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PALAEOECOLOGICAL STUDIES OF LAKES IN THE HIGHLANDS OF PAPUA NEW GUINEA

I. THE CHRONOLOGY OF SEDIMENTATION

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SUMMARY

(1) Sediment cores were obtained for palaeoecological study from three small lakes in the Highlands of Papua New Guinea, as part of a study aimed at dating and characterizing the ecological changes associated with subsistence gardening in the region.

(2) A chronology of sedimentation for the cores was established, so that the results obtained from subsequent work on sediment chemistry, magnetic properties and pollen content of the cores could be expressed on a well-dated 'influx' basis.

(3) By using magnetic measurements to establish correlations between volcanic ash bands common to most of the cores, and then dating the correlated cores by means of the sedimentary trace of geomagnetic secular variation, radiocarbon, lead-210 and caesium-137 assay, and historical evidence, a chronology of sedimentation spanning the last 10 000 years is proposed.

(4) The sedimentary record from one site (Lake Ipea) suggests that little or no sediment accumulated at the sampled points during the periods 10 000–5000 and 4000–1600 yr B.P.

(5) At Lake Pipiak, where the small drainage basin bounded by a volcanic crater rim was still mostly forested in 1973 A.D., sedimentation rates have varied little, and no significant recent acceleration is recorded. At Lake Egari, a nearby crater lake with extensive gardens and secondary re-growth in the catchment area, sedimentation began to increase 150–300 yr ago, and the rate of increase has accelerated during the 20 yr prior to sampling (in 1973). Lake Ipea, surrounded largely by anthropogenic grassland and gardens within a more extensive catchment area, has experienced an even more rapid acceleration in sedimentation during the last 300 yr, and especially since 1950 A.D.

(6) A possible link is postulated between the first increase in rate of sedimentation at Lakes Egari and Ipea, and the intensification of land-use believed to have resulted from the introduction of the sweet potato (*Ipomoea batatas*), and its adoption as the staple crop in the region. The most recent acceleration in sedimentation may be related to the post-1950 impact of 'Western' peoples.

INTRODUCTION

Since the first contact between Western observers and the peoples of the New Guinea Highlands some 40 yr ago, numerous papers have been published dealing with the geology, ecology, anthropology and human geography of these remote areas. As a result, many aspects of the environment and of human subsistence within it are by now well documented (Meggitt 1958; Brookfield 1961; Clarke 1971; Waddell 1972). Throughout the area the sweet potato (*Ipomoea batatas* (L.) Lam.) is the staple crop, though a wide range of native and exotic edible plants is also raised (Powell 1975).

In the Wahgi Valley near Mt Hagen, some 100 km east of the study sites, Golson

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(1977a, b) and Powell (1977) have identified evidence of human occupation and activity spanning at least 9000 yr. At the same time, they and other authors have drawn attention to the likelihood of a date within the last 400 yr for the introduction of sweet potato from the New World (cf. Watson 1965 a,b). Its introduction is thought to have had a dramatic effect on population densities, the intensity of land-use and the impact of man on the balance between forest, grassland and garden.

Interpretations of the present-day pattern of grassland, forest and garden in the New Guinea Highlands vary in the relative emphasis they place on climatic and anthropogenic factors (e.g. Conroy 1963; Robbins & Pullen 1965; Walker 1966; Bowers 1968; Gillison 1972; Smith 1975). Even where, as in most cases, human activity is accepted as the dominant factor in the change from forest to grassland, widely divergent views exist about the extent to which the present pattern is one of approximate equilibrium or of rapid and progressive transformation. The complex vegetation mosaic includes some signs of advanced reversion and forest recolonization (cf. Powell 1970) as well as of extensive forest destruction and gardening.

None of the views of human impact on the forest–grassland balance gives any clear evaluation of man's long-term impact on soils and soil fertility (Clarke & Street 1967). Lack of such evidence renders highly speculative any inferences about the long-term impact of past and present gardening practices on vegetation, soils and horticultural yield and makes it difficult to estimate the productive potential of less intensively settled and cultivated, or still densely forested areas. Nevertheless, questions about long-term carrying capacities, sustainable yields and soil-fertility maintenance under conditions of low capital input are of vital importance to the local, predominantly subsistence economy of much of the New Guinea Highlands.

Where lake sediments are available for study, reconstruction of past ecological conditions may shed light on these problems, since the sediments preserve not only a record of ecological change in the form of fossil pollen, but also a partial record of mineral input from the drainage basin of the lake. Studies of contemporary mineral cycling, and of the rates and regulation of mineral loss from soils through erosion and leaching, show how clearly these processes reflect human interference (Bormann, Likens & Beaton 1969). Moreover, analysis of the chemistry of lake sediments in temperate latitudes has shown how changing rates and patterns of deposition are related in part to man's activities in the drainage basin of the lake (Mackereth 1965, 1966). Both types of study suggest that under suitable circumstances lake drainage basins may form suitable units of study within which to reconstruct the changing role of man in terrestrial ecosystems (Oldfield 1977).

Before any such reconstruction is attempted, it is necessary to establish an accurate and precise chronology of sedimentation. This is essential not only for dating events, but also for the calculation and expression of results in terms of influx per unit time, and hence eventually for the portrayal of past ecological processes and the estimation of rates of change. The present paper establishes a chronological framework for continuing pollen-analytical, chemical and magnetic studies of the sediments of three lakes in the Highlands of Papua New Guinea.

THE STUDY SITES

All three sites lie in the Lower Montane forest zone (Walker & Guppy 1978), within or close to densely settled and intensively cultivated intermontane areas in the Western

Highlands. Lake Ipea (5°24′S, 143°24′E) lies about 2500 m above sea-level in the Enga Province (Fig. 1). The area surrounding the lake, and the swamp through which the main inflow to the lake passes, have been the subject of intensive ecological and palaeoecological study over the last two decades (Walker 1965, 1966; Walker & Flenley 1979; Bowler *et al.* 1977). The lake itself is roughly L-shaped, and lies on the col between tributaries of the Fly and the Sepik, two of the major rivers of New Guinea. Maximum water depth is *c.* 7 m, and landforms around the lake are subdued. Air photographs dating from 1959–74 A.D. show the catchment as substantially deforested, with grassland and, more locally, garden covering most of the area save for the high land near the rim of the catchment and for isolated spurs of wooded ground. Walker (1966) and Flenley (1967) both describe the vegetation of the area. Bedrock comprises mostly shales, though limestones and mudstones are also represented; the soils are mainly acid and often truncated by the effects of gardening. Such climatic data as exist (Walker 1966) record high rainfall (*c.* 2000 mm yr^{-1}), with a seasonal minimum from May to August. Annual temperatures average *c.* 15 °C, with a high risk of damaging frost (cf. Brown & Powell 1974).

Lakes Egari and Pipiak (6°5′S, 143°65′E) both occupy small craters less than 1 km apart, beyond the western fringe of the massive lava shield of Mt Giluwe (4370 m). Lake Egari has a maximum depth of 11 m and Lake Pipiak a maximum depth of 8·5 m. Both sites lie at about 1800 m above sea level, both have very small drainage basins limited by the crater rims, and both have poorly developed outflows into a tributary of the Mendi River, which then flows southwards. Both sites are surrounded by deeply-weathered, clay-rich soils developed on acid volcanic bedrock. Lake Egari lies next to the village of the same name, and much of the drainage basin is actively gardened; only the low, steep, eastern rim is wooded, though none of the catchment carries the apparently permanent

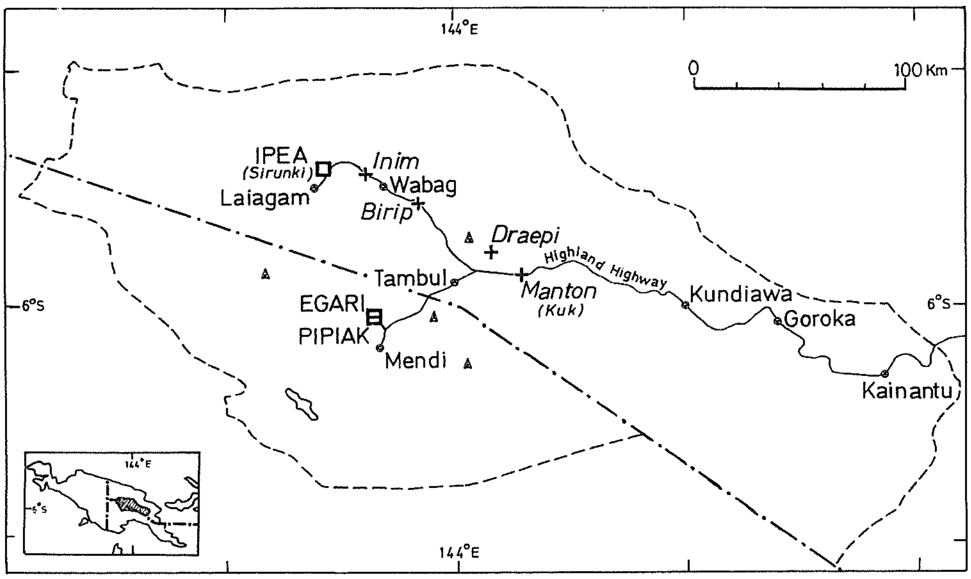

FIG. 1. Map showing location of sampling sites (□). Sirunki, Inim and Birip are the sites studied by Walker (1965, 1966); Flenley (1967) and Walker & Flenley (1979); Draepi and Manton are the sites studied by Powell (1970). Manton is also close to the site of the Kuk excavations (Golson 1977a, b). Inset, map of New Guinea.

TABLE 1. Depth of sediment at the sampling sites

Site	Lake Ipea						Lake Egari					Lake Pipiak	
Core no.	1	2	3	4	5	6	1	2	3	4	5	A	B
Sediment depth (cm)	56	80	84	88	85	88	72	100	83	95	90	95	100

grass swards of *Miscanthus floridulus* Warb. and *Imperata cylindrica* Beauv. which characterize much of the Ipea basin. In the year of sampling (1973), the catchment of Lake Pipiak was largely forested, with only local discontinuous areas of garden present. Both the Egari and Pipiak catchments are surrounded by lower valley slopes which are extensively cleared. Rainfall is comparable to that at Lake Ipea, but temperatures are higher and there is a much lower risk of damaging frost. The ecology and subsistence gardening of the immediate locality have not been intensively studied, though the nearby area of the upper Kaugel valley around Tambul, some 16 km from Egari, is settled by related human groups and has been studied by Bowers (1968).

THE DATING PROCESS

Collection of cores

Cores spanning the mud–water interface at the three sites were collected inside 100 × 5-cm perspex tubes, either manually (Lake Ipea) or using a portable pneumatic minicorer (Mackereth 1969). Thirteen cores were obtained, as follows:—

Lake Ipea

Six cores within *c.* 50 m of each other; cores 1–5 were taken in 3·0–3·5-m depth of water, *c.* 30 m from the S.W. shore of the lake, while core 6 was taken in 3 m of water 20 m from the shore.

Lake Egari

Five cores; cores 1 and 3 were taken in 6·5 and 7·0 m depth of water, respectively, at sites *c.* 30 m from the gardened W. shore of the lake; core 2 was taken in 10·5 m of water, 30 m from the forested E. shore, and cores 4 and 5 from the centre of the lake in 11 m of water.

Lake Pipiak

Two cores; core A was taken in 8·5-m depth of water, in a bay with forested shores; core B was taken in 7·5 m of water, close to the far shore, with evidence of present and former cultivation nearby.

Lengths of the cores are given in Table 1.

For all cores, except Ipea core 4 and Egari cores 2 and 5, at least the topmost sediment was extruded section by section in 1-cm or 2-cm slices in the field, in order to avoid subsequent disturbance of mobile material just below the mud–water interface. The three unextruded cores were kept vertical and undisturbed during transport overland and by air to the laboratory. Stratigraphic changes visible in the field through the transparent core tubes were recorded; more detailed sediment description was carried out in the laboratory during the course of extrusion. All the sediments sampled were gyttjas, ranging in colour from olive-green through brown to black. Loss-on-ignition values varied from 20 to 60% dry weight.

Magnetic measurements

Thompson *et al.* (1975) and Oldfield *et al.* (1978a) have demonstrated the use of magnetic-susceptibility measurements on extruded single samples and on whole cores as a means of correlating profiles from comparable depositional environments in the same lake, especially where influx events have produced variations in sediment supply characterized by changes in the type or concentration of magnetic minerals. In the context of the present sites, a sequence of magnetite-rich volcanic-ash layers, common to all three lakes, allows not only within- but between-lake correlation on the basis of whole-core and single-sample magnetic-susceptibility measurements.

Magnetic susceptibility was measured and expressed on three different bases. Whole-core measurements were carried out using apparatus described by Molyneux & Thompson (1973); this allows measurement of each core to be made in a few minutes, and provides computer output of the results in graphical or numerical form. The resulting measurements are in arbitrary units. Volume-susceptibility, expressed as Gauss per Oersted per cm^3 (G Oe^{-1} cm^3), was measured by means of a low-field susceptibility bridge (Molyneux 1972), using 10-cm^3 samples of wet sediment shortly after extrusion. Specific susceptibility was measured in the same way on oven-dried material (units, G Oe^{-1} cm^3 g^{-1}). Because of variations in the water content of near-surface sediments, specific-susceptibility measurements are the only ones which can be used to record variations right up to the mud–water interface. In some cases (e.g. Ipea core 6), the single-sample measurements were carried out on samples too small to give repeatable susceptibility measurements. In this case, Saturation Isothermal Remanent Magnetization (SIRM; units, G cm^3 g^{-1}) was determined as an alternative related magnetic measurement. A full discussion of methods and units is given in Oldfield *et al.* (1978a).

Figure 2 illustrates specific-susceptibility measurements on two of the cores from Lake Ipea; correlations based on the recorded sequence of volcanic ashes are shown in each case. Figure 3 summarizes single-sample volume-susceptibility measurements from Lake Pipiak. Figure 4 plots continuous-core susceptibility traces from each lake, and indicates the relative ease with which cores within and between lakes can be correlated on the basis of the high magnetic component of the ash layers (cf. Radhakrishnamurthy *et al.* 1968; Lal & Somayajulu 1975).

In addition to the measurements described above, other remanent magnetic properties were also measured (cf. Thompson 1973, 1978). The results are reported in Thompson & Oldfield (1978); they contribute directly to the dating of the most recent sediments, and also help to confirm the position and significance of breaks in sedimentation in the oldest material from Lake Ipea.

Radiocarbon-dating

Three samples were submitted to the Birmingham Laboratory in 1974 and ten to the NERC-SURRC Laboratory in 1976. Of the latter, three proved to contain too little carbon for effective measurement. The ten dates obtained are listed in Table 2.

Lead-210 profiles

One ^{210}Pb profile was obtained from Egari core 2 in 1974, and six subsequent profiles, three from Lake Egari and three from Lake Ipea, were obtained in 1976. The analyses were carried out in the Atomic Energy Research Establishment, Harwell, by J. D. Eakins, using the methods described in Eakins & Morrison (1976). Dates were originally calculated assuming a constant initial concentration (c.i.c.) of unsupported ^{210}Pb

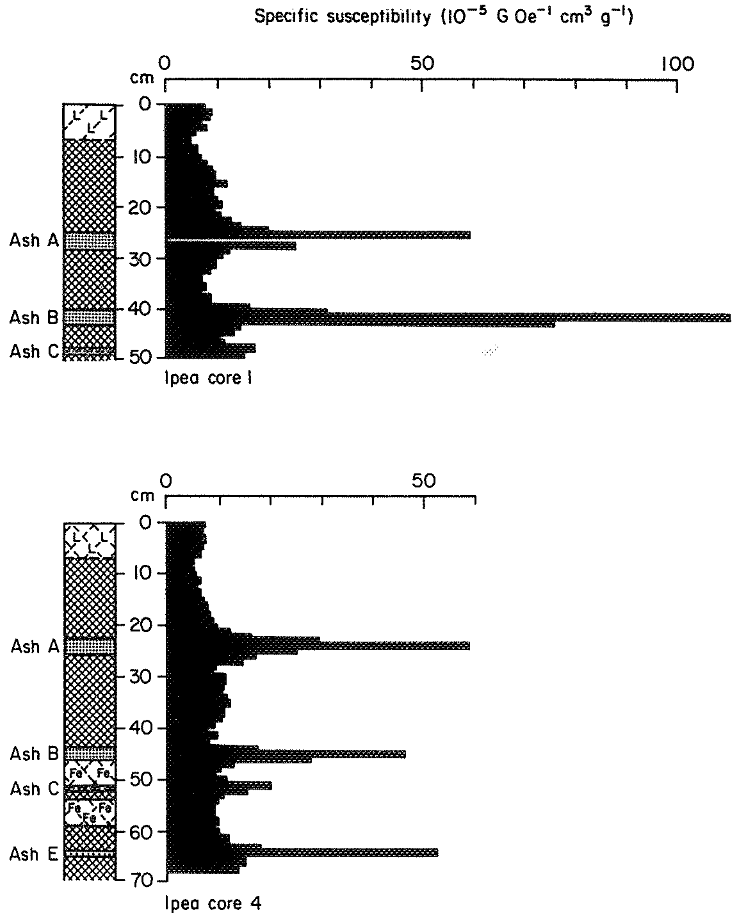

FIG. 2. Stratigraphy and specific magnetic susceptibility of single samples from Lake Ipea, cores 1 and 4. Two other cores (5 and 6) contain the additional earliest volcanic ash layer labelled F in the text and in Fig. 6. ▩, gyttja, ▤, sand/ash; ◫, clay; Fe Fe, marked iron staining.

i.e. that proportion of the total ^{210}Pb used in dating which has reached the lake either directly or indirectly from the atmosphere via emission of radon from ^{226}Ra in rocks and soils, cf. Pennington *et al.* (1976), but were shown to be incompatible with other evidence for the age of the most recent volcanic ash layer (Oldfield, Appleby & Battarbee 1978b). The alternative assumption of a constant net rate of supply (c.r.s.) of unsupported ^{210}Pb to the sediment was thus used (Appleby & Oldfield 1978) to provide the dates, the age/depth profiles and the dry-mass sedimentation rates discussed below (Figs 7–12).

Caesium–137 profile

Pennington, Cambray & Fisher (1973), Ritchie, McHenry & Gill (1973), and Pennington *et al.* (1976) have shown that in a number of British and North American lakes the changing concentration of ^{137}Cs in the topmost sediments parallels the recorded deposition of ^{137}Cs as fall-out from nuclear testing in recent times. These and other authors

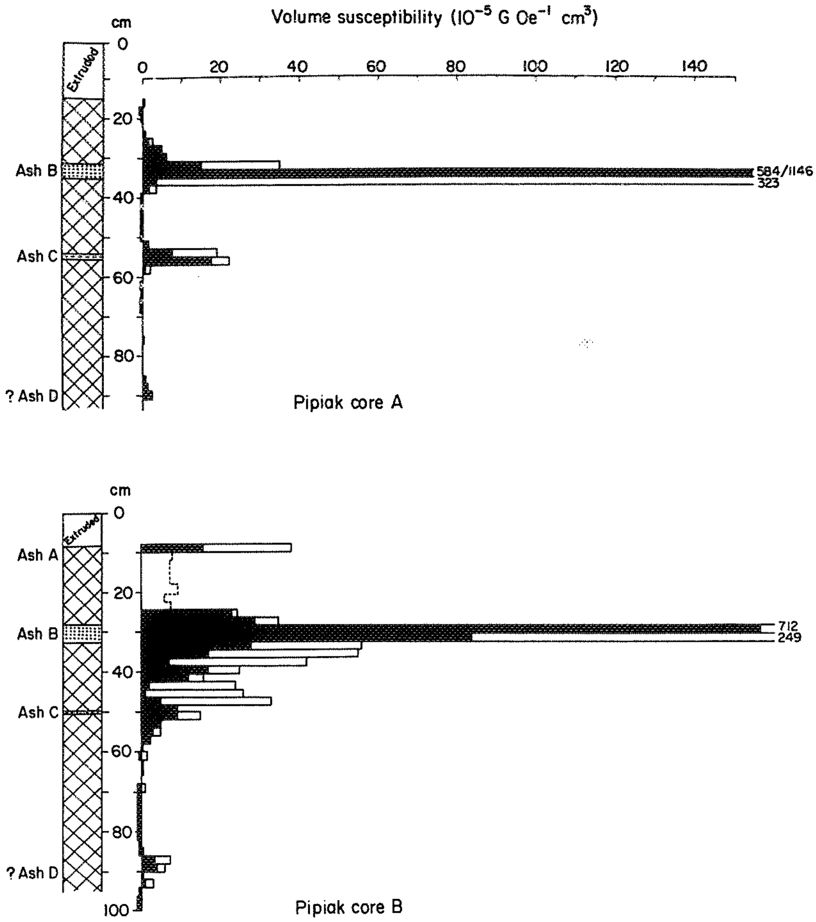

FIG. 3. Stratigraphy and volume magnetic susceptibility of paired single samples from Lake Pipiak, cores A and B; stratigraphic symbols as in Fig. 2. For each depth sampled, a solid bar indicates the volume susceptibility of the less magnetic and an open bar the volume susceptibility of the more magnetic of the pair of samples. Core-sections between 10 cm and 50 cm in Pipiak core B yielded mud samples contaminated by small quantities of volcanic ash otherwise undetectable at the time of extrusion. Susceptibility may thus be used under some circumstances to screen samples for further (e.g. chemical) analyses.

have therefore used the trace of ^{137}Cs concentration in sediment-profiles as a direct dating technique for the period since 1954 A.D. The New Guinea sites studied here are at very low latitudes and in the southern hemisphere; as a consequence, ^{137}Cs fall-out from nuclear testing in the northern hemisphere has been both delayed and substantially diluted. The 1954-onset and 1963-peak of recorded ^{137}Cs in the atmosphere in the northern hemisphere are registered in 1955 and 1964 respectively in the southern hemisphere. Because of dilution, a composite profile had to be obtained from a number of cores; this was done by combining samples from the Ipea cores using single-sample specific-susceptibility measurements as a basis for detailed correlation. The resulting ^{137}Cs profile is shown in Fig. 5. The ages inferred from the ^{137}Cs assays and the ^{210}Pb profiles (Figs 7, 8 and 9) are both shown on the diagram.

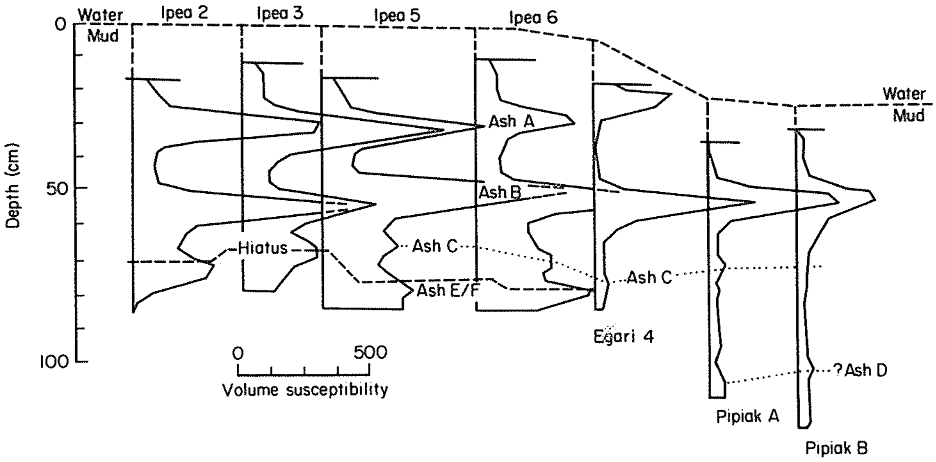

FIG. 4. Whole-core susceptibility profiles from all three lakes. Upper sediment (interrupted vertical line) was extruded for subsequent study prior to whole-core measurement. In the case of the Lake Pipiak cores this extruded portion included Ash A. The main volcanic ash/susceptibility-based correlations are shown. The horizontal scale is in arbitrary units of volume susceptibility.

TABLE 2. Radiocarbon dates (yr B.P.) for sediment samples from Lakes Egari, Ipea and Pipiak

SRR–1029	Lake Egari, core 1; 22–26 cm (between Ash B & Ash A)	600 ± 60
SRR–1026	Lake Pipiak, core B; 26–34 cm (spanning Ash B)	1153 ± 125
Birm–587	Lake Ipea, core 3; 52–56 cm (spanning Ash B)	1220 ± 150
Birm–588	Lake Egari, core 4; 90–94 cm (below Ash C)	1850 ± 100
SRR–1023	Lake Ipea, core 6; 62–66 cm (below Ash C, spanning underlying hiatus)	2232 ± 150
SRR–1027	Lake Pipiak, core B; 84–88 cm (immediately above possible fine Ash D)	2790 ± 130
SRR–1028	Lake Pipiak, core B; 92–100 cm (immediately below possible fine Ash D)	2694 ± 60
SRR–1024	Lake Ipea, core 6; 72–76 cm (immediately below Ash E)	4220 ± 110
Birm–588	Lake Ipea, core 3; 78–82 cm (underlies Ash E)	5140 ± 110
SRR–1025	Lake Ipea, core 6; 79–83 cm (immediately above Ash F)	10 288 ± 150

THE CHRONOLOGICAL FRAMEWORK

Ash layers F to B

The volcanic ash layers provide marker horizons common to all three lakes, so that it is convenient to begin by describing and dating the ash sequence. The labels given to each ash are specific to this investigation, though their correlation with tephra investigated by other workers is discussed where appropriate.

Ash F

This, the oldest ash recorded, is present in Ipea cores 5 and 6 only. It is grey and sandy, and gives rise to specific-susceptibility values around 180×10^{-6} G Oe^{-1} cm^3 g^{-1}.

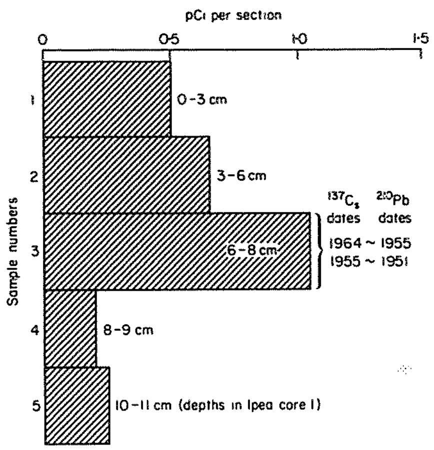

FIG. 5. Composite ^{137}Cs profile from the Lake Ipea sediments. Inferred ^{137}Cs and ^{210}Pb dates are shown for comparison (see text). The depth-scale is that derived from Ipea core 1, with which the samples contributed from other cores were correlated magnetically (Oldfield *et al.* 1978a).

Mud from the 4 cm spanning and immediately above it (79–83 cm) in Ipea core 6 (SRR–1025) gave a radiocarbon age of 10 288 ± 150 yr B.P.

Ash E

This ash is recorded in all the Ipea cores except the short Ipea 1. It also is sandy and predominantly grey in colour, with maximum specific-susceptibility values of 500–700 × 10^{-6} G Oe^{-1} cm^3 g^{-1}. Sediment immediately below Ash E in Core 6 gave a radiocarbon age of 4220 ± 100 yr B.P. (SRR–1024). The ash occurs at a depth of 72–74 cm in Ipea core 3, and is separated by 4 cm only from material at 78–82 cm depth giving a radiocarbon age of 5140 ± 100 yr B.P. (Birm–588). The two oldest radiocarbon dates at lake Ipea, from different but adjacent cores, are thus separated by a long time-interval represented by negligible sediment accumulation, suggesting a substantial gap in deposition between the two lowest ashes, from *c.* 10 000 to *c.* 5000 radiocarbon-yr B.P.

Ash D

This has not been confidently detected visually in the sediment, nor has its presence been confirmed mineralogically. The only evidence for it at present is the consistent minor peak in volume-susceptibility near the base of both Pipiak cores (*c.* 50 × 10^{-6} G Oe^{-1} cm^3), compared with zero or apparently negative values for the overlying mud. The basal radiocarbon dates from Pipiak core A (SRR–1027, 1028) ascribe an age of around 2700 yr B.P. to this peak.

Ash C

This is clearly represented in cores from all three lakes. It is cream-coloured, clayey in texture, and gives specific-susceptibility values of 150–200 × 10^{-6} G Oe^{-1} cm^3 g^{-1} in each lake. Ash C lies between dated ashes or muds in the majority of the profiles, and occurs 18 cm above basal mud in Egari core 4 dated to 1850 yr B.P. (Birm–588). Age-estimates derived by interpolation assuming constant accumulation are, with only one exception, very close to 1600 yr B.P. The upper part of sample SRR–1023 (2232 ± 150 yr B.P.) from 62–66-cm depth in Ipea core 6 spans Ash C, but it also appears to include considerably older material, pre-dating all or part of a break or series of breaks in accumulation between *c.* 4000 and *c.* 1600 yr B.P.

Ash B

This is represented in every core from all three lakes. It is normally 2–3 cm thick, sandy and grey in colour, and often gives specific-susceptibility peaks well in excess of 1000×10^{-6} G Oe^{-1} cm^3 g^{-1}. Radiocarbon dates from both Ipea core 3 and Pipiak core B place Ash B at *c.* 1200 yr B.P. Strontium–rubidium analysis by R. Blong confirms that it corresponds with his 'Q' ash ('Olgaboli' tephra), widely represented in soil and peat sections in the Western New Guinea Highlands and independently dated to the same age (Blong, unpublished).

The age of Ash A

Ash A is present in every profile. Its colour varies from grey to sage green, and it is seldom less than 2 cm thick. It gives rise to high specific-susceptibility values, comparable with those for Ash B. At Lake Pipiak this ash lies only 6–8 cm below the mud–water interface. In the Egari cores its depth ranges from 14 to 22 cm, and in the Ipea cores from 24 to 34 cm. Evidence summarized by Blong (1975 and unpublished) shows that the time of this, the most recent ash-fall in the region, is consistently recorded in oral history as the 'time of darkness'. Blong has shown by means of an analysis of strontium: rubidium ratios that this ash in the lake-sediment profiles is the same as his 'Z' ash ('Tibito' tephra). Geochemical evidence identifies Long Island (5°20′S; 147°15′E), some 300 km distant, as its source.

Several lines of evidence are available for estimating the age of this recent ash-fall.

Oral history

A comprehensive analysis of age-estimates from oral tradition in the Enga Province, within the general area of the sites, places the 'time of darkness' some four to six generations ago (W. Lacey, personal communication). This would indicate a probable age about the middle of the nineteenth century. Orally-derived chronologies are notoriously unreliable, however, and frequently underestimate the true age of events.

Documentary evidence

Evidence summarized by Ball & Johnson (1976) shows that Long Island, the source of the ash-fall was visited continuously by European observers from 1827 A.D. onwards. They fail to record any evidence for a volcanic eruption either immediately before or during the period of European contact. A post-1820 age for the ash can therefore be precluded. Additional evidence comes from Dampier, who visited New Guinea in 1700; his sketch from off-shore portrays a topography so similar to that of the present-day that some authorities find it difficult to envisage a post-1700 age for an eruption generating the volume of tephra represented by the known extent of Ash A (R. Blong, personal communication).

Palaeomagnetic secular variation

Thompson & Oldfield (1978) plot measurements of secular variation in Geomagnetic Inclination in the upper sediments from Lake Ipea. The directional properties are shown to be repeatable within and between cores, and the traces closely parallel the post-

1650 A.D. secular variation in Inclination for the site derived from calculations based on all available observatory records (D. R. Barraclough, personal communication; Thompson & Oldfield 1978). Matching of the observed sedimentary record with the calculated record indicates a pre-1700 A.D. age for Ash A.

Radiocarbon dates

Several radiocarbon determinations on a variety of terrestrial materials directly associated with Ash A, where it lies interstratified in peat and soil, all give dates close to 1700 A.D., with standard errors of ± 40 yr (Blong 1975).

Lead-210

Using the c.i.c. model of deposition for the unsupported ^{210}Pb, dates of Ash A range from 1800 to 1880 A.D., with a mean value between 1840 and 1850 A.D. This is much too late in the light of the evidence already summarized. Using the c.r.s. model, initial dates from the four cores with the greatest degree of internal consistency fall within the time span 1800–1840 A.D., with a mean age around 1815 A.D. (Oldfield *et al.* 1978b). These dates were based on calculations assuming uniform ^{226}Ra content and hence uniform supported ^{210}Pb concentrations in each sample (0·2 pCi). In order to carry out improved calculations it has been necessary to re-evaluate the level of supported ^{210}Pb activity in both the ash and the sediments.

Measurements made on the ash indicate that it has a higher ^{226}Ra content (0·5 pCi g^{-1}) than the lake sediments on either side. Further, the magnetic-susceptibility measurements indicate that a number of samples assayed for ^{210}Pb lying above and below the ash included some ash as a result of inwash, mixing or contamination, and so have abnormally high ^{226}Ra concentrations. Using the specific-susceptibility measurements it is possible to assess the approximate proportion of ash in these samples, and so to determine a corrected ^{226}Ra content. When the above corrections are made, it becomes clear that there is negligible unsupported ^{210}Pb at or beneath the ash, and hence that the ash is significantly older than previously calculated.

The revised ^{210}Pb age/depth curves are believed to be reliable for the upper 85% of the mud above each ash, representing a period of 130–160 years. Estimates of the age of Ash A can be made by extrapolating these curves through points dated by radiocarbon. In Ipea cores 1, 4 and 6 and Egari cores 2 and 4, the depth of ashes B and C are well-determined, and dated by radiocarbon to *c.* 1200 B.P. and 1600 B.P. respectively. The ^{210}Pb age/depth curves have a good match with the quadratic extrapolation through these points. Further, this extrapolation provides the most consistent estimates of the age of the ash:

Ipea core	1	280 yr	mean 280 yr
	4	270 yr	
	6	290 yr	
Egari core	2	330 yr	mean 290 yr
	4	250 yr	

The mean value of 285 yr before sampling in 1973 (1688 A.D.) is too close to 1700 A.D., the year of Dampier's cruise, to be acceptable, but it lies halfway between the mid-17th century age favoured by Blong and an alternative early-18th century age which cannot be conclusively dismissed on present evidence. We have accordingly used this value in all subsequent calculations, and in the diagram showing the time-scale covered by the various cores (Fig. 6).

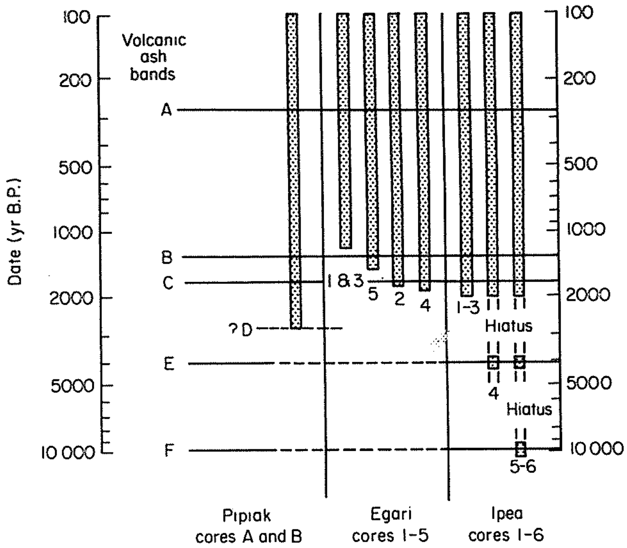

FIG. 6. Time-span covered by cores from all three lakes plotted on a logarithmic time-scale from 100 to 10 000 yr B.P. All cores have an undisturbed mud-water interface, and so include sediment spanning the last 100 years.

AGE/DEPTH CURVES AND SEDIMENTATION RATES

Lead-210 age/depth curves were calculated in accordance with the c.r.s. model, using the equation

$$A(x) = A(0)\, e^{-kt} \tag{1}$$

(Appleby & Oldfield 1978, p. 4), where

$$A(x) = \int_x^{\infty} \rho C \, dx \tag{2}$$

is the total residual unsupported ^{210}Pb per unit area beneath sediments of depth x,

$$k = \log_e 2/22{\cdot}26$$

is the ^{210}Pb radioactive decay constant, ρ is the dry wt: wet volume ratio, and C is the unsupported ^{210}Pb concentration. A is the dating parameter. A(x) refers to the value of A at the depth x; A(0) refers to the value of A when $x = 0$, i.e. at the surface. The dry-mass sedimentation rate (r) was calculated using the equation

$$r = \frac{kA}{C} \tag{3}$$

From the age of Ash A and the total residual unsupported ^{210}Pb in the core, Eqns (1) and (3) were used to assess the theoretical ^{210}Pb concentration of sediments dating from the ash, and the total residual unsupported ^{210}Pb beneath these sediments. The dating parameter was recalculated from these values to give a corrected ^{210}Pb age/depth curve which was compatible with the inferred age of Ash A.

The ^{210}Pb age/depth curve from a single core will inevitably contain inaccuracies due to errors in the data, assumptions and methods of calculation. Some of these inaccuracies

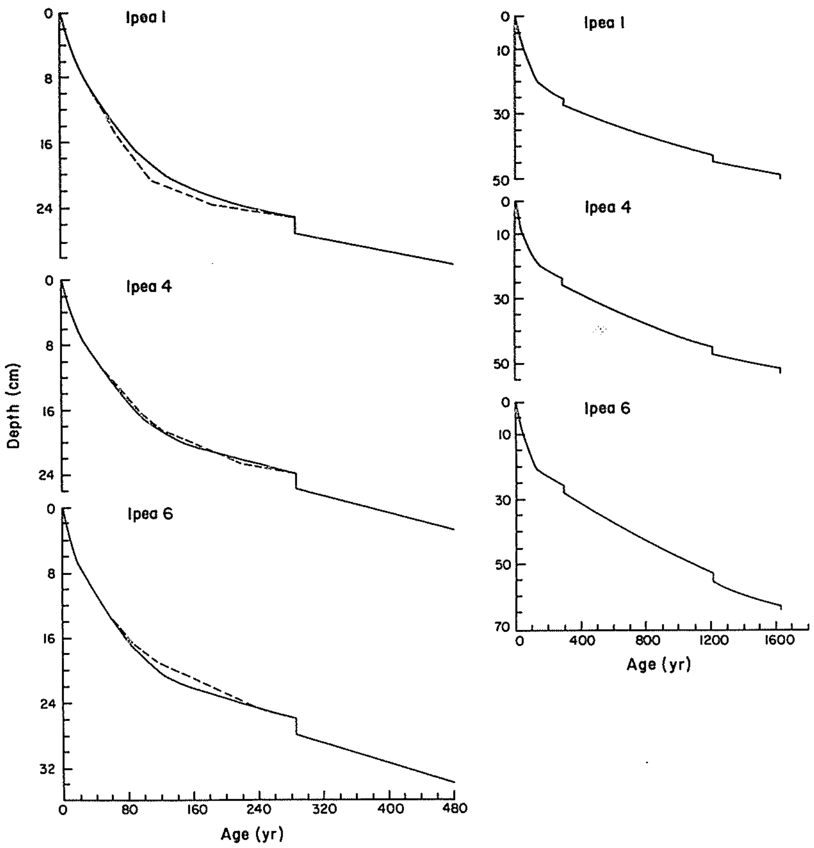

FIG. 7. Age/depth-profiles for Lake Ipea, cores 1, 4 and 6. Right-hand diagrams plot the total timespan since volcanic ash C; left-hand diagrams show the recent detailed variations on an expanded scale. The pecked lines show age/depth profiles calculated directly from the individual ^{210}Pb measurements for each core; the solid lines use the core-correlation procedure detailed in the text and the Appendix. Year 0 is 1973 A.D.

can be eliminated by inter-core correlation of data from cores from the same lake using the method outlined in the Appendix. Age/depth curves for Ipea cores 2, 3 and 5 and Egari core 3, constructed by inter-core correlation, are given in Figs 7–11.

Figure 5 shows some possible divergence between the apparent ^{137}Cs and ^{210}Pb dates for the uppermost sediments at Lake Ipea, especially if the ^{137}Cs peak at 6–8 cm is taken to represent peak fall-out in 1964 A.D. Changes in sedimentation rates and the derivation of values by sample aggregation reduce the reliability of the ^{137}Cs profile. The possible level of the 1955 onset of fallout at 8 cm agrees fairly well with the ^{210}Pb age.

The age/depth curves for Ipea cores 1, 2, 4, 5 and 6 and Egari core 2 derived from corrected ^{210}Pb values are compatible with a quadratic age/depth curve through the age/depth points of Ashes A, B and C. The curve for Egari 4 had a discontinuity in the tangents, and hence in the sedimentation rates. In this case we have constructed a cubic curve through Ashes A, B and C whose tangent at Ash A is the slope of the ^{210}Pb age/depth curve. In Ipea 3 and Egari 5, in which the depth of Ash C has not been determined

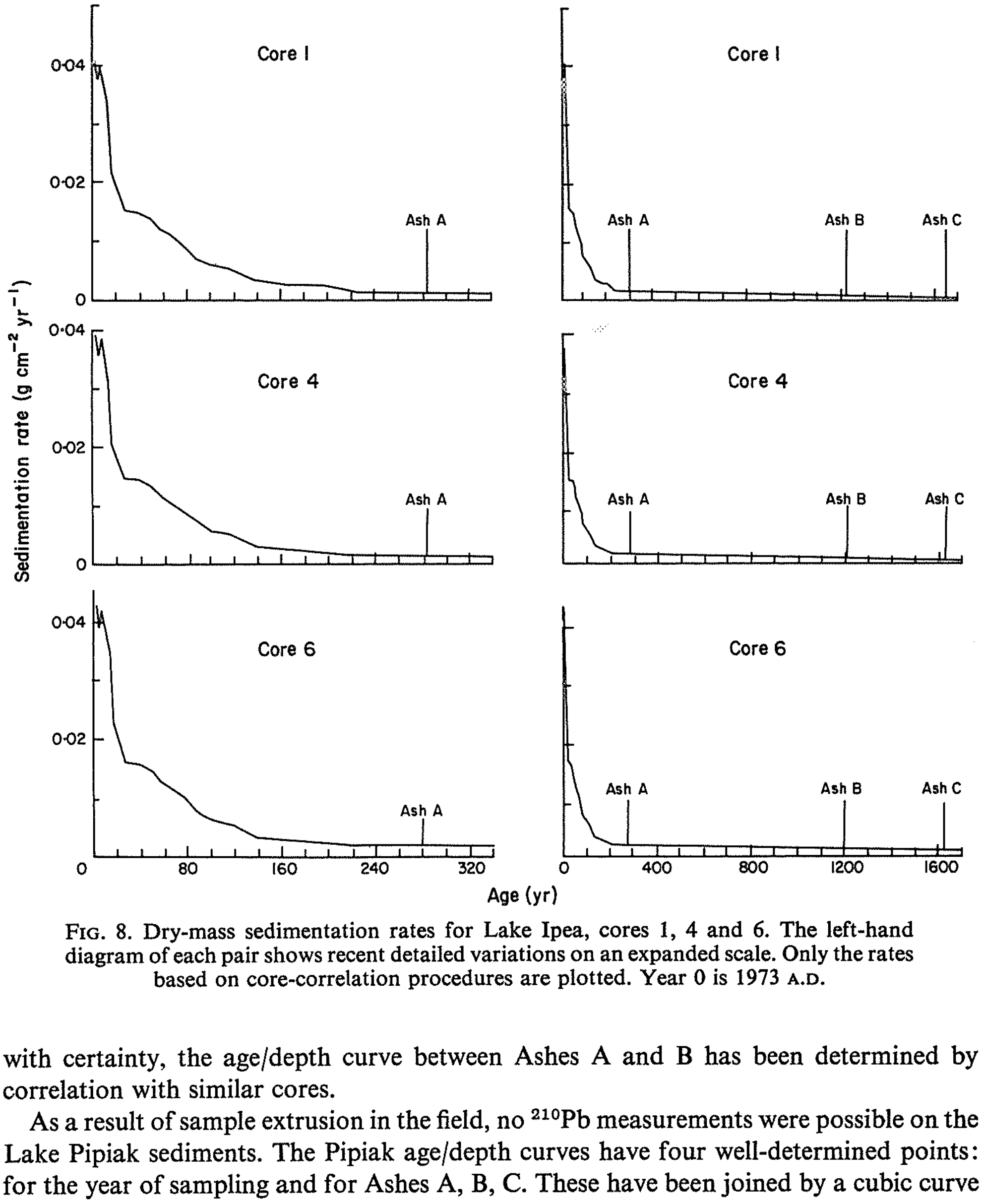

FIG. 8. Dry-mass sedimentation rates for Lake Ipea, cores 1, 4 and 6. The left-hand diagram of each pair shows recent detailed variations on an expanded scale. Only the rates based on core-correlation procedures are plotted. Year 0 is 1973 A.D.

with certainty, the age/depth curve between Ashes A and B has been determined by correlation with similar cores.

As a result of sample extrusion in the field, no ^{210}Pb measurements were possible on the Lake Pipiak sediments. The Pipiak age/depth curves have four well-determined points: for the year of sampling and for Ashes A, B, C. These have been joined by a cubic curve (Fig. 12).

DISCUSSION

The range of techniques used, especially the combination of radiometric dating and magnetostratigraphic correlations based largely on a volcanic tephra sequence, have provided a coherent chronological framework for continuing chemical, magnetic and biostratigraphic studies. The cores represent varying time-intervals within the last 10 000 yr, though only at Lake Ipea have sediments older than *c.* 3000 yr B.P. been recovered. At that site, during the period from *c.* 10 000 to 1600 yr B.P., the marginal

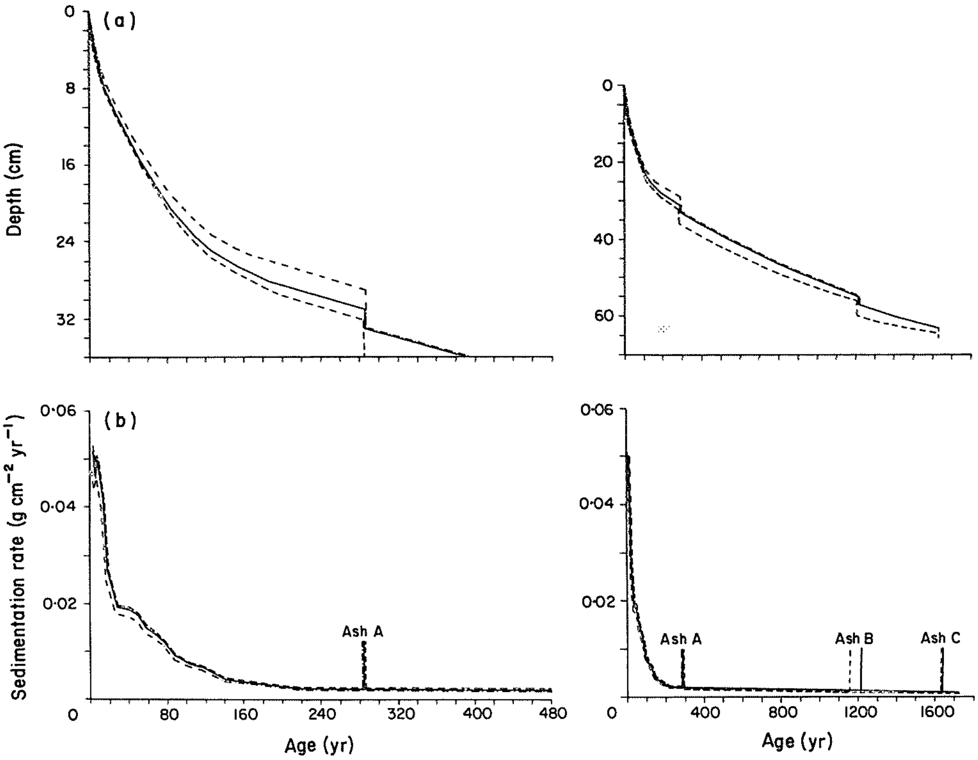

FIG. 9. Age/depth profiles (a) and dry-mass sedimentation rates (b) for Lake Ipea, cores 2, 3 and 5. The left-hand diagram of each pair shows recent variations on an expanded scale. No ^{210}Pb-analysis of these cores was carried out. The dates and rates are derived from direct correlation with the dated cores. Year 0 is 1973 A.D. ——Ipea 2, —·—·— Ipea 3, – – – Ipea 5.

sediments sampled do not represent an uninterrupted sequence; the available radiometric and palaeomagnetic evidence is consistent between cores in suggesting that little or no sediment accumulated during the periods 10 000–5000 and 4000–1600 B.P. The magnetostratigraphic records are closely parallel in each core and suggest that the gaps in sedimentation are not anomalies particular to individual sites.

It seems likely that the gaps in the sedimentary record were the result of lower lake levels. The sediments at the points of sampling lack any evidence for the growth of terrestrial or aquatic macrophyte vegetation during these periods, though it cannot be determined whether some sediments were exposed above the lake water, vegetated and then subsequently removed, or whether the old sediment surface remained below water but at depths shallow enough to lead to sediment removal and no significant net accumulation.

The two cores from Lake Pipiak span the last 3000 yr, with no evidence for any breaks in sedimentation. At Lake Egari, the deep-water cores (2, 4 and 5) span the last 1500–2000 yr, and the shallow-water marginal cores (1 and 3) accumulated during the last few centuries only (Fig. 6).

The rates of dry-mass sediment accumulation calculated for the periods of uninterrupted sedimentation at each site show several interesting features:—

(i) The three deep-water Egari cores and both the Pipiak cores show a pattern of decelerating accumulation throughout almost all of the last two to three millenia.

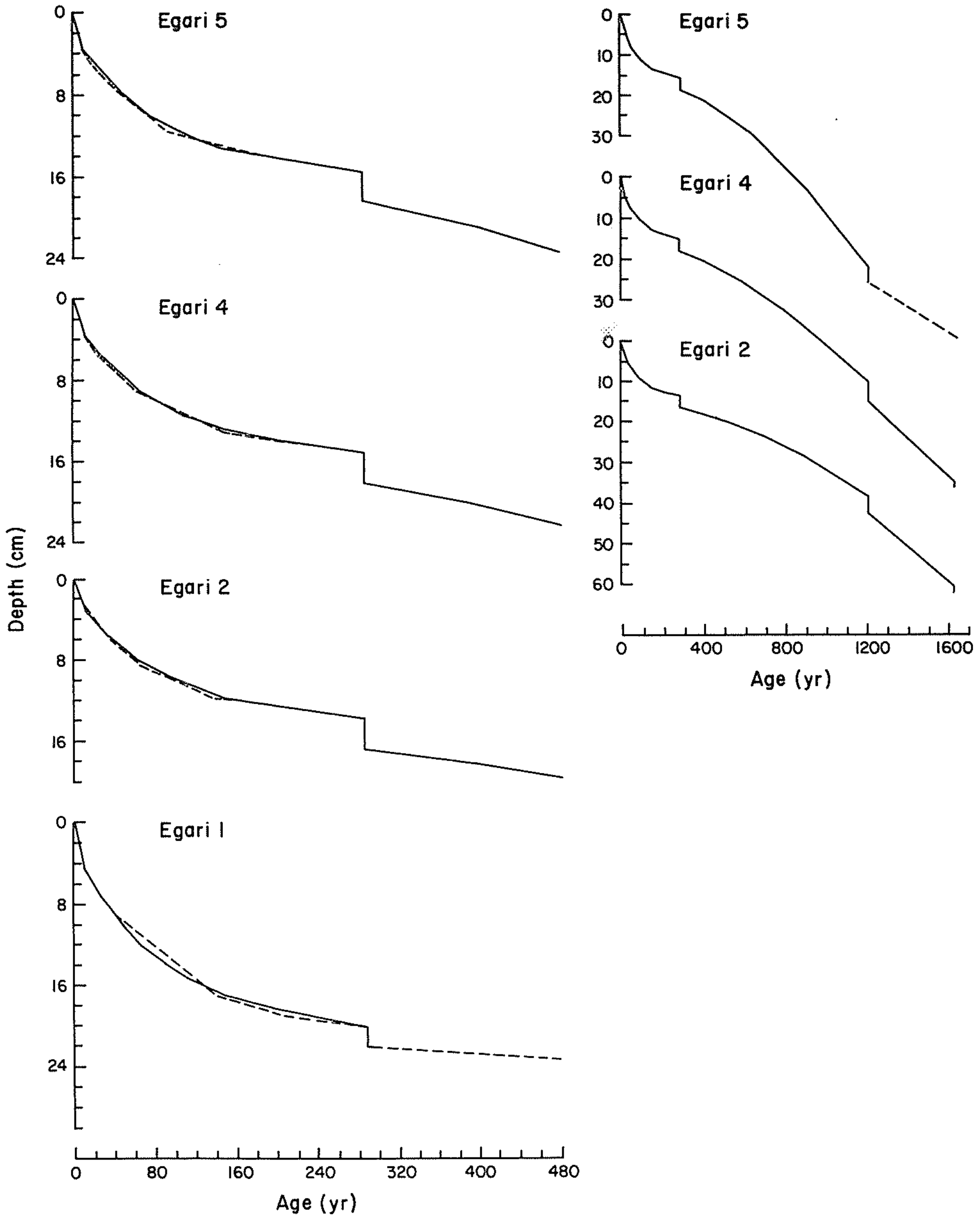

FIG. 10. Age/depth profiles for Lake Egari, cores 1, 2, 4 and 5 (cf. Fig. 7). The left-hand diagrams have an expanded time-scale. No long-term profile is plotted for core 1, as Ashes B and C were not recovered at that site. Year 0 is 1973 A.D.

(ii) During the same period, the rate of accumulation in the Ipea cores from shallower water appears to have increased slightly and steadily. Evidence from the only dated marginal core from Lake Egari (1) is less secure, but appears to parallel the Ipea record rather than that from the deeper water in Lake Egari. In view of the possible difference in response between central and marginal cores at the same sites, it is not possible, therefore, to determine to what extent reduced sediment input to either lake as a

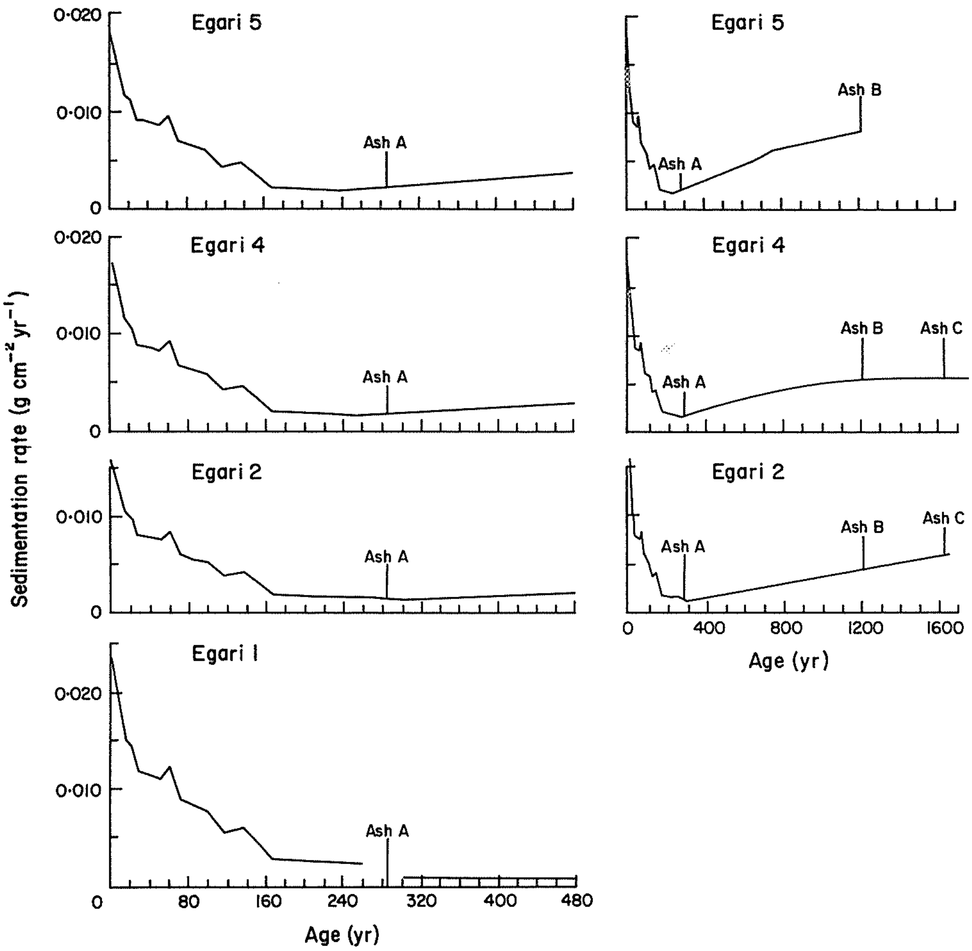

FIG. 11. Dry-mass sedimentation rates for Lake Egari, cores 1, 2, 4 and 5 (cf. Fig. 8). The left-hand diagram of each pair shows recent variations on an expanded scale. Year 0 is 1973 A.D.

whole may be inferred, although it would be tempting to interpret the evidence in terms of one of Lehman's schemes of sedimentary infilling (1975).

(iii) Over the last 200–300 yr patterns and rates of sedimentation have changed dramatically within and between the sites. At Lake Egari, dry-mass sedimentation began to accelerate slowly about 160–300 yr ago, though the clear-cut representation of this feature in Fig. 14 may in part be an artefact of the calculations used. From 160 to about 20 yr ago, a further acceleration is common to all cores, and the rate increases again over the last 20 years. At Lake Ipea the rate of acceleration increased some 250–300 yr ago, and then again much more sharply *c.* 140 yr ago. As at Lake Egari, there is a dramatic upsurge in the rate during the last 20 yr. All the sediments representing the periods of accelerated accumulation are minerogenic, with much lower loss-on-ignition values than the underlying material. Moreover, both lakes have remained acid and oligotrophic to the present-day. The increased sediment yield is therefore interpreted as being largely the result of accelerated allochthonous input.

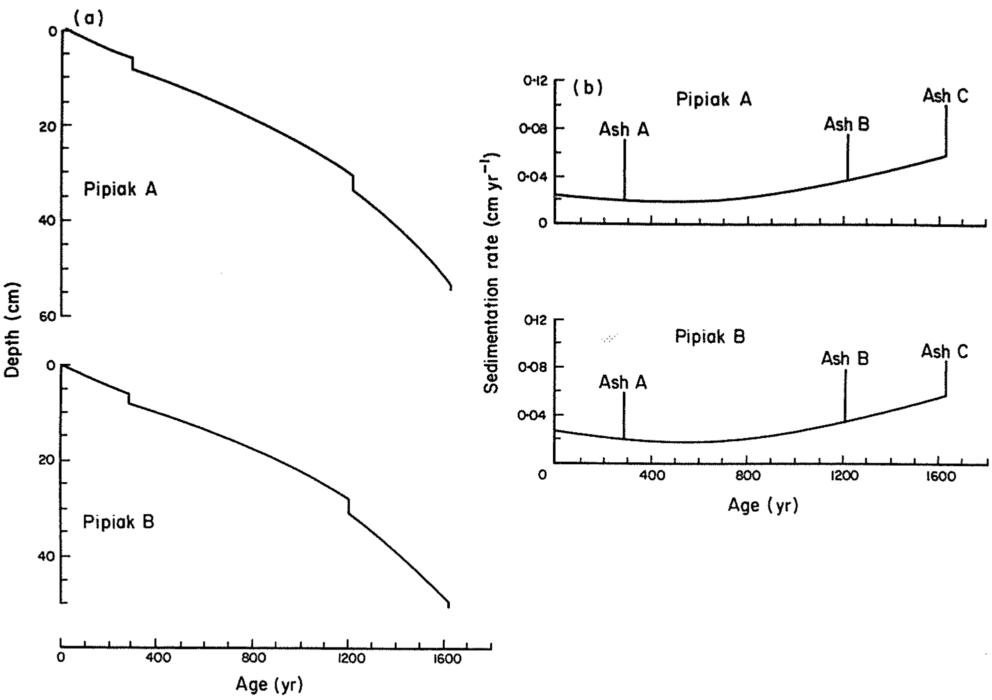

FIG. 12. Age/depth profiles (a) and wet-volume sedimentation rates (b) for Lake Pipiak, cores A and B. Year 0 is 1973 A.D.

(iv) In contrast to the results from Lakes Egari and Ipea, the rate of sedimentation in the Lake Pipiak cores shows very little increase in recent times, and the estimated rate at the time of sampling (1973 A.D.) is lower than that recorded prior to *c.* 1000 B.P.

Table 3 summarizes some of the salient features of the recent changes in sedimentation at each site.

At both Lake Egari and Lake Ipea, where acceleration in sedimentation has taken place, the beginning of the increase almost certainly post-dates the introduction of the sweet potato. There is supporting archaeological and anthropological evidence for larger populations and more intensive land-use and upward extension of the altitudinal limits of subsistence resulting from the introduction of this plant. At both these sites, the period of effective 'Western' contact over the last 20 yr coincides with peak sedimentation

TABLE 3. Calculated rate of dry-mass sedimentation (10^{-2} g cm^{-2} yr^{-1}) at different dates for Lakes Ipea and Egari, and of wet-volume sedimentation (cm per 100 yr) for Lake Pipiak; for details of calculation, see text

		Date 500 B.P. (a)	200 B.P. (b)	100 B.P. (c)	40 B.P. (d)	1973 A.D. (e)	(e)/(a)	(e)/(b)
Lake Ipea:	maximum	0·21	0·26	0·77	1·92	5·26	31·6	25·0
	minimum	0·13	0·18	0·57	1·42	3·88	19·2	14·9
Lake Egari:	core 1	~0·10	~0·30	~0·80	~1·10	~2·35	~23·5	~ 7·8
	core 2	0·20	0·18	0·53	0·78	1·58	7·9	8·8
	core 4	0·32	0·20	0·59	0·87	1·75	5·5	8·8
	core 5	0·44	0·21	0·61	0·90	1·81	4·1	8·6
Lake Pipiak:	core A	1·91	2·01	2·15	2·24	2·35	1·23	1·17
	core B	1·74	1·98	2·18	2·30	2·43	1·40	1·23

rates. The range of cultural, technological and demographic factors which may have provoked the increased erosional loss indicated, however, lie outside the scope of the present paper. The recent acceleration in sedimentation is registered to different extents between cores and sites, and the most marked effects are at Lake Ipea, now surrounded mostly by grassland. However, the difference in rates in Lake Egari between marginal and deep-water cores, though inconclusive, suggests that sedimentation may have responded to the recent changes more strongly in marginal than in central depositional environments. This would be compatible with an allochthonous terrestrial origin and a relatively high terminal velocity for the recently sedimented material. By contrast, Lake Pipiak, the lake with the catchment still almost completely forested and least affected by human activity up to the time of sampling, shows negligible acceleration in accumulation.

Magnetic, chemical and pollen-analytical evidence for the type and source of the recent sediments and for the nature of the vegetation and land-use changes associated with the inferred accelerated erosion will form the subject of subsequent papers.

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APPENDIX

Inter-core correlation of ^{210}Pb data

The c.r.s. model of ^{210}Pb dating assumes a constant flux of ^{210}Pb into each core site. This assumption may not be valid when there is post-depositional redistribution of sediment. The model can be generalized to take account of this, provided that redistribution is confined to recently-deposited sediments, so that at each site in the lake the sediments in a core are nearly in chronological order.

Let ξ be a depth parameter which identifies synchronous sediment layers. If P is the total ^{210}Pb flux across the sediment/water interface of a given area of the lake, and $A(\xi)$ is the total residual unsupported ^{210}Pb beneath the sediment layer of depth ξ and age t, then, provided redistribution is confined within this area,

$$A(\xi) = \int_t^{\infty} P\,\mathrm{e}^{-kt}\,\mathrm{d}t$$

regardless of the pattern of redistribution. Integration of this equation gives the age/depth relation

$$A(\xi) = A(0)\,\mathrm{e}^{-kt} \qquad \text{(A1)}$$

The total residual unsupported ^{210}Pb, $A(\xi)$, is determined by dividing the area into n sectors of area α_i, measuring the total residual unsupported ^{210}Pb per unit area, $A_i(\xi)$, in a core in each sector, and calculating the sum

$$A(\xi) = \sum_{i=1}^{n} A_i(\xi)\alpha_i$$

In the case of the New Guinea lakes, we have used the depth parameter

$$\xi = x/x_{\mathrm{ash\,A}}$$

where x is the actual depth and $x_{\mathrm{ash\,A}}$ is the depth of Ash A. We have also assumed that each core is typical of a constant area α. In this case Eqn A1 becomes

$$\bar{A}(\xi) = \bar{A}(0)\,\mathrm{e}^{-kt} \qquad \text{(A2)}$$

where

$$\bar{A}(\xi) = \frac{1}{n}\sum_{i=1}^{n} A\,(\xi)$$

Thus the dating parameter is obtained by plotting curves of A_i against ξ for each core, and taking the mean value of these curves for each value of ξ. The relationship between ξ and t is then used to calculate age/depth curves for the individual cores.