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Introduction

Abstract: Rock magnetic **cyclostratigraphy** is a new technique that allows a high-resolution chronostratigraphy to be assigned to a sequence of sedimentary rocks. Concentration variations of magnetic minerals in a sedimentary rock can be tied to astronomically forced global climate cycles with little or no facies interpretation needed. The rock magnetic measurements are nondestructive, relatively quick, and inexpensive. This chapter outlines the basic steps of a rock magnetic cyclostratigraphy study and serves as an introduction to the monograph.

1.1 Rock Magnetic Cyclostratigraphy

The purpose of this monograph is to provide an overview and the practical “how to” for a relatively new technique that can yield high-resolution chronostratigraphy for sequences of sedimentary rocks. Rock magnetic cyclostratigraphy is the result of the merging of environmental magnetism, in which rock magnetic measurements can detect past environmental conditions, and cyclostratigraphy, in which cyclic variations of lithology or a rock’s physical properties are tied to orbitally forced changes in global climate. Orbitally forced cyclic variations in the lithology of sedimentary sequences has been an important research focus for stratigraphers since Hays et al.’s (1976) pioneering study of Late Pleistocene marine sediments. The main reason for this intense interest is that if lithologic variations can be tied to the well-known cyclic variations of solar **insolation** at periods of ~20 kyr, ~40 kyr, ~100 kyr, and 405 kyr, a detailed and high-resolution chronostratigraphy can be established for the rocks, even at distant times in Earth’s history.

Lithologic cyclostratigraphy relies on identifying facies changes in a rock sequence and interpreting them as indicators of cyclic variations in the rock’s depositional environment. These cyclic variations are then tied to astronomically forced climate change. Deep-sea cyclostratigraphy has been

vital in supplying pristine records of astronomically forced signals from the Cenozoic and Late Mesozoic eras. For earlier times, however, pelagic marine organisms had not yet evolved in sufficient “rock-forming” numbers. For the early Mesozoic and earlier times, researchers must rely on shallow marine, hemipelagic, and continental cyclostratigraphy for astronomically forced paleoclimate data. While continental facies preserve high fidelity records of astronomical forcing, e.g., the Newark Basin lacustrine rocks (Olsen & Kent 1996), such facies are in short supply compared with the marine record. Shallow-marine cyclostratigraphy, principally from carbonate-rich peritidal facies, is the main source of astronomical forcing and global climate change data prior to the Jurassic Period (>200 million years ago). However, in any lithologic, facies-based cyclostratigraphic study, the work always involves interpretation, both in the identification of a given facies and in the interpretation of what that facies indicates about the depositional environment.

To advance the study of cyclostratigraphy, stratigraphers have searched for techniques that could provide stable and well-behaved paleoclimatic or paleoenvironmental proxies at high resolution and could be collected over reasonably thick sedimentary sequences. The Holy Grail would be a simple, low cost and fairly quick measurement that would be amenable to time series analysis and require minimal interpretation. For instance, in the recognition of astronomically forced cycles in the Late Triassic lake sediments of the Newark Basin, Olsen & Kent (1996) assigned depth ranks to quantify the depositional environment interpreted from the facies changes in the rocks. With the construction of a rock magnetic time series, the facies/depositional environment interpretation could be short-circuited, and the rock magnetism would directly quantify the paleoenvironmental/paleoclimate change.

Rock magnetism and rock magnetic cyclostratigraphy can fulfill many of these needs. Rock magnetic parameters are used in the subdiscipline of environmental magnetism to detect the ancient depositional environment. Rock magnetic parameters can measure variations in the concentration, particle size, and mineralogy of magnetic minerals in a sedimentary rock. These measurements are relatively quick and, therefore, inexpensive, so 1000s of samples can be collected and measured for a rock magnetic cyclostratigraphic study to document magnetic variations at high resolution. The measurements are also nondestructive, so the samples can be retained for other nonmagnetic measurements and examination. The variations in magnetic mineral concentration and particle size can be tied to changes in the depositional environment and hence to changes in paleoclimate or paleoenvironment. Since magnetic minerals in Earth's crust all contain iron, either as oxides, oxyhydroxides, or sulfides, and iron is the fourth most common element in the crust, magnetic minerals can sensitively delineate the cycling of this ubiquitous element through Earth's atmosphere, biosphere, lithosphere, and hydrosphere. Furthermore, very small concentrations of magnetic minerals (<0.01%) are easily and

accurately measured with modern superconducting rock magnetometers, making rock magnetic measurements very sensitive measures of paleoenvironmental conditions. In one of the case studies presented in Chapter 6, the sensitivity of rock magnetics to paleoclimatic variations will be demonstrated by a study of the Cretaceous Cupido Formation from Mexico in which rock magnetics can detect astronomically forced cycles, even though the repeating, shallowing-upward facies cannot.

Rock magnetic parameters have been successful measures of glacial–interglacial cycles in loess, mainly in the Chinese Loess Plateau, but also in Eastern Europe and Alaska (summarized in Evans & Heller 2003). Rock magnetic measurements of European maar lake sediments have also detected glacial–interglacial climate cycles. **Susceptibility** variations from Lac Du Bouchet in France have been directly correlated to $\delta^{18}\text{O}$ records of glacial–interglacial cycles from the Pacific and Indian Oceans and Greenland ice cores (Heller et al. 1998). Terrigenous input into the north-western Indian Ocean can be tracked by magnetic susceptibility, and the cyclic variations in susceptibility can be directly correlated to astronomical calculations for northern hemisphere insolation (deMenocal & Bloemendal 1995). Susceptibility variations have also detected changes in paleoclimate in Eocene marine sediments off Antarctica (Sagnotti et al. 1998). Various studies of North Atlantic marine sediments have used rock magnetics to study deglaciation (Stoner et al. 1995) and North Atlantic Deep Water circulation (Kissel et al. 1999). These examples show that rock magnetic parameters that measure a quantity as simple as the concentration of magnetic minerals in sediment can easily detect changes as profound as global paleoclimate.

Conducting a rock magnetic cyclostratigraphic study of a sedimentary sequence is fairly straightforward. Most rock magnetic cyclostratigraphic studies measure variations in the concentration of a depositional magnetic mineral in a sequence of rocks. Magnetite (Fe_3O_4) is, in most cases, a primary, depositional magnetic mineral. Therefore, erosional, transport, and depositional processes as well as the depositional environment affect its concentration, making magnetite the preferred target of cyclostratigraphic studies. Furthermore, magnetite has a relatively low magnetic coercivity (for magnetic hardness, see Chapter 2) and its concentration is easily measured by applying an **anhysteretic remanent magnetization (ARM)** (for more details, see Chapter 2) to the cyclostratigraphy samples. ARM, as will be shown in Chapter 2, also allows the researcher to target the concentration variations of only one magnetic mineral (magnetite) in the rock compared to the multiple mineral sources for magnetic susceptibility, so the interpretation of any rock magnetic cycles recorded by an ARM will be straightforward. However, as shown in the case studies presented in Chapter 6, other rock parameters can be used with equal success for identifying astronomically forced cycles in a sedimentary sequence. The rock magnetic parameters used must be chosen on a case-by-case basis.

1.2 Basic Steps of a Rock Magnetic Cyclostratigraphy Study

The steps to a rock magnetic cyclostratigraphy are summarized in Figure 1.1. The first step in conducting a rock magnetic cyclostratigraphy is to select the stratigraphic section for study and estimate its sediment accumulation rate, so that the correct sampling interval can be chosen. The frequencies that can be detected by the time series analysis are limited by the **Nyquist frequency**. The shortest cycle that can be observed by time series analysis must be sampled at least twice per cycle; therefore, if **precession** (nominally a 20 kyr period) is to be captured, the rocks should be sampled at least once every 10 kyr of stratigraphic thickness. In some cases, previous work, either biostratigraphy, **magnetostratigraphy**, or geochronology of ash layers, can be used to calculate the sediment accumulation rate. In most cases, though, only an estimate of the sediment accumulation rate, based on the rock's lithology and depositional environment, is available. Sadler's (1981) comprehensive study of sedimentary record completeness can be an important source of these estimates. However, sampling precession twice per cycle is only a bare minimum. **Aliasing** could occur if shorter cycles present in the data are undersampled, producing apparent longer period cycles which are only an artifact of the sampling interval. It may be better to target possible precession cycles with three or four samples per cycle.

Once the sampling interval is selected, unoriented rock samples, ~4–5 cm in size, are collected throughout the section. If the modulation of precession (~20 kyr) by short (~100 kyr) and long (405 kyr) **eccentricity** is the desired target for detection, then the sampling interval is at least a 10 kyr stratigraphic thickness of sediment (ideally 5–7 kyr), and the stratigraphic thickness of the sampled interval should be long enough to record about six repetitions of the longest period cycle (Weedon 2003). Furthermore, the longer the series, the better the bandwidth resolution, i.e., the narrower the spectral peaks and hence the better one can resolve the frequency of individual cycles. If long eccentricity is the longest period targeted for detection, then the section should be at least ~2–2.5 million years long. For typical hemipelagic marine sediments with sediment accumulation rates of about 10 cm/kyr (Sadler 1981), these requirements would mean a sampling interval of about 0.5–1 m and a section thickness of at least 200–250 m, generating a minimum of 200–250 samples. For best results, at least three or four samples should be collected for every precessional cycle, increasing the number of samples to 500 samples for the 2- to 2.5-million-years long section. The work needed to collect this large number of samples is offset somewhat because the samples do not need to be oriented, as would standard paleomagnetic samples, because only the intensity of the sample is measured, not the direction of its magnetization. Sampling a 250 m section at 75 cm intervals would take about 3–4 days in the field.

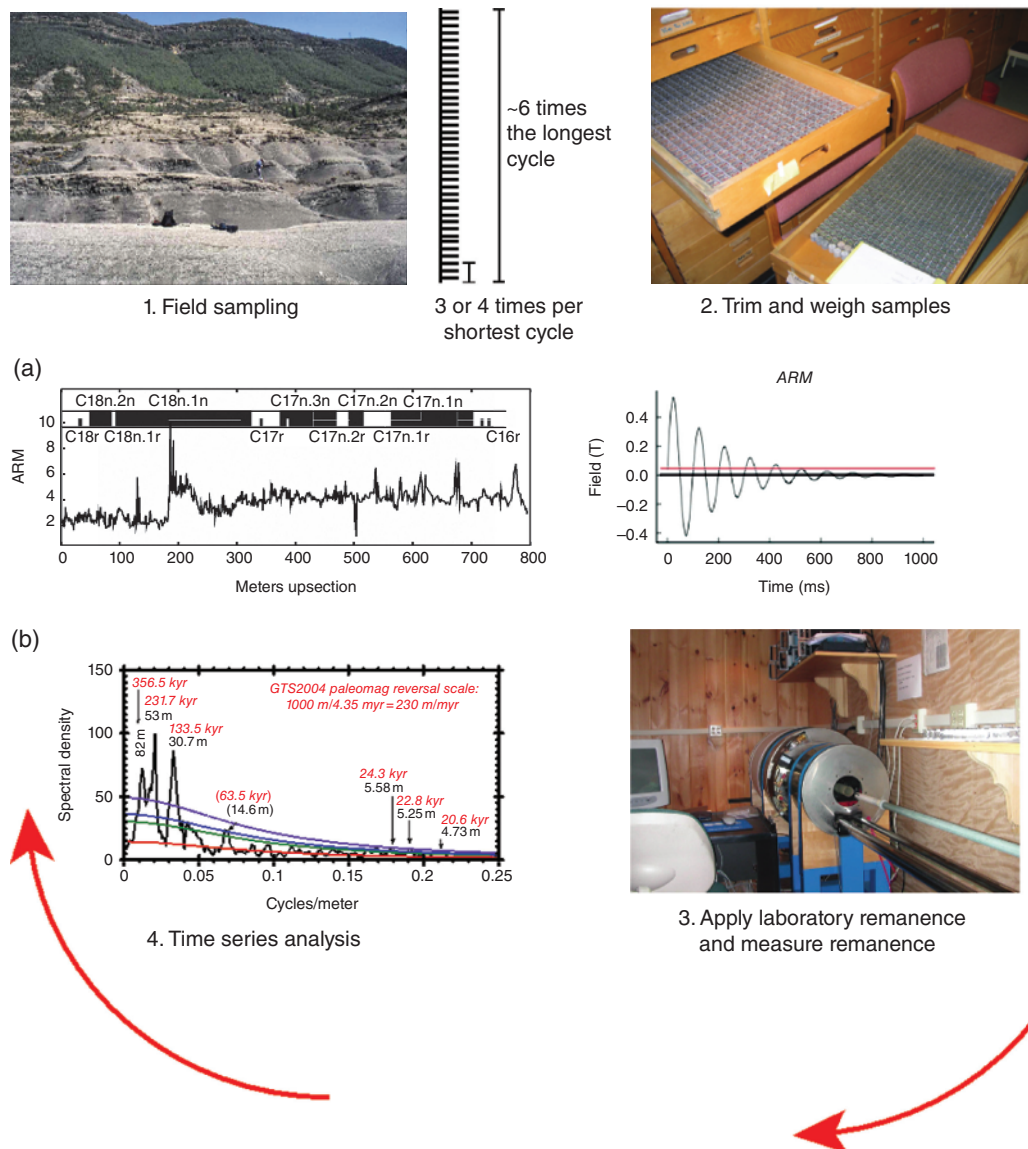


Figure 1.1 Steps to a rock magnetic cyclostratigraphy. Step 1: The field sampling picture is the Eocene Arguis Formation in the Spanish Pyrenees. Step 2: Cretaceous Cupido Formation limestone samples in 8 cm³ plastic sampling boxes. Step 3: Diagram of alternating and direct fields during application of an ARM. Lehigh University 2G Enterprises superconducting rock magnetometer. Step 4: (a) Arguis Formation ARM series and magnetostratigraphy developed for the Arguis Formation. (b) **Multitaper method (MTM)** power spectrum of the Arguis Formation ARM time series. Source: Kodama, Anastasio, Newton, Pares & L. A. Hinnov 2010. Reproduced with permission of John Wiley & Sons, Inc.

After the samples are brought to the laboratory, they must be trimmed to fit into standard paleomagnetic/rock magnetic plastic sample boxes (nominally $2\text{ cm} \times 2\text{ cm} \times 2\text{ cm}$ in size). The samples should be weighed because the magnetic measurements of intensity must be normalized by sample mass for an accurate cyclostratigraphy. Alternatively, small diameter ($\sim 11\text{ mm}$) 15 mm long cores can be drilled from the samples. After the samples are trimmed or cored, placed in sample boxes and weighed, they are ready for rock magnetic analysis.

If ARM is the rock magnetic parameter selected for the cyclostratigraphy, it is applied to each sample using a specialized piece of equipment, an alternating field demagnetizer modified so that a small, constant, biasing magnetic field can be applied during **demagnetization**. After application of the ARM, the sample's magnetic intensity is measured in a rock magnetometer. Usually a superconducting rock magnetometer is used for speed of measurement and high accuracy. The measurement of each sample takes on the order of about 5–7 minutes for both the ARM application and the magnetic intensity measurement. Five hundred samples can be processed in about 50–60 hours, once they have been trimmed and weighed.

Time series analysis (Chapter 4) is used to deconstruct the ARM data series into its constituent frequencies. Determining whether any cycles observed are Milankovitch (astronomically forced) is the most difficult part of the study. Ideally, some independent control on time is available to unequivocally identify astronomically forced cycles. Biostratigraphy or magnetostratigraphy (Chapter 3) are two important ways of doing this. The time assignment can be at a fairly coarse scale, just high enough resolution to allow the identification of the longest (~ 100 or 405 kyr eccentricity) astronomically forced cycles targeted for detection in the sampling. Once these cycles are identified, the series can be tuned either to a theoretical insolation series (e.g., Laskar et al. 2004) or to a simple sinusoid at that frequency to remove the effects of varying sedimentation rates in the record. Time series analysis of the tuned series can determine whether the shorter astronomically forced cycles (precession, **obliquity**) are more pronounced in the power spectrum, thus providing further evidence that astronomically forced cycles have been identified. The identification of astronomical cycles has now translated the coarse resolution biostratigraphy or magnetostratigraphy to a high-resolution chronostratigraphy for the sedimentary sequence.

1.3 The Significance of Rock Magnetic Cyclostratigraphy

The realization of a high-resolution chronostratigraphy using rock magnetic cyclostratigraphy has the potential to be a transformative chronostratigraphic technique for the Earth sciences. High-resolution time

can be critical to understanding many important Earth processes. Rock magnetic cyclostratigraphies have already been used to study tectonic processes. Gunderson et al. (2012) have used a susceptibility record of obliquity in Plio-Pleistocene marine sediments from the Po River Valley in northern Italy to time the deposition of growth strata that, in turn, constrain the folding of the Salsomaggiore anticline, and hence fault slip on the blind thrust pushing up the folded rocks. A similar study of folded Eocene marine growth strata in the Spanish Pyrenees is the ultimate goal for the ARM cyclostratigraphy already produced for the Arguis Formation marine marls (Kodama et al. 2010). Not only high-resolution chronostratigraphies will result from rock magnetic cyclostratigraphies, but high-resolution correlation of sedimentary sections that are distant globally, or even cores drilled from an oil or gas field for petroleum exploration and exploitation.

Rock magnetic cyclostratigraphy also has the potential for outperforming the resolution of radioisotope geochronology, particularly for very ancient rocks. Minguez et al. (2014) have demonstrated rock magnetic cyclostratigraphies at different localities of the Neoproterozoic Johnnie Formation from near Death Valley, CA. These chronostratigraphies yield precession-scale resolution that in the Neoproterozoic is on the order of 15 kyr. Bowring and Schmitz (2003) indicate errors of approximately ± 0.3 –3 Ma on Neoproterozoic age (~ 550 Ma) rocks in their discussion of the problems dating the Cambrian–Neoproterozoic boundary with zircon U–Pb ages. Even the 555.0 ± 0.3 Ma age they report for the Neoproterozoic has an error 20 times larger than the precision realized by the Johnnie Formation rock magnetic cyclostratigraphy. Furthermore, radioisotopic dates give spot ages at irregular intervals, whereas cyclostratigraphy yields a continuous chronology and preserves high-precision ages through several million year intervals.

1.4 Layout of the Book

This book is organized to provide the background information needed to conduct a rock magnetic cyclostratigraphic study of a sedimentary sequence. Chapter 2 covers the important points about rock magnetism necessary for conducting rock magnetic cyclostratigraphy studies and for understanding the interpretation of rock magnetic data. Chapter 3 is a primer for the basics of conducting a magnetostratigraphic study needed to assign time at a coarse scale to the data series acquired in a cyclostratigraphic study. Chapter 4 covers the basics of time series analysis needed to extract and interpret cycles in rock magnetic data series; step-by-step procedures and commands are demonstrated with MATLAB® scripts. Chapter 5 gives the theoretical background of astronomical forcing mechanisms and provides step-by-step description for how to calculate

obliquity and **precession index** solutions using FORTRAN code. Chapter 6 presents case studies of rock magnetic cyclostratigraphy. The Appendix contains scripts and codes used throughout the book.

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