATIVE METHODS—REFLECTANCE MEASUREMENT	78
5.1	Introduction / 78	
5.2	Measurement Techniques / 82	
5.3	Applications to Mineral Identification / 90	
5.4	Applications to the Compositional Characterization of Minerals / 93	
5.5	Quantitative Color / 95	
5.6	The Correlation of Electronic Structure with Reflectance Variation / 101	
5.7	Concluding Remarks / 103	
	References / 104	
6	QUANTITATIVE METHODS—MICROINDENTATION HARDNESS	106
6.1	Introduction / 106	
6.2	Vickers Hardness Measurement / 107	
6.3	Shapes of Hardness Microindentations / 110	
6.4	Factors Affecting Microindentation Hardness Values of Minerals / 112	
6.5	Concluding Remarks / 117	
	References / 119	

7 ORE MINERAL TEXTURES	120
7.1 Introduction / 120	
7.2 Primary Textures of Ore Minerals Formed from Melts / 123	
7.3 Primary Textures of Open-Space Deposition / 123	
7.4 Secondary Textures Resulting from Replacement (Including Weathering) / 129	
7.5 Secondary Textures Resulting from Cooling / 138	
7.6 Secondary Textures Resulting from Deformation / 145	
7.7 Secondary Textures Resulting from Annealing and Metamorphic Crystal Growth / 153	
7.8 Textures of Placer Grains / 157	
7.9 Special Textures / 160	
7.10 Concluding Statement / 161	
References / 162	
8 PARAGENESIS, FORMATION CONDITIONS, AND FLUID INCLUSION GEOTHERMOMETRY OF ORES	164
8.1 Introduction / 164	
8.2 Paragenetic Studies / 165	
8.3 Examples of Paragenetic Studies / 175	
8.4 Ore Formation Conditions and the Application of Phase Equilibria Data / 188	
8.5 Fluid Inclusion Studies / 193	
References / 205	
9 ORE MINERAL ASSEMBLAGES OCCURRING IN IGNEOUS ROCKS AND VEIN DEPOSITS	209
9.1 Introduction / 209	
9.2 Chromium Ores Associated with Mafic and Ultramafic Igneous Rocks / 210	
9.3 Iron-Nickel-Copper Sulfide Ores Associated with Mafic and Ultramafic Igneous Rocks / 215	
9.4 Iron-Titanium Oxides Associated with Igneous Rocks / 220	
9.5 Copper/Molybdenum Sulfides Associated with Porphyritic Intrusive Igneous Rocks ("Porphyry Copper/Molybdenum" Deposits) / 226	
9.6 Copper-Lead-Zinc-Silver Assemblages in Vein Deposits / 232	
9.7 The Silver-Bismuth-Cobalt-Nickel-Arsenic (-Uranium) Vein Ores / 235	

- 9.8 Tin-Tungsten-Bismuth Assemblages in Vein Deposits / 241
- 9.9 Gold Vein and Related Mineralization / 243
- 9.10 Arsenic-, Antimony-, or Mercury-Bearing Base-Metal Vein Deposits / 247
- References / 253
- Bibliography / 255

10 ORE MINERAL ASSEMBLAGES OCCURRING IN SEDIMENTARY, VOLCANIC, METAMORPHIC, AND EXTRATERRESTRIAL ENVIRONMENTS

259

- 10.1 Introduction / 259
- 10.2 Iron and Manganese Ores in Sedimentary Environments / 260
- 10.3 Opaque Minerals in Coal / 271
- 10.4 Uranium-Vanadium-Copper Ores Associated with Sandstones and Unconformity-Type Uranium Deposits / 275
- 10.5 Modern Placer Deposits / 281
- 10.6 Gold-Uranium Ores in Ancient Conglomerates / 284
- 10.7 Lead-Zinc Deposits in Carbonate Rocks and Other Sediments / 288
- 10.8 Stratiform Base-Metal Sulfide Ores in Sedimentary Rocks / 294
- 10.9 Copper-Iron-Zinc Assemblages in Volcanic Environments / 297
- 10.10 Opaque Minerals in Metamorphosed Massive Sulfides / 303
- 10.11 Skarn Deposits / 309
- 10.12 Extraterrestrial Materials: Meteorites and Lunar Rocks / 313
- References / 319
- Suggested Readings / 322

11 APPLICATIONS OF ORE MICROSCOPY IN MINERAL TECHNOLOGY

326

- 11.1 Introduction / 326
- 11.2 Mineral Identification in Mineral Beneficiation / 329
- 11.3 Ore Textures in Mineral Beneficiation / 333
- 11.4 Examples of Applications of Ore Microscopy in Mineral Beneficiation / 337

11.5	The Study of Mattes, Slags, Ashes, Sinter, and Other Smelter and Incinerator Products / 343	
11.6	Concluding Remarks / 348	
	References / 349	
APPENDIX 1	TABLE OF DIAGNOSTIC PROPERTIES OF THE COMMON ORE MINERALS	351
APPENDIX 2	CHARACTERISTICS OF COMMON ORE MINERALS	405
APPENDIX 3	ANCILLARY TECHNIQUES	411
	A3.1 X-Ray Powder Diffraction / 411	
	A3.2 Electron Probe Microanalysis / 412	
	A3.3 Microbeam Methods of Trace Element (and Isotopic) Analysis / 415	
	References / 417	
AUTHOR INDEX		419
SUBJECT INDEX		424