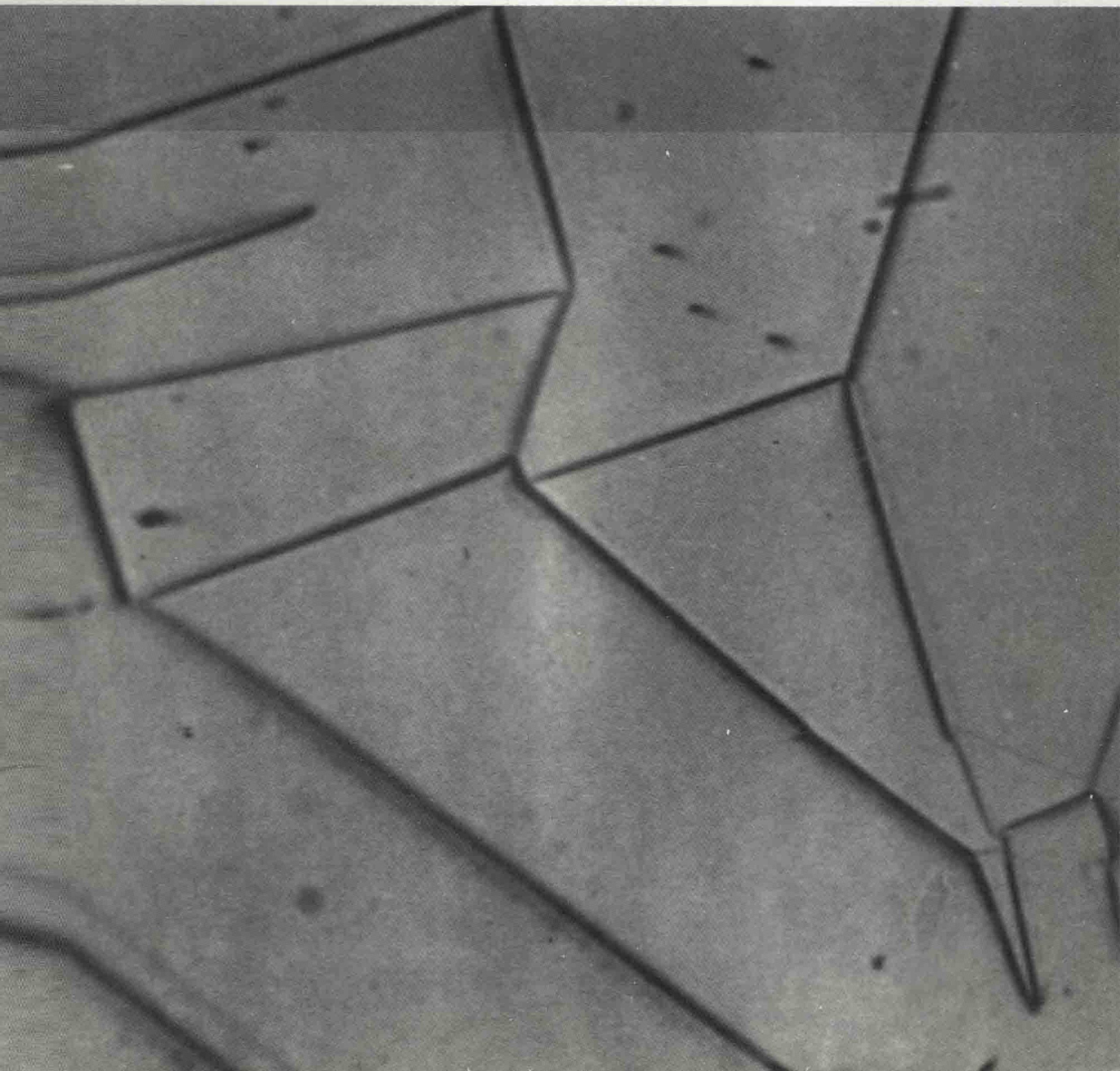
Cambridge Studies in Magnetism

Rock Magnetism

Fundamentals and frontiers

David J Dunlop and Özden Özdemir



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To those who have gone before us, the pioneers of rock magnetism, and to our students and colleagues, from whom we have learned so much.

Preface

The magnetic compass was one of mankind's first high-technology devices. Possession of the compass gave the Islamic world an early edge in navigation and led to the rapid eastward spread, by sea, of their trade, religion and civilization. But man was a comparative latecomer in magnetically aided navigation. Birds, fish, insects, and even bacteria had evolved efficient compasses millions of years earlier.

Magnetic memory, whether of a compass needle, a lava flow, or a computer diskette, is a remarkable physical phenomenon. The magnetic moment is permanent. It requires no expenditure of energy to sustain. Yet it can be partly or completely overprinted with a new signal. Nowhere is this more strikingly demonstrated than in rocks. A single hand sample can record generations of past magnetic events. This family tree can be decoded in the laboratory by stripping away successive layers of the magnetic signal.

Paleomagnetism is the science of reading and interpreting the magnetic signal of rocks. Rock magnetism is more concerned with the writing or recording process. The principles are no different from those of fine-particle magnetism as applied in permanent magnet and magnetic recording technology. But the physical parameters are rather different. Weak magnetic fields are involved, on the order of the present geomagnetic field (0.3–0.6 G or 30–60 μT), much less than the switching fields of the magnetic particles. Temperatures may be high: thermoremanent magnetization of igneous rocks is acquired during cooling from the melt. Times are long, typically millions of years.

Rock magnetism and paleomagnetism trace their origins to the mid-nineteenth century, but they really came into prominence in the 1950's and

1960's because of two daring questions that shook and ultimately revolutionized earth science: Does the earth's magnetic field reverse itself? And do the continents drift? Because rocks record in their magnetizations the polarity and direction of past geomagnetic fields, paleomagnetism was able to answer both questions.

Rocks of the same age from around the globe always recorded the same geomagnetic polarity. Their ancient compasses pointed north (normal polarity) during certain time intervals and south at other times. Most strikingly, strips of seafloor on either side of mid-ocean ridges (the birthplace of new seafloor) were unmistakably striped magnetically: either normal or reverse in response to the prevailing geomagnetic polarity as they formed. The earth's field does indeed reverse.

The same internal compasses showed that continents or subcontinents (now recognized as sections of lithospheric plates, containing ocean floor as well as continent) had rotated away from present-day north and had changed latitude during geological history. But prior to 175 Ma ago, their compass bearings coincided. They were originally assembled in a single supercontinent.

These findings shook earth science to its foundations and led to its rebuilding around a new guiding principle, plate tectonics. The revolution was not quite as straightforward as we have implied. The multiple generations of magnetization in rocks clouded the issue until methods were developed to strip away all but the most ancient. The stability of this ancestral magnetization came under scrutiny. It seemed to many inconceivable that rocks could preserve an unchanging magnetic memory for 175 Ma when the best products of human technology could be rather easily remagnetized by extraneous fields or stresses.

Such is the exciting history of rock magnetism. In this book, we will show how rocks manage to achieve a fidelity of magnetic memory that is beyond human experience. After developing the principles of ferromagnetism in Chapters 1–5, we will see in Chapter 6 how ferromagnetic domains appear under the microscope and in Chapter 7 what new micromagnetic structures are currently being predicted in grains too small to observe optically. Chapters 8, 9 and 10 reveal how the joint influences of temperature or time and magnetic fields permit the writing of a magnetic signal that cannot be erased by subsequent geomagnetic field changes. These are the fundamentals.

Chapters 11, 12 and 13 deal with some of the frontiers in understanding rock magnetic recording. As well as developing laboratory parameters and techniques that can predict stability on geological time scales (Chapter 11), we will look at how rather large particles can achieve stable memory that rivals that of submicroscopic particles (the pseudo-single-domain effect: Chapter 12) and how chemical changes in minerals degrade or enhance magnetic memory (Chapter 13).

Paleomagnetists sometimes complain that the 'rock' is frequently left out of 'rock magnetism'. Rock magnetic research looks too much like magnetic materials research. We have tried to answer that criticism in Chapters 14–17 by looking at magnetic minerals and their magnetic signals in the real world of igneous, sedimentary, metamorphic, and extraterrestrial rocks. This is a whole subject in itself and no one person can claim to be expert in all aspects, the present authors included. We have tried to convey the flavour of current thinking and research, rather than serving up an overwhelming banquet.

What background do you need to appreciate this book? A grounding in electricity and magnetism at junior undergraduate level is a help. Those with more geological background may wish to skip over the mathematical details. The key results can stand without them, and we have tried to maintain the story line uninterrupted wherever possible. Similarly a knowledge of basic earth science is helpful, but those with a physical science or engineering background should not turn away because they can't tell a hyperbyssal rock from a descending plate. This knowledge too is usually peripheral to the main message of the book.

We enjoyed writing this book and hope you will enjoy reading it. It would certainly never have been completed without a lot of help from our friends. We would especially like to mention those who taught us and passed on so much of their knowledge: Subir Banerjee, Ken Creer, Zdenek Hauptmann, Ted Irving, Takesi Nagata, Bill O'Reilly, Minoru and Mituko Ozima, Frank Stacey, David Strangway, Emile Thellier and Gordon West. With our colleagues Susan Halgedahl, Ron Merrill, Bruce Moskowitz, Michel Prévot, Valera Shcherbakov, Wyn Williams and Song Xu, we have passed countless hours of pleasurable discussion. Among our former students, we want to mention in particular Ken Buchan, Randy Enkin, Franz Heider and Andrew Newell; their work has had a central influence on the ideas in the book. Sherman Grommé, Ted Irving, Ed Larson, Michel Prévot and Naoji Sugiura kindly read and commented on early versions of some of the chapters.

We are grateful to Jennifer Wiszniewski, Carolyn Moon and Li Guo for patiently shepherding the manuscript through its many incarnations. Thanks to Khader Khan and Raul Cunha, different generations of figures were skillfully drawn and transformed through successive changes in technology. The photography was done with dedication and skill by Alison Dias, Steve Jaunzems and Judith Kostilek. Unlike some authors' families, ours did not eagerly await the appearance of each new chapter, but they did heave a collective sigh of relief when the last page was written and life returned to normal.

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