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Improvement of cyclostratigraphic studies by processing of high-resolution magnetic susceptibility logging: Example of PEP1002 borehole (Bure, Meuse, France)

Études cyclostratigraphiques : traitement des données diagraphiques haute résolution de la susceptibilité magnétique, exemple du forage PEP1002 (Bure, Meuse, France)

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ABSTRACT

Logging opens wide paths for cyclostratigraphic studies of sedimentary successions. In clay-dominated rocks, magnetic susceptibility (MS) is very informative and the quality of the results can be further enhanced by deconvolution, where the deformation of the original susceptibility versus depth variation by the instrument is filtered out by its impulse response (thin layer response). This is illustrated by processing the data acquired in the PEP1002 borehole (Bure, Meuse, France) using two coils 0.25 m apart where high-frequency, 0.5 to 0.8 m, period precession cycles (21 kyr) can be identified, as well as the 2.5 to 4 m period eccentricity (95 kyr) ones.

RÉSUMÉ

Les mesures en puits par diagraphies différées satisfont à l'exigence de très haute résolution des études cyclostratigraphiques. Les déformations apportées par l'outil à l'enregistrement des différents cycles, notamment haute fréquence, peuvent être corrigées par un traitement par déconvolution à partir de la réponse impulsionnelle d'une couche mince. Cette méthode a été appliquée aux données de susceptibilité magnétique du forage PEP1002 réalisé à Bure (Meuse) dans la série argileuse Callovo-Oxfordienne de l'Est du Bassin de Paris. Les cycles de basse fréquence sont clairement identifiables sur les données brutes. L'analyse des données déconvoluées montre une amélioration considérable des amplitudes associées aux cyclicités haute fréquence, telles la période de 0,5 m à 0,8 m caractérisant dans cette étude les cycles de précession d'une durée de 21 000 ans et la période de 2,5 m à 4 m les cycles d'excentricité, d'une durée de 95 000 ans.

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1. Value of magnetic susceptibility measurements in cyclostratigraphy

The first, evident, criterion in the choice of a measured parameter is that a sufficient correlation exists between climate events recorded in the sedimentary sequence and this parameter. The second criterion is the ability to measure it with a sufficiently small sampling step: sedimentation processes can be slow and depend on the periods of astronomical cycles that can force climate changes and thus the sedimentation rate. Whatever the type of measurement, one must try to reach the finest possible resolution.

Magnetic susceptibility (MS) respects these criteria. All sedimentary rocks contain different types of magnetic minerals with widely varying content as well as size and shape of the magnetic grains (Esteban et al., 2006). Erosion, sedimentation and diagenesis processes play a major part in these characteristics, which can thus reflect variations induced by Earth orbital periodic changes. Consequently, for several years, MS has been used in correlation studies (Ellwood et al., 1999, 2000, 2001); it is applied to quaternary climate-change records (Allen et al., 1999; Bloemendal et al., 1995; Heller and Evans, 1995; Nio et al., 2005; Röhl et al., 2001) and investigations into earlier periods promise important results (Boulila et al., 2008, 2010; Huret, 2006; Weedon, 1989; Weedon et al., 2004).

MS measurements are very rapid and easy, non-invasive and non-destructive; they can be made on cores in the laboratory, on outcrops in the field and by logging in boreholes. The latter has major advantages: measurements are recorded continuously without any gaps, the volume of rock taken into account can be chosen and thus be significantly larger than that of cores, the rock is not weathered and stays in the same pressure and temperature conditions, logging is far cheaper than core recovery. Parts of these advantages are shared with other logging techniques of which the best known and most widely used for clay-content determination in sedimentary rocks is natural gamma rays measurements (GR). In MS measurements, however, one can choose and easily change the volume of the rock taken into account, the magnitude and the frequency of the applied field (thus increase the signal-to-noise ratio and/or reduce the measurement duration) and the sampling step. Moreover, magnetic parameters are independent of K, U and Th content and the new information they bring always improves the interpretation, which justifies the study of the new possibility(ies) they open up in cyclostratigraphic studies (Cleaveland et al., 2002; Huret, 2006; Mayer and Appel, 1999; Pozzi et al., 1988; Thiesson et al., 2009).

2. Magnetic susceptibility logging

MS measurements in boreholes began in conjunction with surface magnetic prospecting in mining geophysics, where huge contrasts can be expected and observed between ore bodies and their surroundings. The first project of "magnetic well logging" in a non-mining, low contrast, sedimentary context was developed by the Field Research Laboratory of Magnolia Petroleum and its results were published by Broding et al. (1952). This project was very ambitious: it consisted in designing two coupled logging instruments, a MS tool and a total magnetic field tool. The first can also deliver electrical-conductivity measurements and the combination of susceptibility and magnetic field data can help to determine the remanent magnetisation of the layers. The susceptibility tool was a long (12-inch) single-coil solenoid (the coil is both the transmitter and the receiver). Other single-coil tools have been developed (Scott et al., 1980) especially in uranium-ore prospecting.

Later, the progress achieved in shallow-depth surface prospecting for the simultaneous measurement of both electrical conductivity and MS of soils showed the advantages of two-coil instruments (Parchas and Tabbagh, 1978). Analogous instruments were then designed for logging in mining applications (Clerc et al., 1983) and others for studying the oceanic crust (Daly and Tabbagh, 1988) and sedimentary layers (Pozzi et al., 1988) in combination with magnetic field logging. This concept of combined tools opened very interesting lines of research for studying the magnetic field inversion scale. The observed high sensitivity of the MS to slight changes in sediments properties (Tabbagh et al., 1990) led us to consider it as a relevant proxy to determine Milankovitch cycles in sediments.

The aim of this article is to consider cyclostratigraphic identification through susceptibility logs. After having shown the value of deconvolution of the raw data by presenting synthetic case results, it discusses the processing and interpretation of the data acquired in the PEP1002 borehole at the Bure (Meuse, France) underground research laboratory of ANDRA.

3. Reconstruction of magnetic susceptibility variations by deconvolution

3.1. Principle

In logging, the raw data do not correspond to the measured parameter value (here MS) in front of the instrument. It is a representation of the parameter that depends on the measurement frequency and depth. This representation is a complex summation of the different responses of the layers above, in front and beneath the sensor. These responses can be cross-coupled and the restitution of the original parameter-depth function is not a simple task.

In the particular case of susceptibility measurements, it has been established (Tabbagh, 1990) that the relationship between raw data and layer susceptibility is linear with a very good approximation and corresponds to a convolution product. Measurements have thus to be 'deconvoluted', this operation depends on the geometric characteristics of each instrument which is illustrated in the following synthetic case.

3.2. Impulse response: definition

In logging, the impulse response of a tool is the response it gives when passing in front of an infinitely thin horizontal layer, $R(z)$ (Fig. 1). The MS impulse response is complex, but, as the influence of the electrical properties