doi: 10.22564/brjg.v12i1.2283

SPECTRAL ANALYSIS OF THE MAGNETIC SUSCEPTIBILITY RECORD OF CHINESE LOESS

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The magnetic susceptibility record of Chinese Loess Plateau for the last 2.5 million years was subjected to Maximum Entropy Spectral Analysis. The portion 0 - 800 ka B.P. showed 95,000 years as the strongest peak, resembling the 98,000 year peak in the spectra of oxygen isotope series from deep-sea cores, and matching the eccentricity peak of Earth's rotation axis. The astronomical peaks 19,000 and 23,000 years related to Earth's precession and 41,000 years related to Earth's obliquity were also observed but weakly. For earlier periods (800 ka - 2400 ka B.P.), nine peaks were observed (including 41,000 and 100,000 years) but weakly.

ANÁLISE ESPECTRAL DOS REGISTROS DE SUSCEPTIBILIDADE MAGNÉTICA DOS "LOESS" CHINESES *Os registros de susceptibilidade magnética do Platô Chinês "Loess" nos últimos 2,5 milhões de anos foram sujeitos à Análise Espectral de Máxima Entropia. A porção 0-800 mil anos anteriores ao presente mostrou 95.000 anos como o mais intenso pico, aparecendo com um pico de 98.000 anos no espectro da série de isótopos de oxigênio apresentada nos sedimentos marinhos profundos, e coincidem com o pico na excentricidade do eixo de rotação da Terra. Os picos astronômicos em 19.000 e 23.000 anos relacionados à precessão da Terra e em 41.000 anos relacionados à obliquidade da terra foram observados, porém muito fracamente. Para períodos anteriores (800-2.400 mil anos anteriores ao presente), nove picos foram observados (incluindo 41.000 e 100.000 anos), porém fracamente.*

INTRODUCTION

Climate in the past is known to have undergone large fluctuations. Glaciations have resulted in episodes of high-sea level (low ice volume) which are reflected in the oxygen 18 isotope content of deep-sea cores. Time series of the oxygen isotope show many significant periodicities, some of which have astronomical implications (Milankovitch, 1930). Methodology of obtaining the data has been described in several publications (Emiliani, 1955, 1978; Kemp and Eger, 1967; Hays et al., 1976; Siddiqui and Wang, 1984; Imbrie et al., 1984; Shackleton and Imbrie, 1990) and periodicities of about 19,000, 23,000, 42,000 and 100,000 years have been reported, of which the first three could be related to obliquity and precession of the earth's axis of rotation. For the oxygen isotope data for the last 782,000 years, published in Imbrie et al. (1984), Kane and Trivedi (1992) used the method of Maximum Entropy Spectral Analysis (MESA) and reported 98,000 years as the most prominent periodicity, followed by 40,000 years of less than half the amplitude and peaks at 24,000, 67,000, 84,000, 107,000 and 786,000 years of less than one third the amplitude, which compared well with the results of Thomson (1990) who used the method of multi-taper spectrum analysis. Using the data from four deep-sea cores from the Atlantic, Pacific and Indian oceans, Berger et al. (1991a) have reported mean periodicities of 117,700, 43,600, 24,900 and 19,300 years.

Geological time series can be obtained for other parameters also. Loess-soil (dust) deposits have been observed in China and their lithology and magnetic stratigraphy studied (e.g. Liu, 1988). Kukla et al. (1990) reported results from the study of a single stacked file obtained as the average of the records of the low field magnetic susceptibility at three sites in the Chinese Loess Plateau in north central China. The data refer to the last 2.5 Ma (million years) and Kukla et al. used MESA technique for spectral analysis, but only for the upper 736,000 years of the stacked time series and compared the results with those for the oxygen isotope record of Imbrie et al. (1984) for a similar period, mainly with a view to study the changing behaviour of the 41,000 and 23,000 year orbital periodicities. In the present note, we present results of a spectral analysis (MESA) of the whole series of stack susceptibility values of the Chinese loess for the last 2.5 million years as given in Appendix I of Kukla et al. (1990).

DATA

Fig. 1 shows a plot of the magnetic susceptibility values (crosses) for 0 to 0.8 Ma (million years) B.P. in Fig. 1(a), and 0.8 - 2.5 Ma B.P. in Fig. 1(b), (c), (d). In Fig. 1(a), the smooth curve is for the oxygen 18 isotope (Imbrie et al., 1984). The numbers represent the spacings between successive peaks, in units of thousand years. As can be seen, the oxygen isotope series shows many spacings at 20-26 ka (thousand years) and 40 ka which could correspond to the bimodal 23,000 and 19,000 year peaks of earth's precession and the 41,000 year peak of obliquity. However, as pointed out by Imbrie et al. (1984) themselves as also by Thomson (1990) and Kukla et al. (1990), these astronomical frequencies are used by Imbrie et al. (1984) for tuning (refining) the isotope record time scales. Hence, their presence does not necessarily indicate astronomical origin. In the magnetic susceptibility plot of Fig. 1(a) (crosses), where near surface values (0 - 10 ka B.P.) are omitted, the 20-24 ka separation is not very frequent, while 40 ka occurs often. The correlation coefficient between the oxygen isotope and susceptibility series was about +0.6. In Fig. 1(b, c, d), 40 ka and 50-70 ka seem to occur very often. In a gross way, some major features of the oxygen isotope and susceptibility plots seem to match e.g., the maxima at -100, -200, -300, -400 and -500 ka, indicating a 100 ka year wave.

SPECTRAL ANALYSIS

From Fig. 1, it seems that the spectral characteristics have not remained the same through the whole period of 0 - 2.5 Ma B.P. Nevertheless, we divided the data into 3 groups of roughly 800,000 years each (11 ka - 830 ka, 831 ka - 1650 ka, 1651 ka - 2470 ka B.P.) and subjected it to MESA (Maximum Entropy Spectral Analysis), developed by Burg (1972) and critically reviewed by Ulrych and Bishop (1975). In this method, there is an adjustable parameter LPEF (Length of the Prediction Error Filter). At small LPEF, only smaller periodicities are revealed. For larger LPEF, larger periodicities (almost approaching data length) can be revealed but with possible errors as large as 20% (Chen and Stegen, 1974). Also, the lower periodicities start showing peak splitting. Hence, our prescription is to locate

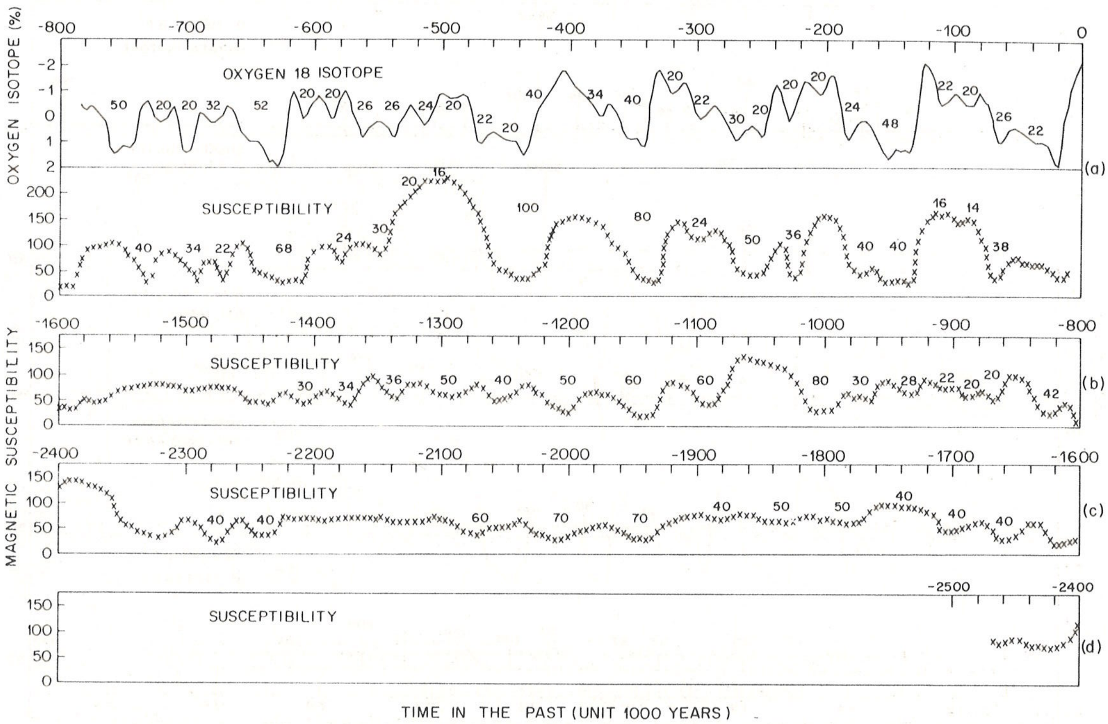

Figure 1. Plot of magnetic susceptibility (crosses) of the Chinese Loess (m^3 kg^{-1}) for (a) 0 - 800 ka B.P., (b), (c) and (d) 800 - 2500 ka B.P. The numbers represent spacing (thousand years) between successive peaks. In (a), the full line represents oxygen isotope record from deep-sea cores.

Gráfico da susceptibilidade magnética (cruzes) do "Loess" chines (m^3 kg^{-1}) para (a) a 800 mil anos antes do presente (B.P.); (b), (c), (d) 800 a 2500 B.P. Os números representam a separação (mil anos) entre os picos sucessivos. Em (a), a linha sólida representa o registro isotópico do oxigênio de testemunhas oceânicas profundas.

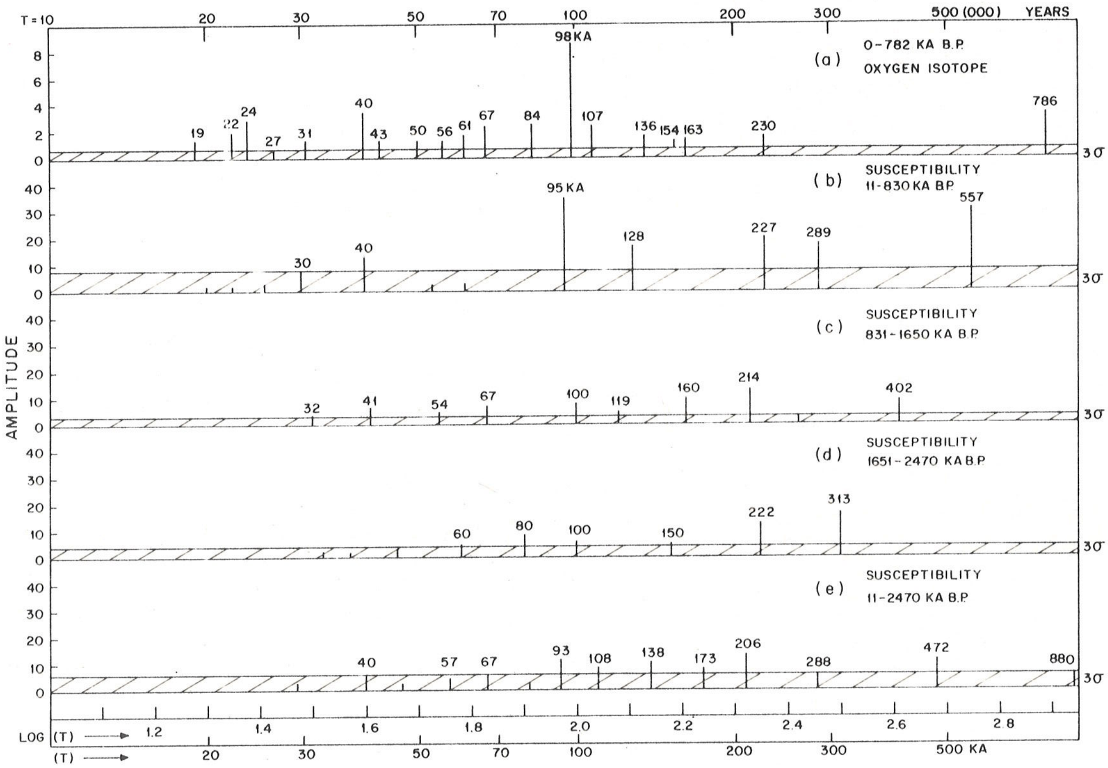

Figure 2. Amplitudes of the various periodicities detected by a Maximum Entropy Spectral Analysis. The abscissa scale is log(T).

Amplitudes de várias periodicidades detectadas pela Análise Espectral de Entropia Máxima. A escala da abscissa é log(T).

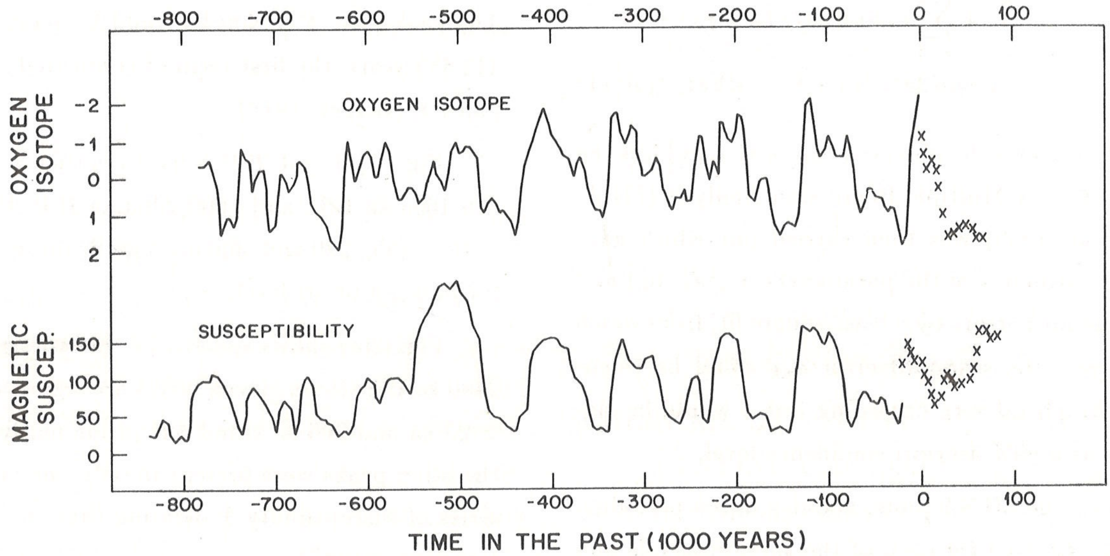

Figure 3. Oxygen isotope and susceptibility series for the last 800,000 years (full lines) and their extrapolations (crosses) as predictions for future.

Séries temporais de susceptibilidade e isotópica do oxigênio para os últimos 800.000 anos (linhas sólidas) e suas extrapolações (cruzes) como previsão futura.

low periodicities (one tenth of the data length) in the low LPEF (33% of data length) plots and larger periodicities in the larger LPEF (50% of data length) plots. Also, since amplitude (or power) estimates in MESA are unreliable (errors could exceed 20%) and are sensitive to the LPEF used, we used MESA only for detecting possible periodicities T_k (k = 1 to n) and then use these T_k in the expression:

$$\begin{aligned} f(t) &= A_o + \sum_{k=1}^{n} B + E \\ &= A_o + \sum_{k=1}^{n} r_k Sin(2\pi t/T_k + \phi_k) + E \\ B &= [a_k Sin(2\pi t/T_k) + b_k Cos(2\pi t/T_k)] \quad (1) \end{aligned}$$

where f(t) is the observed time series and E is the error factor. A Multiple Regression Analysis (MRA, Bevington, 1969) was then carried out which gave the best estimates of the parameters A_o (a_k, b_k) and their standard errors by a least-square fit, from which (r_k,ϕ_k) and the standard error σ_{rk} could be calculated. Amplitudes r_k exceeding 3 σ_{rk} would be significant at a 99% a priori confidence level.

From the MESA plots, about a dozen periodicities were selected for each of the three intervals and MRA yielded amplitudes as shown in Fig. 2. The abscissa scale is not the conventional f (frequency), nor T (period) but log(T). Fig. 2(a) refers to oxygen isotope series for 0 - 800 ka B.P. (Kane and Trivedi, 1992) and Fig. 2(b) refers to magnetic susceptibility (Kukla et al., 1990) also for 0 - 800 ka B.P. The hatched regions indicate the 3 sigma (a priori) significance limit and only peaks exceeding this limit (99% confidence level) are shown, with numbers indicating periodicities in units of 1000 years. As expected, the strongest peaks in both are near T = 100. In their paper, Kukla et al. (1990) presented results of MESA for this period but only for 200 ka intervals at a time with steps of 25 ka. Thus, spectra were shown for 11 ka - 211 ka, 36 ka - 236 ka, ... 536 ka - 736 ka and the emphasis was on studying the behaviour of the 22 ka and 41 ka peaks only. However, their Fig. 11 does indicate a significant peak near T = 100 ka, which they ignored in their text. For astronomical comparison, T = 94,945 years and T = 107,807 years are known to be the second and fourteenth terms of eccentricity series expansion as given by Berger (1978). In contrast, the peaks at T = 23 ka and 19 ka corresponding to the most prominent precession peaks and T = 41 ka corresponding to most prominent obliquity peak of Earth's rotation are seen rather weakly in Fig. 2(a) and (b). There are significant peaks near T = 200 ka and these do not match with any astronomical peaks. The peak near T = 400 ka could be related to T = 412,885 years, the first term of eccentricity series expansion (Berger, 1978).

Fig. 2(c) and 2(d) refer to earlier periods viz. 800-1600 ka B.P. and 1600-2400 ka B.P. Peaks at T ≐ 100, 155, 220 and 300 are significant, at a 6 sigma (or more) a priori level.

Fig. 2(e) shows spectra for the whole series 0 - 2400 ka B.P. Here, eleven peaks are significant and T = 93 ka and 206 ka stand out prominently. Some of the other peaks were present in only one of the three series of susceptibility, indicating that these are of a transient nature.

In a general way, the spectra in Fig. 2(a) and Fig. 2(b) are similar. The larger amplitudes of T = 19 ka and 22-24 ka in Fig. 2(a) are probably due to the fact that these are used in the tuning of the oxygen isotope data. But otherwise, the resemblance is still remarkable, specially due to the 100 ka sequence and, as concluded by Kukla et al. (1990), the atmospheric and oceanic circulation changes which accompanied the glaciations were of a global scale, with some astronomical control of the gross climate variations.

The T = 100,000 years signal is quite intriguing. In addition to the oxygen isotope (and now the susceptibility series), Hays et al. (1976) found this signal in Ts, an estimate of summer sea-surface temperature at the core site, as also in the percentage of C. davisiana, a radiolarian species, and advanced the hypothesis that the radiation-climate system responds nonlinearly to changes in the geographic and seasonal distribution of insolation. If the ice sheets wasted faster than they grew i.e. if the cryosphere responded to the orbital forcing with two different constants (see Broecker and Van Donk, 1970; Calder, 1974), the modulation effect of eccentricity on the precession index could generate a 100,000 year component. The intriguing part is that the 100 ka component seems to be present prominently only in the last 800,000 years, or, to be more precise, in the last 600,000 years. Why it is not seen prominently in earlier intervals, is a moot question.

PREDICTION

Since the periodicities (specially 100,000 years) are prominent in the last 800,000 years, the spectral peaks for this interval could be used for predicting the future behaviour. In Kane and Trivedi (1992), such an attempt was made for the oxygen isotope data and indicated a possible increase in the next 20,000 years, in agreement with the predictions from various models (Calder, 1974; Peterson and Larsen, 1978; Imbrie and Imbrie, 1980; Kukla et al., 1981; Berger et al., 1981; Berger et al., 1989; Melice and Berger, 1989) as reviewed by Berger et al. (1991b). Fig. 3 illustrates the prediction (crosses) by our method (Kane and Trivedi, 1992). The susceptibility is expected to decrease in the next 20,000 years and then rise for the next 70,000 years.

CONCLUSION

A spectral analysis of the time series of the magnetic susceptibility in the Chinese Loess Plateau in north Central China for the last 2.5 million years was carried out. When divided into 3 equal parts, (roughly 11 - 830 ka, 831 - 1650 ka, 1651 - 2470 ka B.P.), the spectra varied considerably from one part to another. In the first part (11 - 830 ka B.P.), the most prominent periodicity was 95,000 years and resembled the 98,000 year periodicity of oxygen 18 isotope in deep-sea cores, probably matching with the 100,000 year eccentricity band of Earth's orbital motion. The precession bands (19,000 and 23,000 years) as well as the obliquity band (41,000 years) were also observed but with much smaller amplitudes. In earlier intervals (831 - 1650 ka and 1651 - 2470 ka B.P.), the periodicities had amplitudes smaller than those observed during the recent period (11-830 ka).

ACKNOWLEDGEMENTS

This work was partially supported by FNDCT Brazil under contract FINEP 5373 CT.

REFERENCES

BERGER, A.L. (1978) Long-term variations of daily insolation and Quarternary climate changes. J. Atmos. Sci., 35, 2362-2367.

BERGER, A., GUIOT, J., KUKLA, G. and PESTIAUX, P. (1981) Long-term variations of monthly insolation as related to climate change. Geologischen Rundschau Bd., 70(2), 748-758.

BERGER, A., GALLÉE, H., FICHEFET TAND TRICOT, C. (1989) Testing the astronomical theory with a coupled climate-ice sheet model. In Global and Planetary Change. Labeyrie L. (ed.) (in press, as mentioned in Berger et al., 1991b).

BERGER, A., MÉLICE, J.L. and HINNOV, L. (1991a) A strategy for frequency spectra of Quarternary Climate records. Climate Dynamics, 5, 227-240.

BERGER, A., GALLÉE, H. and MÉLICE, J.L. (1991b) The earth's future climate at the astronomical time scale. In Future climate change and radioactive waste disposal. (Goodeess C.M.

and Palutikof J. Eds.), Climatic Research Unit, University of East Anglia, Norwick, U.K.

BEVINGTON, P.R. "Data reduction and error analysis for the Physical Sciences" (McGraw-Hill Book Co., New York, 1969) pp. 164-176.

BROECKER, W.S. and VAN DONK, J. (1970) Insolation changes, Ice volumes and the $^{18}0$ record in deep-sea cores. Rev. Geophys. Space Phys., 8, 169-198.

BURG, J.P. (1972) The relationship between maximum entropy spectra and maximum likelihood spectra. Geophys., 37, 375-376.

CALDER, N. (1974) Arithmetic of Ice Ages. Nature (London), 252, 216-218.

CHEN, W.Y. and STEGEN, G.R. (1974) Experiments with maximum entropy power spectra of sinusoids. J. Geophys. Res., 79, 3019-3022.

EMILIANI, C. (1955) Pleistocene temperatures. J. Geol., 63, 538-578.

EMILIANI, C. (1978) The cause of Ice ages. Earth and Planetary Science Letters, 37, 349-352.

HAYS, J.D., IMBRIE, J. and SHACKLETON, N.J. (1976) Variations in the Earth's orbit: Pacemaker of the Ice ages. Science 194, 1121-1132.

IMBRIE, J.I. and IMBRIE, J.Z. (1980) Modelling Climate response to orbital variations. Science, 207, 943-953.

IMBRIE, J., HAYS, J., MARTINSON, D., MCINTYRE, A., MIX, A., MORLEY, J., PISIAS, N., PRELL, W. and SCHACKLETON, N. The orbital theory of Pleistocene climate: Support from a revises chronology of the marine $_{18}0$ record. In Milankovitch and Climate, Part I (eds. Berger et al.) D. Reidel, Hingham, Mass. 1984) pp. 269-306.

KANE, R.P. and TRIVEDI, N.B. (1992) Maximum entropy spectral analysis of the geological time series of the oxygen isotope record from deep-sea cores. Pure Appl. Geophys., 139, 145-162.

KEMP, W.C. and EGER, D.T. (1967) The relationship among sequences with applications to geological data. J. Geophys. Res., 72, 739-751.

KUKLA, G., BERGER, A., LOTTI, R. and BROWN, J.P. (1981) Orbital signature of interglacials. Nature, 290(5804), 295-300.

KUKLA, G., AN, Z.S., MELICE, J.L., GAVIN, J. and XIAO, J.L. (1990) Magnetic susceptibility record of Chinese Loess. Trans. Roy. Soc. of Edinburgh, 81, 263-288.

LIU, T.S. (1988) Loess in China, Beijing: China Ocean Press and Berlin: Springer Verlag.

MÉLICE, J.L. and BERGER, A. (1989) Modele de prevision statistique du type Box-Jenkins pour la prévision du climat des 10,000 prochaines années. Scientific Report 1989/6 Institut d'Astronomie et de Géophysique G. Lemaitre, Universitée Catholique de Louvain-la-Neuve, Belgium.

MILANKOVITCH, M. Mathematische Klimalehre und Astronomische Theorie der Klimaschwankungen. In Handbuch der Klimatologie I(A) (eds. Koppenand W. and Geiger R.) (Gebruder Borntraeger, Berlin 193) pp. 1-176.

PETERSON, E.L. and LARSEN, S.E. (1978) A statistical study of a composite isotope paleotemperature series from the last 700,000 years. Tellus, 30, 193-200.

SCHACKLETON, N.J. and IMBRIE, J. (1990) The $_{18}0$ spectrum of oceanic deep water over a five-decade band. Climatic Change, 16, 217-230.

SIDDIQUI, M.M. and WANG, C.C. (1984) High-resolution frequency analysis of geological times series. J. Geophys. Res., 89, 7195-7201.

THOMSON, D.J. (1990) Quadratic-inverse spectrum estimates: Applications to Palaeoclimatology. Phil. Trans. R. Soc. London A., 539-597.

ULRYCH, T.J. and BISHOP, T.N. (1975) Maximum entropy spectrum analysis and autroregressive decomposition. Rev. Geophys., 13, 183-200.

Submetido em 14.10.93
Revisado em 21.03.94
Aceito em 23.03.94

Palavras chave
Susceptibilidade magnética
Loess chinês
Análise espectral

Key words
Magnetic susceptibility
Chinese Loess
Spectral analysis