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Palaeomagnetic Secular Variation Curves Extending Back to 13,400 years B.P. Recorded by Sediments Deposited in Lac de Joux, Switzerland

Comparison with U.K. Records

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Abstract. Palaeosecular variation records have been obtained from three cores from Lac de Joux, Switzerland (46°37′N, 6°16′E) on which a parallel biostratigraphy has been constructed. All three cores show a well developed Late-glacial sequence which extends to beyond 13,400 years B.P. and the recorded palaeomagnetic declination and inclination variations can be correlated between these cores. The longer core (no. 3) also shows a well developed Post-glacial sequence and the declination and inclination records can be correlated in detail with the independently dated United Kingdom records which extend back to about 10,000 years B.P. Ages along Lac de Joux core 3, obtained by palaeomagnetic correlation with U.K. cores, are compared with ages based on the local palynology and thus a timescale has been attached to the Lac de Joux record back to beyond 13,400 years B.P. during which time there is no evidence of any geomagnetic excursion or short event.

Key words: European geomagnetic secular variation – Lake sediments – Palaeomagnetism – Palynology.

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1. Introduction

In the summer of 1975 several lakes in the region of the Alps were cored as part of a research project to investigate the behaviour of the geomagnetic field through the Holocene. The field work was carried out by a team from the Department of Geophysics, University of Edinburgh, and from the Department of Mineralogy, University of Geneva. This paper deals with results obtained from Lac de Joux.

Lac de Joux is situated just to the north of Lake Geneva at an altitude of 1,014 m and lies between latitudes of 46°41′N and 46°38′N and longitudes 6°17′E and 6°20′E. A map of the lake, which has only two small rivers flowing into it, is shown in Fig. 1. Four cores were taken using a pneumatically controlled Mackereth corer (Mackereth 1958). The bottom sediments were very hard and the longest core (no. 3) was 5.5 m long but the average length was only 4 m due to the hardness of the sediment penetrated.

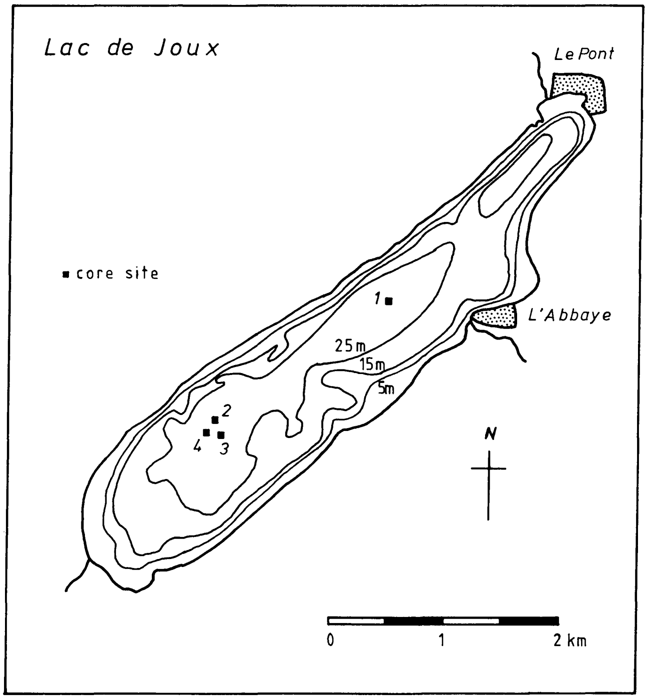

Fig. 1. Sketch map of Lac de Joux (46.6° N, 6.3° E) showing coring sites. Contours show water depths in the lake

The cores were transported to Edinburgh for study. They were split in half lengthwise and samples were withdrawn for palaeomagnetic study in square shaped polystyrene boxes of side 17 mm, at about 2 cm intervals, from one of the halves of each core. The other halves were sent to Geneva for palynological study.

2. Pollen Studies

Pollen analyses were carried out in the limnogeological laboratory of the University of Geneva and supported financially by the

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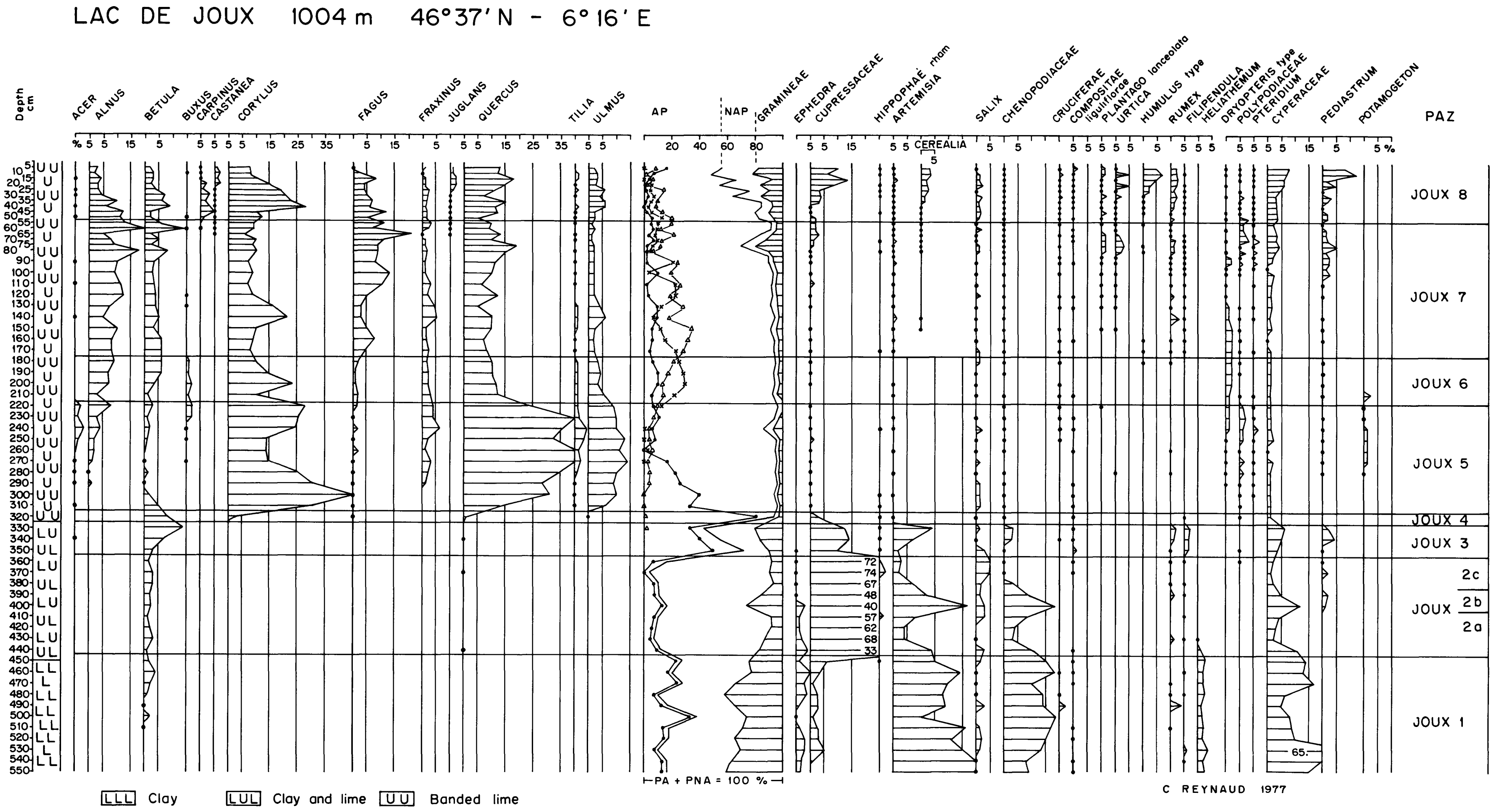

Fig. 2. Pollen diagrams for Lac de Joux core 3 presenting the most important taxa. The biozones Joux 1–Joux 8 are described in Sect. 2.1. *AP* = arboreal pollen; *NAP* = non-arboreal pollen

'Fonds national de la Récherche scientifique' (Switzerland). Laboratory treatment followed the recommendation of Faegri and Iversen (1964). One cm^3 of fresh sediment was treated with concentrated HCl and 40% HF and an acetolysis was performed on the Post-glacial sediments with rich organic content. In core no. 3, the sediments analysed consisted of clay up to 450 cm, of clay and calcaereous mud up to 325 cm and of banded lime in the upper part of the core which, in total, was 550 cm long. The results are presented (Fig. 2) in the form of conventional relative pollen diagrams in which the total pollen arboreal (AP) plus non-arboreal (NAP) = 100%. Cyperaceae, spores, and other microfossils have been excluded from the NAP and expressed as percentages of the pollen sum.

2.1. *Local Biozone Descriptions (Fig. 2)*

Joux 1: Herbs Zone, 550–445 cm. The relative AP values are very low: less than 30% of the pollen sum. Among the herbs the dominating taxa are Gramineae, *Artemisia*, Chenopodiaceae, *Helianthemum*, *Thalictrum*, and *Plantago alpina*. Shrubs are also present with *Ephedra*, *Salix* and *Juniperus*, each being less than 5%.

Joux 2a: Juniperus Zone, Juniperus Sub-zone, 445–405 cm. The AP values are still low and are represented as in Joux 1 by pine (20%) and birch (5%). *Juniperus* dominates all the other taxa with high values: between 33 and 74%. A few *Hippophaë rhamnoides* are also present.

Joux 2b: Juniperus Zone, Juniper-Herbs Sub-zone, 405–385 cm. Juniper values are lowered to less than 50% and there is a sudden increase of steppic elements such as *Artemisia* and Chenopodiaceae.

Joux 2c: Juniperus Zone, Juniper-Pine Sub-zone, 385–355 cm. Juniper first and then pine increase again. The AP values are much higher, up to 70% of the total pollen sum.

Joux 3: Pine-Herbs Zone, 355–325 cm. The sudden relative increase of pine (to 50%) is depressed by the rising values of the herbs: Gramineae, *Artemisia*, Chenopodiaceae, *Helianthemum*, *thalictrum*, and *Plantago alpina*. In the level 340 cm many spores of fungi were found.

Joux 4: Pine-Birch Zone, 325–315 cm. All the herbs are depressed to values of less than 5%. Birch and pine (80%) are the main components of the AP curve.

Joux 5: Oak-Hazel-Elm Zone, 315–215 cm. The thermophilous trees appear suddenly and are dominated by oak. Pine decreases to less than 10%.

Joux 6: Fir-Spruce Zone, 215–175 cm. Spruce present in the former biozone increases gently but fir dominates while oak and elm register a corresponding decline. Low percentages of beech (1%–3%) are present.

Joux 7: Spruce-Fir-Beech Zone, 175–55 cm. Fir decreases while spruce and beech are the dominating species. Among the components of the *Quercetum mixtum* only oak and hazel are important.

Joux 8: Spruce-Oak-Herbs Zone, 55–5 cm. The total AP shows a decline while herbs and juniper increase to 40%. In this biozone consistent amounts of common walnut, hornbeams, chestnut, and cerealia are present.

2.2. *Discussion*

According to Wegmüller (1966) the pollen stratigraphy throughout the southeastern part of the Jura mountains starts with a Late Würmian herbs zone (Fig. 3). It is followed by a shrubs zone dominated by *Juniperus* with some *Hippophaë rhamnoides* present. It suggests a treeless landscape although some immigrating and isolated birches might have been present close to the area investigated.

Later on, about 12,300 years B.P., park-forest invaded the Jura and this is clearly indicated by the birch zone. Birch was then replaced by pine and it is in the sediments bearing pine pollen assemblage that ashes emitted by the Laacher Volcano are found; it is dated at 10,980 years B.P. (Wegmüller and Welten 1973).

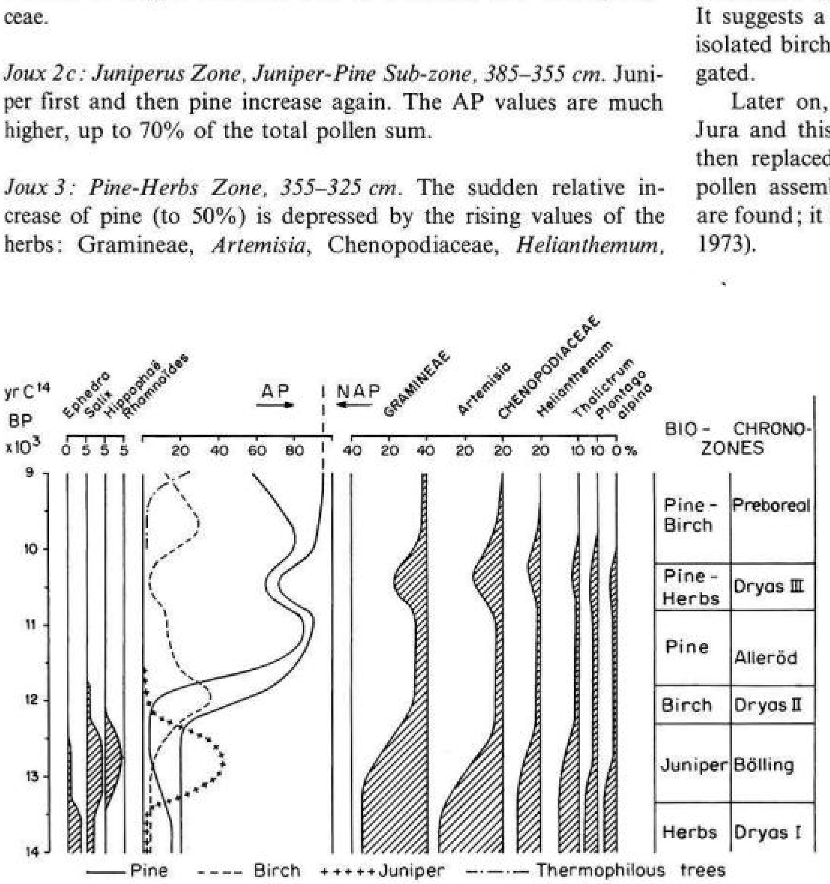

Fig. 3. Schematic diagram for the Late-glacial biostratigraphy in the Jura mountains

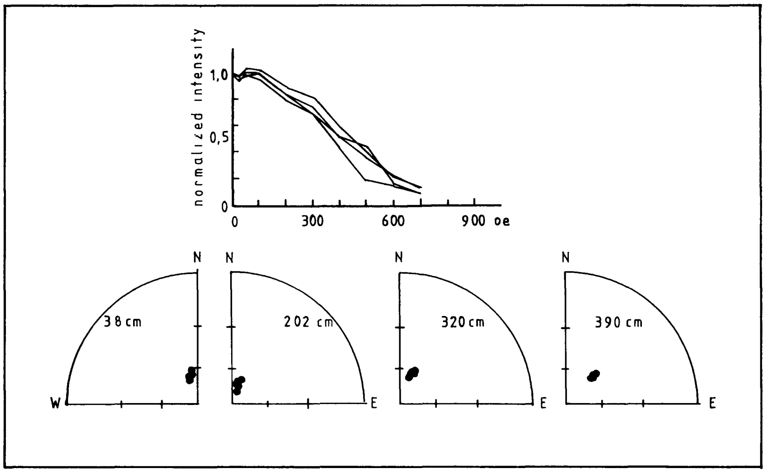

Fig. 4. Alternating field demagnetization plots of pilot samples from core 3. Depths of samples in cm from the top of the core are indicated

At about 10,800 years B.P., herbs increase at the expense of pine and this is interpreted as a climatic deterioration during youngest Dryas (DR III). The Late Würmian/Early Flandrian transition can be distinguished by the re-advance of pine and birch forest and the appearance of thermophilous trees.

The schematic pollen diagram in Fig. 3 is based on the results of Wegmüller (1966) from the Cruilles bog (1,035 m) situated alongside Lac de Joux and on the pollen investigations of Matthey (1971) in the central part of the Juras. When the Würmian Late-glacial sequence of Lac de Joux is compared with Fig. 3 it is clear that both birch and pine zones, ascribed classically to the Older-Dryas-Alleröd complex, are missing in the Lac de Joux core 4.

There is also a hiatus in the biostratigraphy at around 330 cm marked by a very short flip in the pine curve and the sudden appearance of the thermophilous pollen. This may be linked to the rather complicated process of ice retreat in the Joux valley as described by Aubert (1937). This gap in the sedimentation possibly represents a time span of about 1,000 years.

The Post-glacial vegetational development in the Joux valley described above is in agreement with the results of Wegmüller (1966). After a short appearance of the mixed oak forest close to the site, spruce and fir developed around the lake. Land clearance partly destroyed the natural forest (from 75 cm upwards) and this can be dated to the Bronze Age. The progressive thinning of the forest is marked by the relative increase of both herbs and juniper pollen and the abundance of *Cerealia* pollen.

3. Palaeomagnetic Results

3.1 Method

Natural remanent magnetizations (NRM) were measured with a Digico fluxgate magnetometer (Molyneux 1971) and susceptibilities were measured with a Digico bridge. First, pilot samples were progressively demagnetized in alternating magnetic fields (Creer 1958, 1959). Demagnetization characteristics are illustrated for four typical samples in Fig. 4 which shows that a weak viscous component was removed during the first two demagnetization steps of 30 and 60 Oe. The directions of RM of all pilot samples showed very little change on cleaning in alternating fields of up to 700 Oe (peak) and the median destructive field was typically between 400 and 450 Oe. The viscous component could alternatively be removed by storage in zero field for several months, and this procedure was adopted before measuring the NRM of the samples withdrawn from the cores.

3.2. Susceptibility and NRM Intensities Along Core No. 3

The palaeomagnetic logs are shown in Fig. 5. We discuss first the intensity and susceptibility logs. Susceptibility shows an overall correlation with the colour of the mud. Lowest values (< 5 μG/Oe) are encountered in a white Post-glacial mud between 2 m and 3 m depth most of which has been placed in the Joux 5 pollen zone (Sect. 2) Susceptibilities lie mainly in the range 5–10 μG/Oe and attain maximum values in the Joux 4 pollen zone part of the brown mud, i.e., at the base of the Post-glacial. The lower part of this brown mud unit is Late-glacial (Joux 3 pollen zone). There is a sharp discontinuity in susceptibility and an even greater one in intensity at the Post-glacial/Late-glacial boundary (Joux 4/Joux 3).

The shapes of the intensity and susceptibility logs are similar through the cream Late-glacial clay where the Q-ratios (intensity/susceptibility) are low, of the order of unity, but through the Post-glacial sediments where the Q-ratios are high, the shapes of the logs are quite different. In fact, in the banded lime of the Joux 5 pollen zone, Q-ratios attain values of 20–50 suggesting that the magnetic fraction of the detrital grains must have been rather more efficiently aligned than in most lake sediments we have previously studied.

3.3. Directional Variations Along Core No. 3

The declination log recovered from the Post-glacial sediments show several oscillations of about 15° amplitude. In the Late-glacial sediments the oscillations are of larger amplitude and are systematically displaced to the east relative to the Post-glacial ones.

The inclination log, below about 160 cm depth is characterized by four pronounced features, rounded on the high inclination sides with cusps on the low inclination sides. The top part of the inclination log shows less regular variations. In particular, low values between about 90 and 105 cm in the middle of feature ε, separating it into two smaller maxima, labelled $\varepsilon 1$ and $\varepsilon 3$, are

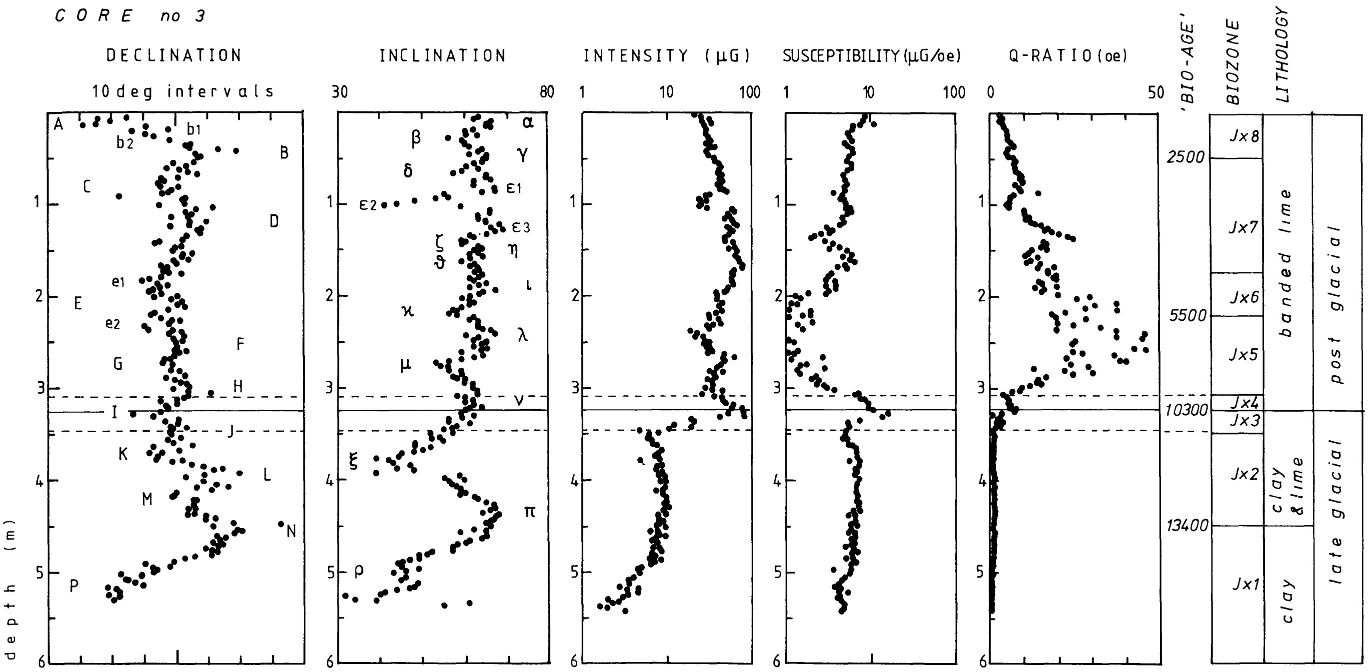

Fig. 5. Declination (D), inclination (I), remanence intensity (J), susceptibility (k) and Q ratio (J/K) logs for core 3, Lac de Joux. Units of J are μG, of k, μG/Oe and of Q, Oe. Declination and inclination features are labelled A–P and α–ρ respectively. Lithological and biozone boundaries shown at right of figure. *Solid line* running across plots represents Post-glacial/Late-glacial boundary. *Broken lines* represent upper limit of Joux 4 and lower limit of Joux 3 biozones respectively

accompanied by low intensities of NRM. One possible explanation is that the sediments at this level have been physically disturbed causing partial disorientation of the magnetic grains since corresponding susceptibility values are similar to those measured just above and below. However, the declinations accompanying the scattered low inclinations are not themselves particularly scattered as they should be if the sediment had in fact been disturbed so that the band of low inclinations recorded in the sediment could possibly reflect low geomagnetic inclinations.

Both logs can be correlated well with United Kingdom (U.K.) palaeomagnetic declination and inclination logs from Lake Windermere (Mackereth 1971; Creer et al. 1972; Thompson and Turner 1979) and with similar, though shorter logs from Poland (Creer et al. 1979). The labels attached to the logs (Fig. 5) illustrate this correlation: the declination labels are the same as previously used for the U.K. logs (Creer et al. 1976b, 1979), and the inclination labels are the same as used for the U.K. logs (Thompson and Turner 1979) and for the Polish logs (Creer et al. 1979). The Lac de Joux record from core 3 extends the European secular variation records by some 3,500 years into the Late-glacial.

3.4. *Results from Core No. 4*

Palynological studies on the samples taken along this rather short core (3.25 m) showed the Late-glacial/Post-glacial boundary to be at 1.5 m depth. The Late-glacial unit consisted of cream clay and carbonate. The Post-glacial deposits consisted of pale grey clay with some varve like stratifications, with carbonate above 1.25 m. The uppermost 12 cm consisted of brown clay carbonate with organic matter.

The palaeomagnetic logs are shown in Fig. 6. The top of the Late-glacial unit is marked by a sharp increase in intensity and by a marked increase in Q-ratio as in core no. 3.

Turning now to the directional logs, starting from the Post-glacial/Late-glacial boundary as marker horizon we can identify in core 4 (Fig. 6) declination features *H–N* and inclination features ν–π which were seen in the logs from core 3. Directions are only poorly recorded in the Post-glacial unit which seems to be rather thin and disturbed at this coring site.

3.5. *Results from Core No. 2*

Palynological study of seven samples from this 3.3 m long core show that it consists of a very well developed Late-glacial sequence of cream carbonate and clay overlain by a very short (27 cm) Post-glacial unit consisting of light yellow carbonate-clay, yellow-banded lime and brown clay-carbonate with organic matter.

The declination and inclination records carried by core 2 (Fig. 7) are not so well defined as for cores 3 and 4, particularly so between about 50 and 120 cm depth. Even so, a correlation can be made with cores 3 and 4 and we conclude that core 2 has penetrated into slightly older Late-glacial clay than either of the other two cores, additional features *P* (declination) and σ (inclination) being observed.

4. Comparison of Swiss and U.K. Records

Second generation lake sediment records from U.K. (Thompson and Turner 1979) show finer detail than the original records from Lake Windermere (Mackereth 1971; Creer et al. 1972). They have

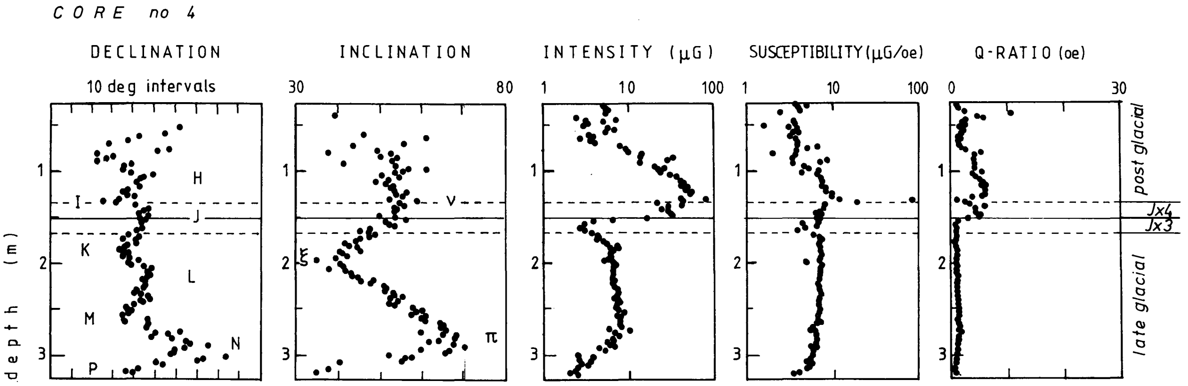

Fig. 6. Palaeomagnetic logs for Lac de Joux core 4. Declination and inclination features are labelled as for core 3. *Solid line* across plots represents Late-glacial/Post-glacial boundary. Jx3 and Jx4 represent biozones

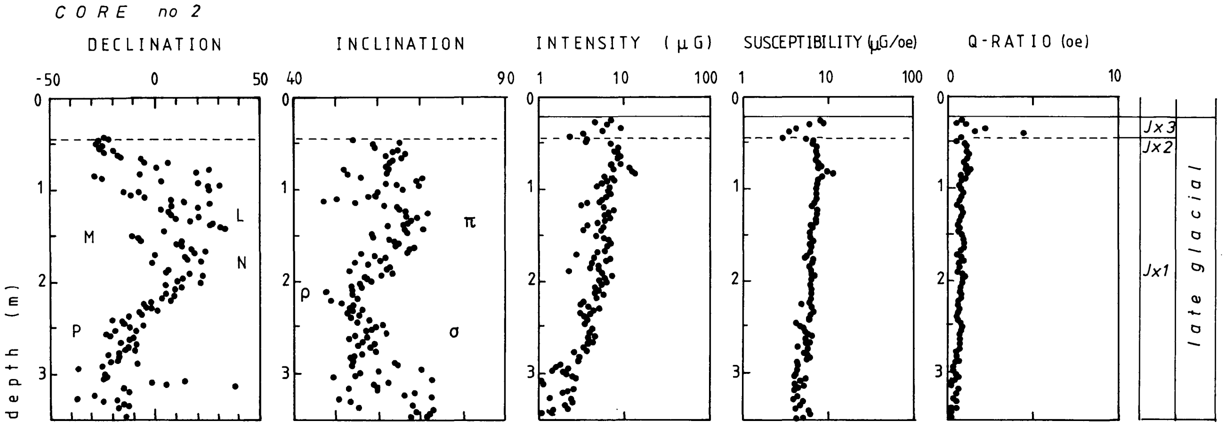

Fig. 7. Palaeomagnetic logs for core 2 Lac de Joux which mainly covers the Late-glacial. Declination and inclination features are labelled as for core 3. *Solid line* across plots represents Late-glacial/Post-glacial boundary. Jx1, Jx2, and Jx3 represent biozones

been dated by radiocarbon and have thus been shown to extend back for 10 millenia (Lake Windermere, NE England) and for 7 millenia (Loch Lomond, Scotland and Lake Geirionydd, Wales). Practical use of palaeomagnetic declination and inclination variation curves for regional age correlation is limited by variations in amplitude and detail of shape of the individual features as recorded from place to place caused by the somewhat imperfect natural magnetic recording process and by spacial variations in the temporal behaviour of the geomagnetic field. Thus we should not necessarily expect to find such good correlation between the Lac de Joux and the U.K. lakes as is observed between the U.K. lakes themselves.

We now compare the Lac de Joux record from core 3 with the record from a Lake Windermere core supplied by Dr. Turner. As noted in Sect. 3.3, most of the features shown by the Lake Windermere records can be identified in the Lac de Joux records. To illustrate the correlation better, the Lac de Joux and Lake Windermere inclination and declination records have been plotted against time rather than sediment depth in Fig. 8a and b respectively in which the time scale is based on the ages determined by Turner (1979) for the U.K. inclination features. This assumes that the geomagnetic variations occurred synchronously in the U.K. and Switzerland. In this respect, we note that westward drift at the historically observed rate of about 0.2 Oe/yr would cause a phase lag between Switzerland and U.K. of only about 30 years which is negligible compared with the precision of absolute dating.

We now compare these 'magnetic' ages, obtained for Lac de Joux core 3, with the independent set of ages based on the observed depths and published dates of biozone boundaries for the Joux Valley. The latter are illustrated in Fig. 9 by a time-depth plot consisting of five straight line portions, together with a dashed line taking account of the suspected hiatus of about 1,000 years at 330 cm depth (Sect. 2.2).

We note that there is some discrepancy between 'magnetic' and 'pollen' ages through the upper 2 m of core comprising the Joux 6, 7, and 8 biozones. While the 'magnetic' ages of the declination and inclination features indicate a steady rate of deposition of about 0.39 mm/yr throughout the whole of the last 5,500 years, the ages of 2,500 years B.P. attached to the Joux 7/8 biozone boundary implies a more rapid depositon rate of about 0.53 mm/yr through the Joux 6 and 7 biozones and a slower rate of about 0.22 mm/yr through the Joux 8 biozone. The ages of the younger declination (*A* and *B*) and inclination (α, β, γ and δ) features are controlled by observatory or archaeological data and therefore are more secure than the ages of the older features which are controlled by radiocarbon and are hence, in the case of lake sediments, subject to systematic error. However, contamination by

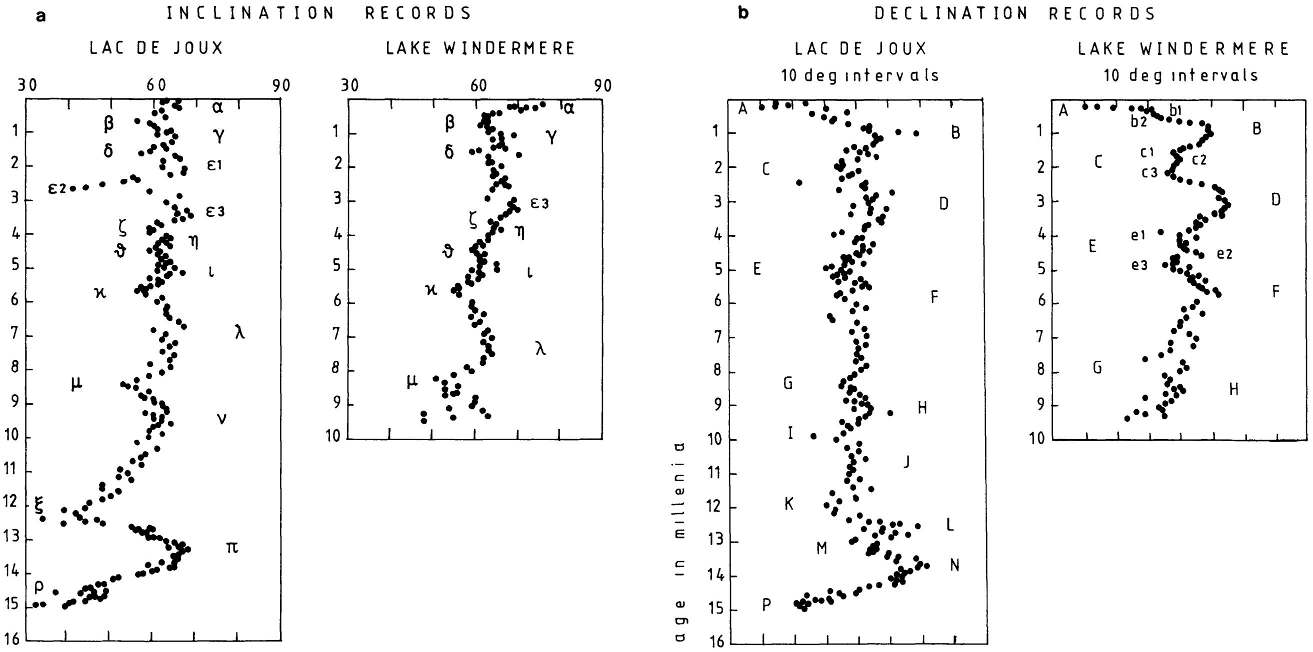

Fig. 8. a Inclination and **b** declination secular variation curves plotted as a function of time for Lac de Joux and Lake Windermere. Time scale constructed using dates of inclination features α–μ as determined for Lake Windermere (Turner 1979). Age control of Late-glacial part of Lac de Joux core is from dated palynology of the Joux valley

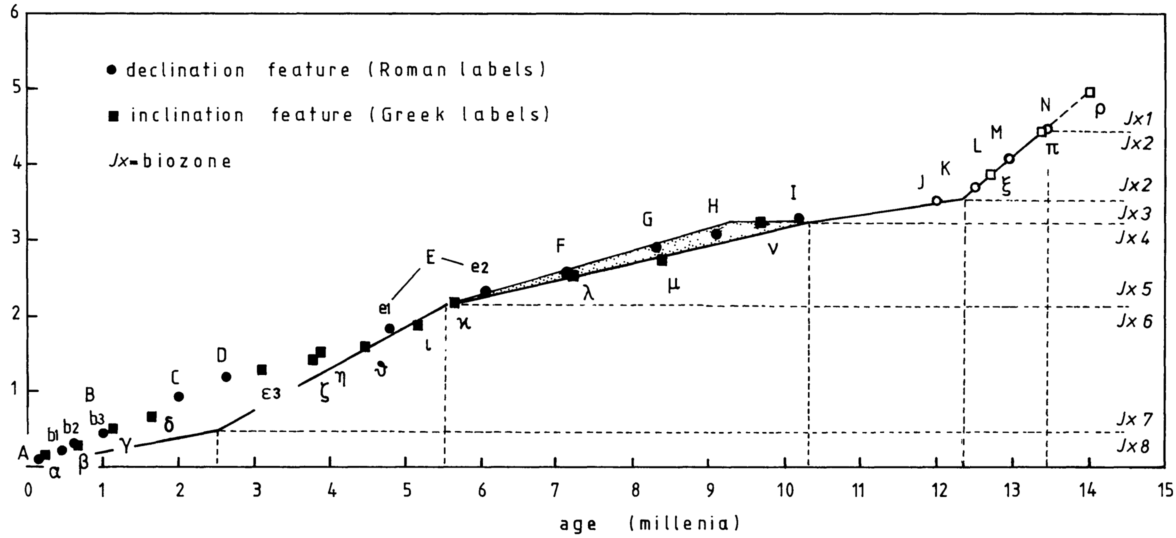

Fig. 9. Sediment accumulation (time vs depth) curve deduced for Lac de Joux core 3. The solid line is constructed from the biostratigraphy (see Figs. 2 and 3). The upper solid line running between 5,500 and 10,300 years B.P. takes into account a suspected hiatus lasting about 1,000 years at about 10,000 years B.P. *Dots* and *squares* represent 'magnetic' ages of declination and inclination features respectively, dated by correlation with U.K. curve

'old' carbon makes radiocarbon ages of lake sediments too old whereas, in this particular case, the 'magnetic' ages are younger than those indicated by the palynologically deduced time-depth curve. Thus it is difficult to account for the age discrepancy by errors in the 'magnetic' ages.

Turning now to sediments of the Joux 5 biozone, it appears that the 'magnetic' ages of the declination (*F, G, H,* and *I*) and inclination (κ, λ, μ and ν) features appear consistent with the existence of the suggested hiatus at 330 cm (Sect. 2.2), since their representative points fall within the shaded triangle bounded by the upper line which supposes a 1,000 years hiatus and the lower line which supposes no hiatus.

The dated U.K. palaeomagnetic declination and inclination curves only extend back to 10,000 years B.P. so we cannot use the depths at which the older declination features (*K*–*P*) and inclination features (ξ, π and ρ) occur as an independent check of the date

Table 1. Ages (in conventional radiocarbon years) of Late-glacial declination and inclination features

Feature label		Assigned age
Declination	Inclination	(year B.P.)
J		11,400
K		12,250
	ξ	12,400
L		12,600
M		13,000
	π	13,250
	ρ	14,200
N		14,250
P		14,500

Dates younger than 13,400 year B.P. assume steady deposition rate through Joux 1, 2 and 3 biozones. Older dates obtained by extrapolating this rate back in time

of 13,400 years B.P. for the Joux 1/2 biozone boundary (Sect. 2.2). Rather we use the biochronological time-depth curve to assign provisional dates to the declination and inclination features as shown in Table 1. If we extrapolate the average deposition rate of 0.39 mm/yr between 10,300 and 13,400 years B.P. for which we have biostratigraphic control back to the bottom of the core we date the bottom of the core at some 15,500 years B.P.

5. The Late-Glacial Record

The Late-glacial inclination records from Lac de Joux show two features ξ and ρ dated at 12,400 and 14,200 years B.P. respectively where values as low as 40° are reached. However, we note that no negative inclinations are encountered: there is no suggestion of a short lived geomagnetic reversal (excursion) as has been reported to be recorded by Late-glacial sediments from Sweden (Mörner et al. 1971) and from Lake Erie, N. America (Creer et al. 1976a). The former, or so-called Gothenberg excursion, dated by Mörner at 12,350 years B.P. has been attributed to a slumping of the sediment in the stratigraphic level corresponding to the Fjard interstadial by Thompson and Berglund (1976). Since the latter (Erieau) excursion is not seen in nearby records from Lake Michigan (Creer et al. 1976b), its reality as a geomagnetic excursion is highly doubtful.

6. Conclusions

The pattern of secular variations in geomagnetic direction recorded by sediments deposited in Lac de Joux shows a remarkable similarity to the pattern recorded by U.K. lake sediments through Post-glacial time. The Lac de Joux sediments are highly stable to alternating field demagnetization and it is probable that the main source of error of the palaeomagnetic logs arises from imperfections in the magnetic recording mechanism rather than remagnetization by geomagnetic fields after acquisition of the primary remanence. Physical disturbance of the sediment due to natural causes such as slumping or due to the coring process has spoilt the palaeomagnetic record at some levels: for example the inclination record in core 3 at about 1 m depth and the top metre or so of cores 2 and 4.

The estimated duration of the minor features of the declination and inclination logs which can be correlated between Switzerland and U.K. is a few hundred years (Fig. 9) and this places an upper limit on the duration of the magnetization process which is thought to be post-depositional.

The largest uncertainty in defining logs of variations in palaeomagnetic directions is in the independent dating control. Radiocarbon dates can be up to several thousand years too old (Mackereth 1971; Creer et al. 1979), so that dating a core to a precision of a few hundred years, the duration of the briefest palaeomagnetic features, is not generally possible. This means that it is not possible to deduce whether there is a phase lag between the U.K. and Swiss based records as one would expect if the field had been systematically drifting to the west throughout Post-glacial time as through the last few centuries: the phase lag expected over the 6° longitude difference would amount only to about 30 years assuming a drift rate of 0.2°/yr. The discrepancy between the magnetic ages of declination features *A–E* and inclination features α–ι with the time-depth curve based on the biostratigraphy (Fig. 9) is more likely due to errors in radiocarbon dating than to a phase difference between the geomagnetic field variations at the respective sites.

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