SOLAR-CLIMATIC EFFECTS ON LAKE/MARINE SEDIMENT RADIOACTIVITY VARIATIONS

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CHAPTER 10

Solar-Climatic Effects on Lake/Marine Sediment Radioactivity Variations

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ABSTRACT: Sediment radioactivity of cores spanning the last 20 kyr and derived from the Lake Bouchet, France, the Black Sea and the Aegean Sea, vary in a quasi-periodic manner most pertinent to palaeoclimatic changes. The causal mechanisms of these variations are reviewed according to the relationship between solar activity, atmospheric phenomena, including climate and the climatic impact on lake/marine sediment radioactivity variations. The latter concerns the uranium, thorium and potassium isotopic partitioning character during sedimentation processes. The common periodicities found between solar-terrestrial phenomena ranging between 0.2–24 kyr provide possible clues about solar activity-climate-sediment radioactivity links.

INTRODUCTION

The large issue of the periodic machinery of the solar system and its possible effects on the sun, and through such effects on the Earth's climate and various terrestrial indices continues to be the object of debate. Short and long-term solar/climatic/terrestrial cycles have been found covering every time scale: from a few months to several thousands years (see selective bibliography by SANDERS and FAIRBRIDGE, in CHPP, 1987, pp. 475–541).

Several arguments have been proposed to explain such periodic oscillations; the Milankovich astronomical theory (BERGER, 1988; LIRITZIS, 1993), the solar and/or solar-planetary dynamic configurations (FAIRBRIDGE and SANDERS, 1987 in CHPP 1987, pp. 446–471; LIRITZIS and PETROPOULOS, 1987), and solar and terrestrial agents (earth's rotation, sea-level changes). The proxy solar/climatic data globally employed include: sea-level changes, atmospheric temperature/pressure, ocean/lake sediments, terrestrial landforms, ice cores, varved sediments, tree-rings, archaeo/palaeo-magnetism, stable and unstable isotopes (BOWEN, 1991; CHPP, 1987).

This paper reviews our work on lake/sea sediment radioactivity variations from the Aegean Sea, the Black Sea and Lake Bouchet, and discusses the solar-climatic origin of these commensurable periodic variations. The application of nuclear counting to these sediments was in anticipation of being able to infer palaeoclimatic variations as reflected in the detrital minerals introduced into the lake/marine environment from weathering-erosion-transportation-deposition processes during the past 30 kyr.

The questions addressed in this study refer to (a) the variation of natural radioactivity derived from clay minerals and aluminosilicates and its cause, (b) the partition character of these natural isotopes (U, Th, K) which participate in the sedimentation processes, (c) the role of palaeoclimate to (a) and (b), (d) the periodic variation of sediment radioactivity, and (e) once the climate factor is established, to try to interpret perhaps certain palaeomagnetic intensity features of the sediments, in terms of climatic changes.

SUN-CLIMATE RELATIONSHIPS

The relationship between variable solar activity (involving streams of solar corpuscular emission) and climate has been strengthened by a stream of new evidence, though for many decades astronomers and meteorologists have sought clues of a causal connection with only limited success (WIGLEY, 1981). In our view, it has now become a matter of high scientific priority to develop and test working hypotheses for the empirical relationships because the effect of solar activity on weather has turned out to be of substantial magnitude and of genuine forecasting significance.

We are keenly aware that the continued absence of a plausible physical explanation for an apparent but evidently complex relationship between sun and climate may deter acceptance of the empirical evidence and slow down the practical applications that are so often implicit in a sound theory. Moreover the causal relationship between solar corpuscular ionising particles, the Earth's magnetic field and climate, has initiated some scientists to propose models which might be correct but, nevertheless, are not entirely unambiguous (PECKER and RUNCORN, 1990).

These models refer variously to either an orbital origin of long-term climatic changes (HAYS *et al.*, 1976; ROBERTS and OLSON, 1973); or to strong negative correlations between temperature and magnetization of sediments (WOLLIN *et al.*, 1974); or a positive one between magnetic intensity and temperature (COURTILLOT *et al.*, 1982) or even no correlation (STERNBERG and DAMON, 1979); also to the detection of a correlation between orbital parameters (their variations of which may trigger changes of the geomagnetic field) and magnetization (KENT and OPDYKE, 1977) and a possible effect of ice ages on the geomagnetic field (DOAKE, 1977).

Mechanisms that relate climate and other atmospheric parameters, *e.g.* ozone, radiocarbon, chemical oxides, atmospheric pressure, temperature (GNEVYSHEV and OL, 1971), may offer links between orbital parameters and climate via the magnetic field of the earth, in the sense that they might trigger larger changes in the atmosphere-hydrosphere-surface dynamics or synchronize terrestrial oscillators as proposed for instance by FLOHN (1974).

Empirical studies of physical relationships between magnetic intensity and climate (ABRAHAMSEN, 1989) are important for indicating appropriate lines of theoretical research. Although no proven theory links between climate and geomagnetism qualitative mechanisms have been presented, the geomagnetic poles may be viewed as flux tubes along which charged particles can propagate into lower regions of the atmosphere changing the strength and orientation of the (non-) dipole field which might then affect the quantity and geographic orientation of the ion corpuscular radiation (LEGRAND and SIMON, 1989). However it would be difficult to conceive of a mechanism that could link all local disturbances of the magnetic field to climate change, hence the lack of a valid statistical relationship found in several cases. While there are many suggested causes for climatic variability, we should note the apparently sound relationship of solar activity, as measured by sunspot numbers, and climate in the period 1650–1710 AD, when sunspots were at a minimum (the Maunder minimum) and Europe was under the "Little Ice Age" (LAMB, 1977).

Such relationships have also been indirectly approached in the investigations of possible common periodicities in the participated phenomena. Different methods of spectral analysis have been applied to short and long time-series of i) precipitation (CURRIE, 1987), precipitation and sunspot numbers (XANTHAKIS, 1975), ii) Aurorae and solar activity (LIRITZIS, 1989; XANTHAKIS *et al.*, 1985; FEYNMAN, 1983), iii) sunspot numbers (KANE and TRIVEDI, 1985; SCHOVE, 1983; ATTOLINI *et al.*, 1985; CASTAGNOLI, *et al.*, 1984a,b), iv) radiocarbon variations in the atmosphere (SONETT and SUESS, 1984; NEFTEL *et al.*, 1981), v) geomagnetic field variations (CURRIE, 1973; BARTON, 1988; CREER and TUCHOLKA, 1982; LIRITZIS, 1986; WANG DING-LI *et al.*, 1982) to mention a few, while particular symposia or volumes have devoted to this subject (SUN and CLIMATE, 1980; CHPP, 1987; WIGLEY, 1980 and references therein; PECKER and RUNCORN, 1990).

Recently, an Italian group led by Castagnoli claimed that they have found the solar activity cycles in the variations of thermoluminescent (TL) signal profiles in layers of marine sediment cores spanning the last 1,500 years. In particular, performing power spectrum analysis, significant periods were found at 11, 22, 50–90, 137 and approx. 200 years. In various papers the authors have presented their results, and from newer evidence certain periodicities (*e.g.* the 59, 137 and 10–12 years) are discussed in terms of possible relations with the fundamental cycles of solar activity.

Their conclusions (CASTAGNOLI *et al.*, 1988) state: "... even if the complete picture of the solar-terrestrial relations is still poorly understood, we find interesting that at least some aspects of the secular variations of the solar cycles can be simply reproduced by four waves whose periods, amplitudes and phases have been determined by the analysis of the TL profile of a sea sedimentary core."

Their results are worth a close inspection, even if one may pinpoint some limitations in the interpretation of their results concerning *e.g.* 1) the assumption of constant sedimentation between Pb-210 dated layers, 2) the relatively parsimonious resolution of the TL data (a sample thickness of D = 2.5 mm corresponds to constant time interval of 3.87 ± 0.04 years between successive data points) which makes the 10–12 year period doubtful and 3) the removal of a 160 year long term trend, thus unabling them to detect the 200 year period, though they have reported this and others in earlier publications (CASTAGNOLI *et al.*, 1984a,b; ATTOLINI *et al.*, 1985). Nevertheless, they have produced (accidentally) an interesting indication of sun-climate-ocean sedimentation relationship; at any rate they obtained similar periodicities between TL data profile and O-18 and Be-10, since the 11th century AD. They have attributed the TL variation to a variable atmospheric dust irradiation. In contrast, we assign the periodic variability in TL signal of sediments to a periodic variation of the natural radioactivity (uranium, thorium, potassium) in these sediments, the driving force being of solar origin via the climate. This rationale unfolds in the following discussion.

RELATIONSHIP BETWEEN CLIMATE AND RADIOACTIVITY IN SEDIMENTS

The denudation of landscapes depends upon weathering, erosion and the type of rocks. The agents of weathering are:

(1) Physical, which is brought about by two main processes; temperature change and crystallization and to a lesser effect the action of plant roots in the purely mechanical sense.

(2) Chemical, which involves a number of distinct processes such as hydration, oxidation, hydrolysis, carbonation, acidation.

(3) Biological, via flora, fauna, action of microorganism, action of plant roots.

The factors affecting the weathering are the mineralogical composition of rocks, their texture and structures, as well as, the effect of different climates. All these factors affect the rate and type of weathering (SPARKS, 1972). However, it is the climate specifically that affects the relative importance of the different types of weathering. Thus, generally speaking, it is said that physical weathering predominates in cold and dry regions and chemical weathering in humid climates, whether temperate or tropical.

For lakes such as Lake Bouchet (France) where the environments are comprised of sedimentary rocks, varied reactions occur during weathering. These sediments are comprised of coarse debris susceptible to chemical weathering, and of clays which are not susceptible to chemical weathering; the soluble products are carried off in solution. The lake sediments thus owe their origin to the deposition and compaction of any of these types. In general, weathering is a complex phenomenon involving a variety of processes and being influenced by a number of factors the most important, however, of which are lithological and climatic. Doubts and differences of opinion exist about the efficacy of the weathering process and any new light shed on this subject is certainly of considerable interest. The agents of transportation (*e.g.*, wind, water), of weathered debris are by themselves only capable of minute wearing action upon the rocks and hence the deposition of this particulate matter in the bottom of the lakes or oceans carries a climatic signature. (The erosion is limited in these cases unless the agents of transport are carrying a load of debris.)

During these weathering-transportation processes the natural radionuclides partition depends, by analogy, upon their trapped sites (minerals) and the geochemistry of the reactions (HANDBOOK OF GEOCHEMISTRY (HG), 1978; IVANOVICH and HARMON, 1982). Thus, uranium is readily oxidised to U^{+6} and combines with oxygen to form the uranil ion UO^{2+} which forms several soluble complexes (THURBER, 1964). Thorium (+4) ion because of its high ionic potential is quickly absorbed or precipitated as insoluble hydrolysates when brought into solution. That is why there is a strong depletion of thorium with respect to uranium in ground waters as a result of differential mobilization during weathering of terrestrial rocks. This is readily obvious when comparing the crustal U/Th = 1/4 and oceanic U/Th = 200/1 ratios (KOCZY, 1956). Once present in a marine environment, uranium in aqueous solution is subsequently coprecipitated with carbonate sediments, whereas thorium is incorporated into detrital oceanic sediments.

During weathering processes uranium may be fractionated, U-234 being enriched in ground waters with respect to its parent U-238. Uranium may be carried into the lake/ocean bottom in minerals as *e.g.* zircons. Thorium is carried by minerals too, and potassium follows the geochemistry of thorium in most rock types and is carried also by minerals *e.g.* feldspars. In warm periods potassium (K) contents are low which implies a limited degree of weathering, *i.e.*, stability in soil production which is related to dense vegetation. The K:U:Th ratios in various rock types have been studied by various authors (ADAMS *et al.*, 1959; QUINIF *et al.*, 1982; LIRITZIS, 1989).

VARIATION OF NATURAL RADIOACTIVITY IN LAKE SEDIMENTS

From the above notes, it is evident that several agents participate in the leaching/transport of radioisotope-bearing minerals/clays and their deposition to lake basin. The most prominent agent is climate (mainly rainfall, temperature, atmospheric circulation such as monsoon). For purely geochemical reasons the deposition of sedimentary layers involves a transfer each time of their radioisotopic content of a partitioning nature. Hence, their emitted energy in terms of absorbed dose (dose-rate) varies with depth in a proportional manner. This radioactivity change by depth is measured here, and refers to alpha and beta particle counting per successive layers.

It is relevant, here, to mention the work on periodicities revealed in organic carbon and uranium concentrations in a deep-sea core from the Santa Barbara basin off California. Preservation of annual varves in that anoxic environment has provided a record of the age of the sediment, there being one varve or distinct layer per year (KALIL, 1976 in LIBBY, 1987). Fourier transform revealed six periodicities in uranium and carbon variations in this marine core ranging between 50–160 years. The same periods were also found in stable isotopes of hydrogen and oxygen in tree-rings and in oxygen isotope variations in ice cores, reinforcing the interpretation of climate variations on a global scale and supporting the attribution of these periodicities to variations of the Sun causing changes in sea-surface temperatures.

Indeed, the sea-surface temperature determines the abundance of organic matter that falls to the ocean bottom and binds uranium ions in the seawater to it as it falls and accumulates; it is well known that in uranium ores the amount of organic carbon is proportional to the amount of uranium. Once the U and Th isotopes and their daughter products coexist with the sedimentary layer, they decay each with a characteristic half-life (t1/2), potassium being unaltered by time due to its high t1/2. In the U-series, the disequilibrium is located in the following decay steps: U-238 → U-234, U-234 → Th-230, Th-230 → Ra-226, Ra-226 → .... Therefore, the total activity varies with time towards radioactive equilibrium.

For the last around 15,000 years only, the Ra-226/U-238 disequilibrium affects the resulted dose-rate from the U-series alone; thereafter Th-230/U-234 becomes important in dose-rate evaluation. The Th-230 content has two components, one accompanied by the Th-232, *i.e.*, the unsupported, and the other one or the supported produced from the parent U-234. The Th-232 series with its short t1/2 daughters is almost always in equilibrium. However, in both U and Th series the gas daughter products (radon for U and thoron for Th) may cause disequilibrium if a considerable diffusion rate occurs in the sediment. The equilibrium for these gaseous products is restored within a couple of weeks for radon and in a few days for thoron. It is evident, therefore, that every sample must be checked to ascertain whether or not daughter nuclides, U-234, Th-230, Ra-226 and Rn-222 are in isotopic equilibrium.

Nearly all samples formed during the Quaternary exhibit some degree of disequilibrium at least with regards the U-234 and Th-230. Thus, the ratios U-234/U-238 and Th-230/U-234 must be known in order to calculate the present dose-rate. As a result, the TL signal in each layer has developed from a variable dose-rate during the lapse of time. For the last approximately 20,000 year period considered here, the variation of natural decay of the isotopes, compared to the variation of their parent content due to climatic changes, is not considered significant.

Having described the mechanisms which may cause periodic variations in natural radioactivity of lake/ocean sediments in general, we present preliminary results for Lake Bouchet (France), the Black Sea and the Aegean Sea sediments (LIRITZIS *et al.*, 1994; XANTHAKIS *et al.*, 1992).

THE DATA

The lake sediment core (B52) for Lake Bouchet, France, was 5.86 meters long which spanned the last 30 kyr and had been studied palaeomagnetically in a multidisciplinary research program (BONIFAY *et al.*, 1987; SMITH, 1985). Samples were obtained in plastic cubes of 2 cm side, which had been measured before by a magnetometer, taken in steps of approximately 2.5 cm.

Lake Bouchet is contained in a volcanic structure of the "maar" type (explosion crater of phreatomagmatic origin) the detrital sediment mineral consisting of weathered/

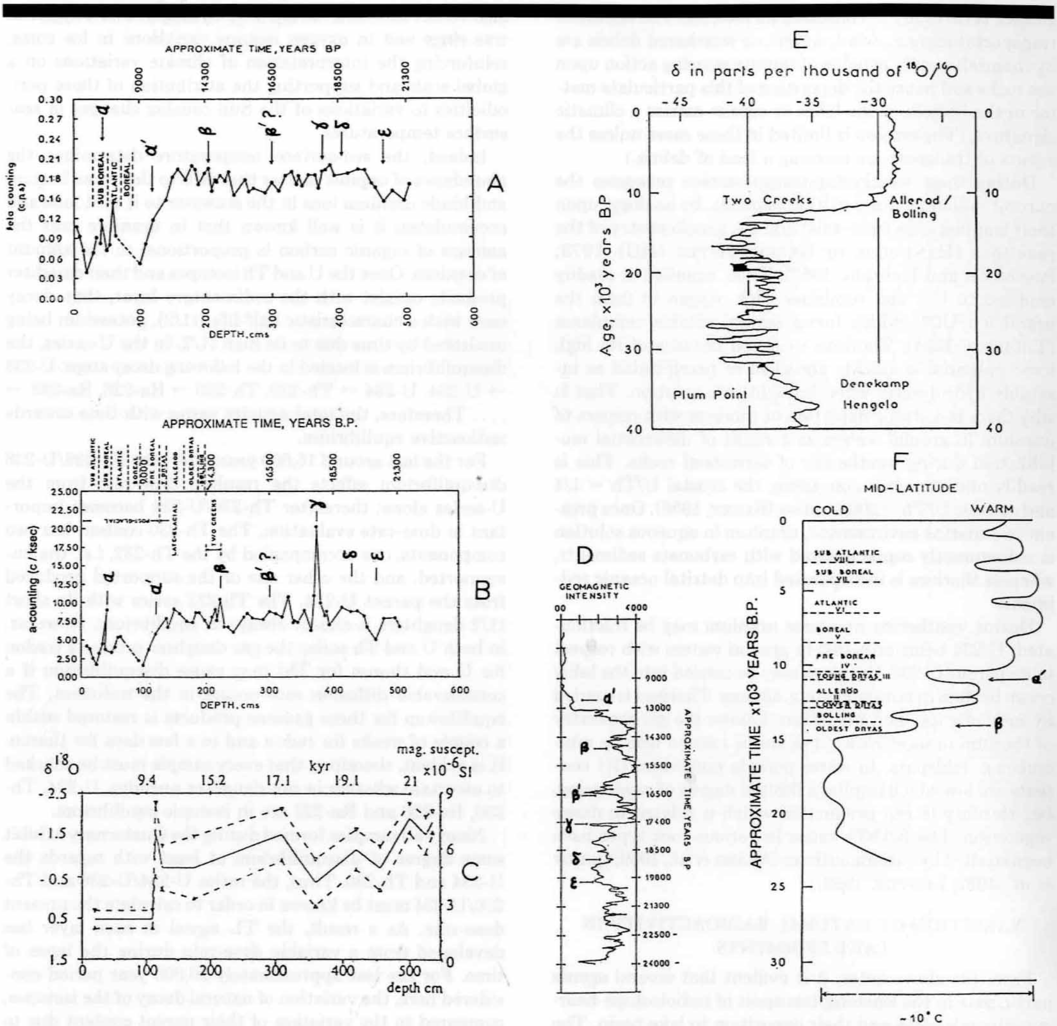

Figure 1. Lake Bouchet data. (A) Beta counting rate dependence on depth-time in core. The Greek letters indicate important changes in the counting rate possibly due to certain climatic phases. (B) Alpha counting rate dependence on depth-time in core. (C) Magnetic susceptibility (Creer *et al.*, 1990), the trend is shown by the line without points, whereas the broken lines indicate the range of the associated Gaussian standard errors. (D) Palaeointensity log of sediment core No.B52D and approximate time (years BP). (E) Average temperatures inferred from ‰^{18}O variations over the last 10 kyr from ice cores, Camp Century northern Greenland. (F) Generalised temperature changes in middle latitudes of the northern hemisphere from tree-line studies during the last 10 kyr.

eroded/basalt flows and scoracious material. The rate of deposition of the mineral phase in the Bouchet sediments were extremely low, from about 0.25 to 0.33 mm/yr, in the lower parts of the core which were deposited in a cold climate, falling to 0.05 to 0.07 mm/yr in the upper (Holocene) levels (Truze and Bonifay, 1984). Similar rates were deduced during the interpolation between the time markers, in the conversion of depth-to-time scale, in our attempt to date the respective measured samples.

The Black Sea samples were derived from two cores. Eleven samples in cubes of 2 cm side come from Borehole-3, Aprelefskaplost (13–23 kyr time span) and thirteen samples from borehole A-34 (12–17 kyr time span). Both cores were extensively studied lithostratigraphically and palaeomagnetically (Kalcheva *et al.*, 1990; Bozhilova *et al.*, 1989).

The approximate depth-to-time conversion was made through time markers determined by C-14 and from comparison with the archaeomagnetic curve from Bulgaria. Sedimentation rate for B-3 is ~1 mm/yr (three times higher than Bouchet) and for A-34 is ~0.08–0.1 mm/yr.

Several Aegean sediment cores are still under study. Two of them (AEG-3 and T-21) are preliminarily presented here for first time, as an additional proof to show the anticipated variation in alpha radioactivity due to palaeoclimate, which strengthens our proposed causal mechanism of commensurable solar activity-palaeoclimate and sediment radioactivity variation.

THE RADIOACTIVITY MEASUREMENTS

Low-level counting of alpha and beta particles was carried out. Total alpha counting was made by a ZnS (Ag) scintillator and beta counting by an NE102A plastic scintillator (LIRITZIS and GALLOWAY, 1982; GALLOWAY and LIRITZIS, 1991). The counting times ranged for alpha counting between 10–60 ksec and for beta counting between 10–30 ksec. The standard deviation was about ±5% for alpha and ±2% for beta counting statistics. The alpha counters were calibrated on standard radioactive powders. The beta counting referred to the integration of the beta particles pulse height spectrum above 116 kev, which was found to be the operating point, an isotopic and effective-Z independence condition (GALLOWAY and LIRITZIS, 1991). Repeated measurements did not reveal any significant radon emanation problem. The alpha and beta counting rates are plotted against time-depth and compared with palaeomagnetic intensity (I, as natural remanent magnetization, NRM) and magnetic susceptibility variations, a generalised temperature variation diagram from tree rings (LA MARCHE, 1974), as well as an O-18 ice-core temperature diagram (DANSGAARD *et al.*, 1971).

Figure 1 (1-F) show the relevant curves for Bouchet data, Figure 2 (A–D) for Black Sea and Figure 3 (A,B) for the Aegean Sea.

DISCUSSION OF THE RESULTS

The Lake Bouchet Data (Figure 1)

There is, in general, a parallel pattern between alpha, beta and (I) logs. The two curves of alpha and beta counting are similar to each other apart from the one point at 375 cm depth where there is a particularly high alpha counting rate. With this exception, both curves show a generally lower counting rate down to a depth of 100 cm (early Holocene), below which within 50 cm the count rate doubles with rather smaller fluctuations in the lower part of the core. That there should be a similarity between the two curves is not surprising, as decays within the U-238 and Th-232 series contribute to both, whereas the beta curve also records the presence of K-40. We identify certain features with Greek letters; α, α', β, β', γ, δ and ϵ, attributed to certain climatic episodes.

(α) Feature. Within the Holocene, though the data points are sparse, certain changes are highlighted in both alpha and beta logs, which seems to correlate with the Sub-Boreal period (~3–4.5 kyr BP; warm, but cooler drier climate), the Atlantic (~4.5–6.5 kyr BP; warm, wet) and Boreal (6.5–8.5 kyr BP; drier, mild, wet).

(α') Feature. This is identified with the Pre-Boreal/Young Dryas period (~8.5–11 kyr BP; cool/wet to cold/drier), or the onset of Postglacial period.

(β) Feature. This is identified with the Two Creeks ice-advance in North America and Oldest Dryas of Europe (~14–15 kry BP).

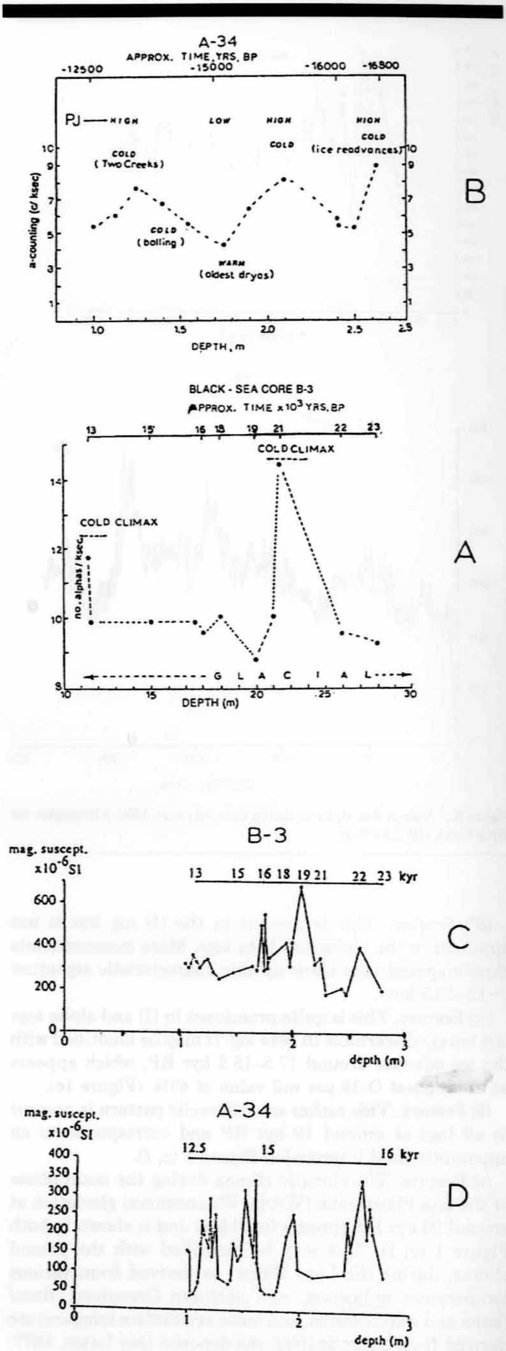

Figure 2. Black Sea data. (A) Borehole 3, alpha counting rate dependence on depth-time in core. (B) Borehole A-34, alpha counting rate dependence on depth-time in core. (C) magnetic susceptibility for B-3 (BOZHILOVA *et al.*, 1989). (D) magnetic susceptibility for A-34 (KALCHEVA *et al.*, 1990).

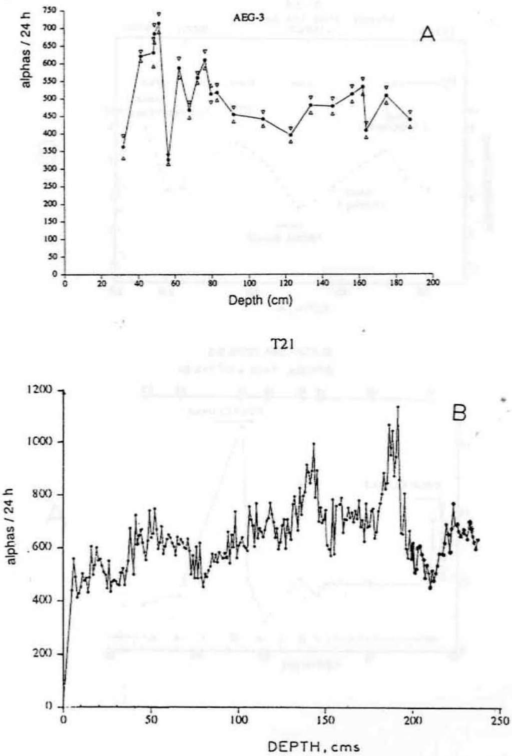

Figure 3. Aegean Sea alpha counting data. (A) core AEG-3 (triangles are error bars). (B) core T-21.

(**β'**) **Feature.** This is present in the (I) log but is not apparent in the alpha and beta logs. More measurements closely spaced may show up this characteristic signature (~15–16.5 kyr).

(**γ**) **Feature.** This is quite prominent in (I) and alpha logs but barely discernible in beta log. It may be identified with the ice advance around 17.5–18.5 kyr BP, which appears as the highest O-18 per mil value of 43% (Figure 1e).

(**δ**) **Feature.** This rather smooth cyclic pattern is present in all logs at around 19 kyr BP and corresponds to an apparently mild interstadial Figure 1 (e, f).

(**ϵ**) **Feature.** The climatic climax during the main phase of the late Pleistocene (Würm, Wisconsinan) glaciation at around 20 kyr BP appears in all logs and is shown in both Figure 1 (e, f). This may be identified with the second climax, during the Late Würm, as derived from various temperature indicators, *e.g.*, northern Greenland, flora/fauna and soil mollusca, and mean sea surface temperature derived from Atlantic deep-sea deposits (see LAMB, 1977, pp. 89–103, 323–386).

These interesting preliminary results seem to strengthen the initial hypothesis that measurements of the varying amounts of natural radioisotopes with depth in a sediment, reflect the influence of climatic history and yield evidence independent of any other. The alpha radioactivity derives from the Uranium and Thorium series alone, while the beta radioactivity comes from K-40 as well. K-40 is the prominent beta emitter and on average accounts for 60–70% of the total beta dose-rate. It is associated with the feldspathic minerals (alkali group) especially the potash-feldspar. The beta-radioactivity is not so susceptible to climatic changes which may imply the insensibility of potassium forming minerals to such changes.

The clay minerals with a dominance of illite and chlorite in the lower levels consist of primary minerals derived from decomposition of the surrounded basalt, under the influence of a cold climate. It is well known that the land-derived material increases when the climate gets colder (frost action and loss of vegetation). During glacial and early post-glacial times their high mineral proportion indicates vigorous erosion of the loose glacial debris in the drainage basins and particularly rapid extraction of the soluble salts of the base-rich soils. Decreased concentration of Na and K occurs in postglacial warm times which clearly points to minimum erosion and soil stability associated with the dense vegetation. This pattern is obtained here from the beta counting variations which derive mainly from potassium content presence. Similarly, calcium is particularly readily dissolved from rock matter and it is only deposited in high concentrations during times of accelerated erosion. As calcium correlates with uranium content, it can explain both the lower/higher alpha radioactivity in postglacial/glacial periods respectively.

Thus, the final partitioning of K:U:Th depends upon progressive leaching of the soils of wet upland regions of a drainage basin, the potassium being in a close association with Th in a variety of rocks. In general, in the sediments of Lake Bouchet, quartz is dominant, with feldspar, microscoria and fragments of volcanic glass, olivine and micas also abundant in variable proportions. The proportions, however, of the diverse constituents seem to be very variable from layer to layer.

Accordingly, the relatively low radioactivity in the sediments complies with the low U, Th, K in basalts. In fact, basalt from the lake shore gave 0.146 cps for beta and 4.92 alphas/ksec for alpha, both values falling in the middle of those in glacial and postglacial times respectively, implying proportional weathering/erosion/dilution of radioisotope bearing minerals due to various climatic agents.

Relationship Between Climate and Magnetism

From Figures 1, 2 the following pattern emerges: high sediment radioactivity corresponds to high susceptibility (and palaeointensity), which reflects cold climate.

The relationship between climate and magnetism is primarily reflected in the magnetic susceptibility of sediments, but for the palaeointensity this is debatable. The mechanism whereby climate causes either high or low palaeointensity values (DOAKE, 1977; ABRAHAMSEN, 1989) for lake and marine sediments may be as follows (XANTHAKIS and LIRITZIS, 1991): theoretically, one may argue that during glacial times the water column is of higher density (n) than in interglacial times so that the depositional velocity (v) is lower (v = A/n, A is grain and fluid constants) and time of deposition (t) is long. This time increase favors easier alignment of magnetic grain dipoles to the ambient geomagnetic field. Thus, the product (magnetic moment × number of grains) will be large, with a resultant high intensity of magnetization.

Experimental evidence has shown, however, that the time taken for grains to sink to the bottom of the water column is not important. All authors agree that alignment is virtually instantaneous. What is important is post-depositional disalignment, if the grains settle on the bottom and roll over, especially if the grains are platelets or ellipsoidal (detrital or depositional remanent magnetization). In deposited sediment, however, magnetic grains are still able to realign themselves in the pore spaces of the non-magnetic matrix (clay, sand and silt) while the interstitial water content remains high. As more sediment is deposited on top, the water content is reduced. At about 20 cm depth, equivalent to about 70% water content, the magnetization is frozen-in (post-depositional remanent magnetization).

The NRM is generally higher during glacial epochs though not invariably true, but in lake sediments it does seem to be the case. In the latter it is thought to be due to differences between the characteristics of sediment deposited in warm climates, where there is much more vegetation and therefore reduced runoff after rainstorms, and sediment deposited in cold climates with steppe-like conditions of little vegetation and fast erosion. In this way, Holocene sediments contain much organic material and little detritus. Hence NRM and susceptibility are lower than in glacial sediments, at least in lakes. But it may be noted that in loess deposits susceptibility is higher in soil (warm climate) than in sediment deposited in cold times, over the past few hundred thousand years (KUKLA *et al.*, 1988); this may be due to the total aridity of loess (dust) deposition, in contrast to the geochemical mobilization during the soil-forming interstadials.

Climatic Cycles from Lake Bouchet Sediment Radioactivity

Spectral analysis with the "successive approximations" method (XANTHAKIS *et al.*, 1992) has been applied to the Bouchet radioactivity data of Figures 1a and b. Several whole or quasiperiodicities were located in different time intervals; for the alpha counting the periods obtained are: 1,000–1,200, 2,000, 6,000 and 24,000 years, and for the beta counting the periods obtained are: 1,000, 3,000, 4,000, 8,000 and 24,000 years.

The non-stationary nature of the periods are believed to be related to palaeoclimatic fluctuations and other solar-terrestrial agents. The higher term in the expansion of precession of equinoxes is the 24 kyr fundamental period, the length of our record. This fundamental period of 24 kyr and the quasi-periods between 0.4–8 kyr in both radioactivity logs of the Lake Bouchet sediments reflect palaeoclimatic and probably palaeosolar activity variation. The rationale for this inference is the mechanism which reflects the solar output-atmosphere (climate)-sedimentation continuum, as described in sections, 2, 3, 4 above. That is, solar activity (solar wind, flares, magnetic field) causes atmospheric and climatic disturbances (clouds, precipitation, temperature variation, monsoon, glacials/interglacials) which in turn cause weathering (erosion, diagenesis) on surface rocks and the surficial geomorphological mosaic of a region, which subsequently cause proportional transportation of radioisotopes (in minerals) in the deep parts of the ocean or lake (LIRITZIS *et al.*, 1994; XANTHAKIS *et al.*, 1992). Consequently, the measured radiation dose per sedimentary stratum is expected to vary in proportion to palaeoclimatic and palaeosolar activity.

Other (quasi-) periodicities have been found in other solar-terrestrial phenomena and are summarised in Table 1. The many periodicities found in common with those of several solar-terrestrial phenomena (*e.g.*, sunspot numbers, C-14, geomagnetic intensity, tree rings, Be-10 and O-18 in polar ice, and even thermoluminescent signal in ocean sediments) may help to develop an interpretation for the possible causes of climatic change; here we consider mainly the potential impact of a past and present variable sun, which exhibits both long (> 1,000 years) and short-term periodicities. However, the apparently interlocking network of periodicities, found here and elsewhere, reinforces the impression of a complicated behaviour of dynamics in the orbital, or pulsed forcing in the solar-planetary system, the observed modulation being a secondary product of self-organization of the Earth's response.

The Black Sea Data (Figure 2)

Similar results were obtained for the alpha counting of the two Black Sea cores, while there is some similarity between the variations in radioactivity with depth and the magnetic susceptibility variations. Unfortunately, neither set of samples encompasses the end of glaciation, which was the most clearly discernible feature of the Lake Bouchet data.

The Aegean Sea Data (Figure 3)

Regarding the two Aegean Sea cores, from data at present available, a similar pattern is obtained; short term fluctuations are superimposed on a longer term variation, which reflects palaeoclimatic variation. At a first glance, we observe cycles of every ~25 cm sediment thickness for both data sets.

CONCLUSION

Our results obtained so far indicate that certain variations in natural radioactivity seem, in general, to correspond to coincident climatic changes and palaeomagnetic features in respective sediment core depths, which provides evidence for earth-climate links. Also, they seem to follow a periodic variation with commensurable cycles in several other solar-terrestrial phenomena. Thus, the sediment radioactivity data records can be used as another proxy climatic data tool. Moreover, such curves offer a swift and accurate chronostratigraphic reference system for lake and marine geology/geophysics/palaeoclimatology studies.

It would be interesting eventually to use such radioactivity changes, especially for the alpha counting, as a normalization factor in the magnetic susceptibility or NRM values (removal of climatic factor), while their ratio with the susceptibility should, ideally, provide a "plateau" (susceptibility/radioactivity plateau test).

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