Application of impulse radar to continuous profiling of tephra-bearing lake sediments and peats: an initial evaluation

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Abstract Subsurface interface radar (SIR), or impulse radar, uses electromagnetic pulses for continuous stratigraphic profiling. It has been applied to lake sediments (dy-gyttja) and peat deposits containing a sequence of thin, late Quaternary, ash-grade tephras at Lake Maratoto, North Island, New Zealand. The SIR system is very rapid, precise, and reasonably accurate compared with conventional coring and probing methods, but still requires good stratigraphic control for reliable interpretation. Radar penetration depths of up to 10 m were attained. Interfaces between lake bottom and lake sediments and underlying volcanogenic materials of varying lithologies could be readily discerned, as could many of the tephra layers preserved within the lake sediments. Peat depths and positions of stumps or logs on the surface of the subpeat materials could also be determined. Given adequate calibration by drilling, the SIR system appears useful for various shallow subsurface exploration studies, particularly those involving tephrostratigraphy and paleoenvironmental reconstructions from limnic and peat deposits, and in projects on buried wood.

Keywords subsurface interface radar; radar methods; electromagnetic logging; pyroclastics; stratigraphy; lake sediments; peat; limnology; paleolimnology; Lake Maratoto; Rukuhia; bogs; organic materials

INTRODUCTION

This paper briefly describes and evaluates the first application in New Zealand of impulse radar to stratigraphic profiling of tephra-bearing lake sediments, peat, and some associated volcanogenic deposits. Impulse radar, known also as subsurface interface radar (SIR) or electromagnetic subsurface profiling (ESP), has only recently become available in New Zealand. It has, however, been used elsewhere since 1970 (Morey 1974), initially for civil engineering purposes but lately for other geoscience applications such as permafrost and ice thickness measurement, alluvial stratigraphy, lake and peat profiling, and subsurface erosion studies (e.g., Campbell & Orange 1974; Kovacs & Gow 1975; Davis et al. 1976; Kovacs 1977; Rossiter & Gustajtis 1978; Bjelm 1980; Ulriksen 1980, 1983; Leggo 1983; Arcone & Delaney 1984).

Conventional studies on peat and lake sediment stratigraphy and subsurface topography are done by laborious and costly drilling, coring, and probing methods (e.g., Davoren 1978; Green & Lowe 1985, this issue), or seismic profiling. Alternative methods such as peat penetrometer and electrical resistivity soundings have also been tried in New Zealand but with little success (Risk 1974). The SIR system, which functions like an echo-sounder but utilises electromagnetic pulses rather than sound waves, has been acclaimed as being extremely rapid and also accurate in shallow subsurface exploration studies (Bjelm 1980), and highly advantageous in providing a continuous subsurface profile. Consequently, it was seen as a potentially valuable tool for investigating the geomorphology of the shallow lakes and peat bogs in the Waikato region as part of the University of Waikato's programme of paleolimnological studies in northern North Island, New Zealand. In addition, the ability of SIR to detect the thin tephra layers preserved within the lake sediments and the peats was of particular interest because a series of profiles, with suitable stratigraphic and chronologic control, would possibly enable developmental stages of the lakes and peats to be accurately and rapidly mapped in both space and time. Thus, Lake Maratoto and the adjacent Rukuhia peat bog (Fig. 1), with a known subsurface geomorphology and tephrostratigraphy (Lowe et al. 1980; Green & Lowe 1985), were selected for a trial investigation of the capabilities of SIR. This study is necessarily only a preliminary evaluation because of limitations posed by the availability of the SIR equipment.

PRINCIPLES OF THE SIR METHOD

The SIR system can be considered the electromagnetic equivalent of single-trace acoustic profiling systems (Morey 1974). It radiates repetitive short-duration (1–6 ns) electromagentic pulses (voltage

Received 10 July 1984, accepted 24 June 1985

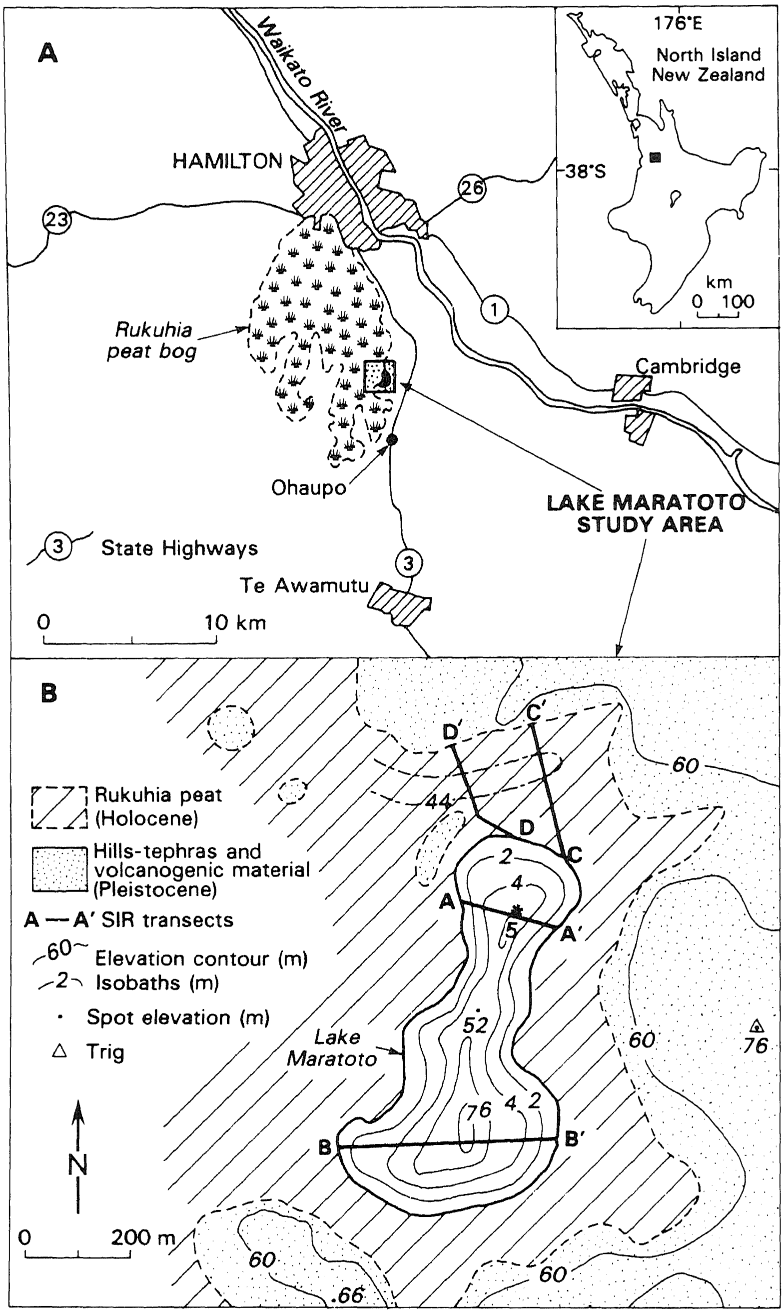
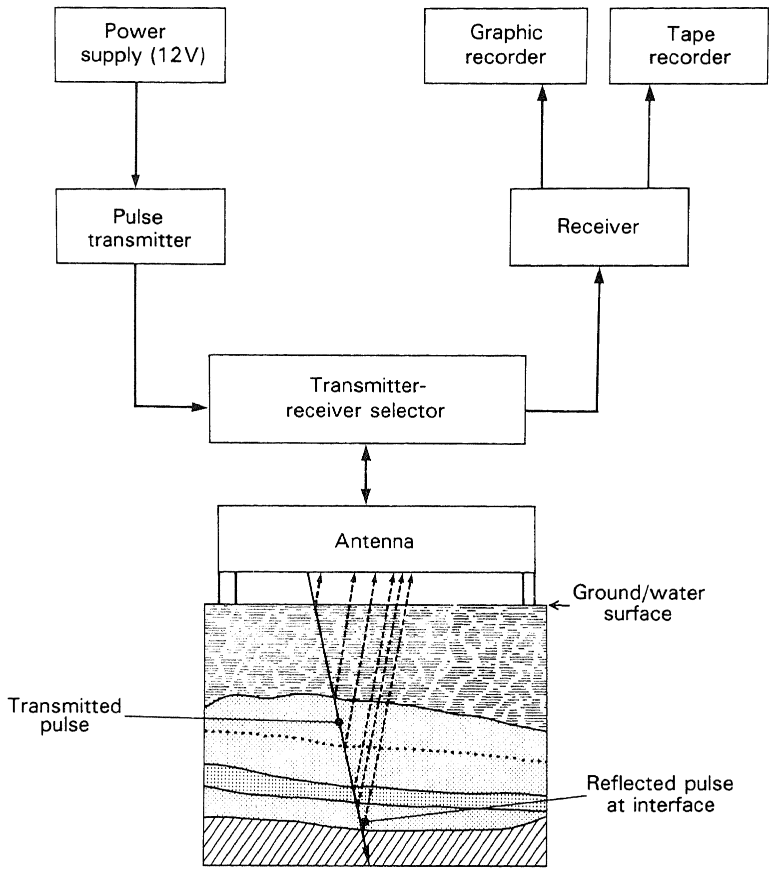


Fig. 1 A Location map of Lake Maratoto and the Rukuhia bog in the North Island, New Zealand. B General site conditions around Lake Maratoto and the positions of the SIR transect lines. The 44 m contour (dash-dot line) outlines part of a 10 m deep subpeat paleovalley. Details of the stratigraphy and subsurface geomorphology are given in Green & Lowe (1985); bathymetry is after Irwin (1982). The asterisk marks the coring site of the core shown in Fig. 3.

pulses) at a repetition rate of 50 kHz from a broadband width antenna (80–1000 MHz) which is moved in contact with the ground or water surface. Reflections are received from surface and subsurface discontinuities (interfaces) because of changes in electrical properties in the materials, and are displayed on a continuous strip-chart recorder (or magnetic tape recorder) (Fig. 2). The travel time from the surface to the interface and back is measured and, since the chart paper is calibrated in nanoseconds, can be readily converted to depth or thickness, after either direct calibration by drilling,

Fig. 2 Schematic block diagram of the impulse radar system (after Morey 1974).



which is usual, or from a knowledge of the electromagnetic parameters of the materials being investigated. The effective (average) propagation velocity through the material overlying a subsurface interface is derived from the relationship

$$v_m = \frac{2D}{t}$$

where D = measured depth to reflecting interface, t = elapsed time between transmitted and received pulse and, once known at one or more sites along a profile of similar deposits, can be used to determine D for other sites along that profile (Morey 1974). (For example, the average velocity through peat is about 0.4×10^8 m/s; Ulriksen 1980.) Another way of estimating v_m without drill calibration is the common point depth method (e.g., see Taner & Koehler 1969; Ulriksen 1980). The effective relative dielectric constant of the penetrated material can be derived from the relationship

$$\varepsilon_r = \left(\frac{c}{v_m}\right)^2$$

where c = propagation velocity in free space (3×10^8 m/s). This is useful for getting an idea of the type of materials being probed and, because ε_r is affected by water, their moisture content (Morey 1974; Ulriksen 1980).

In peat bog studies, volumes of peat can be calculated from the areas of a series of profiles, with accuracies only slightly below those obtained by drilling methods (Ulriksen 1980).

The graphic recorder instrumentation, through an overlapping scale expansion facility, allows any desired ratio of vertical to horizontal scale (the vertical scale is typically greatly exaggerated). In practice, continuous profiling is done by towing the antenna on a sled over the ground surface, or floating it behind a boat on water, at a speed of about 5 km/h.

APPLICATION OF SIR AT LAKE MARATOTO

Investigation site and methods

Lake Maratoto (37°53′S 175°18′E) is a small peat lake up to 7.1 m deep lying on the eastern border of the Rukuhia peat bog near Hamilton (Fig. 1). Its stratigraphy and developmental history has recently been described in detail by Green & Lowe (1985). The lake was formed c. 17 000 years ago when alluvium (Hinuera Formation) deposited by the ancestral Waikato River dammed a southwest-draining embayment in low Pleistocene hills. The lake was initially shallow but for the past 11 000 years or so has been greatly affected by the growth of the Rukuhia bog, becoming deeper and dystrophic but probably maintaining a fairly constant area. The peat is now 8 m deep on the southwestern edge of the lake and up to 10 m deep in a narrow paleovalley to the north of the lake (Fig. 1B).

Between 2 and 3 m of fine-grained, organic-rich lake sediment (gyttja or dy-gyttja) has been deposited in the lake, the uppermost metre or so being peaty in character, and it contains numerous (c. 20) thin, distal, well-preserved tephra layers of 2–40 mm thickness and of mainly fine to coarse ash (Lowe et al. 1980). The 10 or so thickest tephras are compact and clearly distinguished from the soft lake sediment by their contrasting colour and lithology (Fig. 3). The lake sediment is underlain by clays or muds or gravelly sands of the Hinuera Formation, or weathered gritty muds (mainly colluvium) derived from late Pleistocene tephras overlying strongly weathered middle Pleistocene tephras and volcanogenic deposits (Fig. 3; Green & Lowe 1985). Three or four diffuse tephra layers (each about 20 mm thick) can usually be detected, together with occasional woody fragments, in the peat column near the lake.

Four transects were made (Fig. 1B), two across Lake Maratoto (A–A′, B–B′) and two across the peat (C–C′, D–D′). The detailed stratigraphy of the subsurface materials along these transects has been determined by intensive coring and probing as recorded in Green & Lowe (1985). An SIR System 4*, with a 3130 transducer, an antenna centre frequency of 120 MHz, and a pulse time of 3 ns, was used in each of the radar transects.

Lake transects

Sections of the radar profiles (radargrams) as obtained in the field are reproduced in Fig. 4. No subsequent processing has been done. The SIR system was able to clearly show: (1) the lake bottom

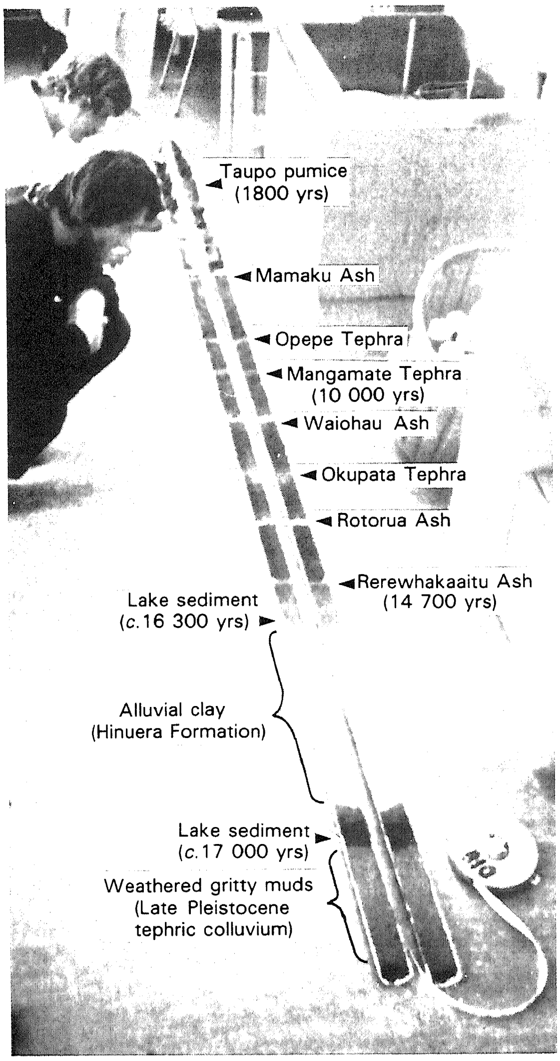


Fig. 3 A 3.3 m long longitudinally sliced core taken from the northern part of Lake Maratoto (Fig. 1B) using a modified Livingstone piston corer. Interfaces between the gross stratigraphic units were identified on the radar profiles along A–A′ (Fig. 4). The stratigraphy and chronology of the core is after Lowe et al. (1980) and Green & Lowe (1985).

(Photo: R. R. Julian)

(i.e., the lake water – lake sediment interface); (2) the boundary between the lake sediments and the underlying materials; (3) multiple interfaces, assumed to correspond to some of the thicker, more compact tephra layers within the lake sediments; and (4) differences in the sublake sediment materials which, from prior knowledge through coring, could be appropriately designated as alluvial muds or clays ("smooth" or linear reflections in Fig. 4) (Hinuera Formation), or gritty muds ("blotchy"

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*Geophysical Survey Systems, Inc., Hudson, U.S.A.

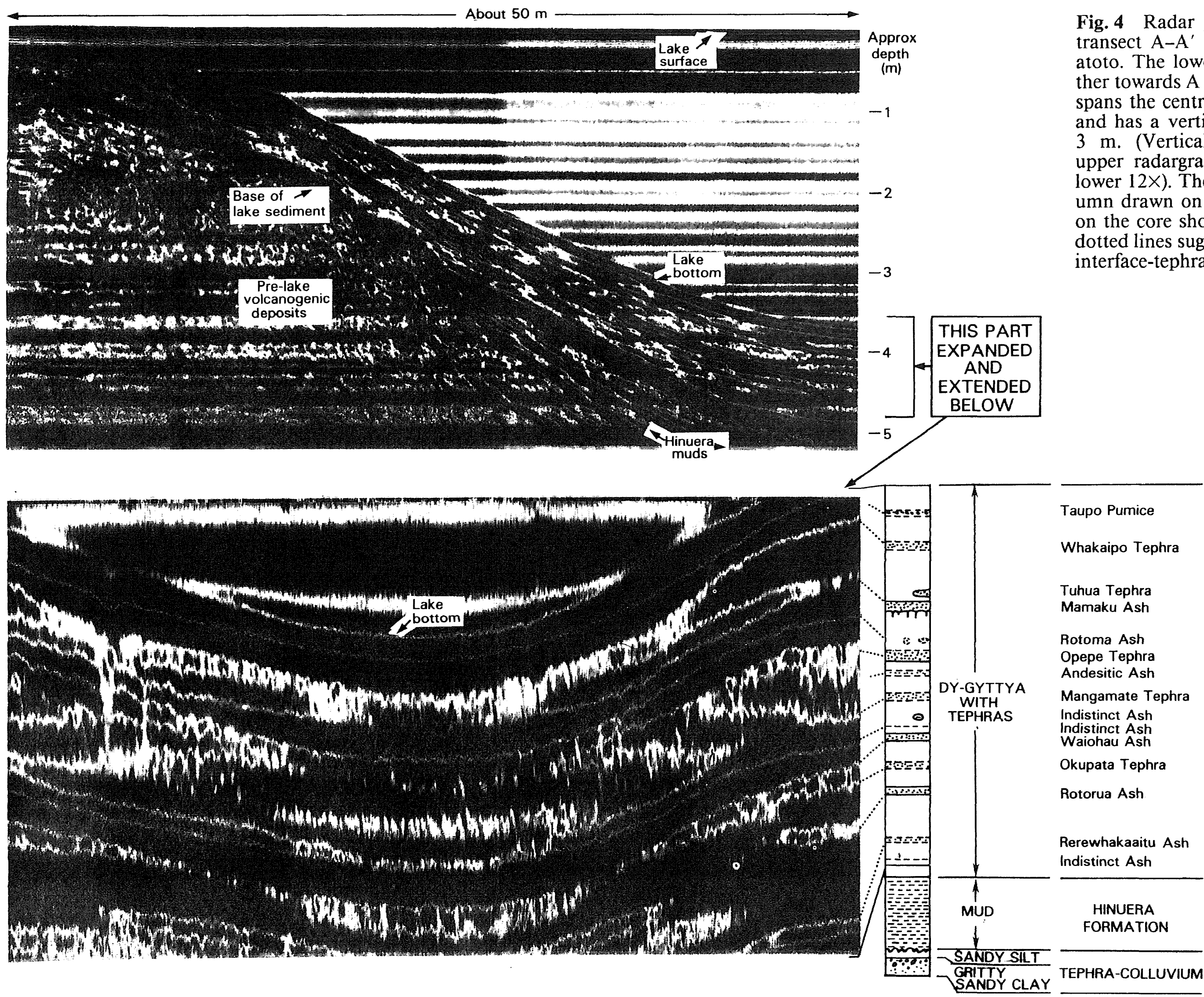

Fig. 4 Radar profiles of part of transect A–A′ across Lake Maratoto. The lower radargram (further towards A along the transect) spans the central axis of the lake and has a vertical scale of about 3 m. (Vertical exaggeration of upper radargram is approx. 5×, lower 12×). The stratigraphic column drawn on the right is based on the core shown in Fig. 3. The dotted lines suggest some possible interface-tephra correlations.

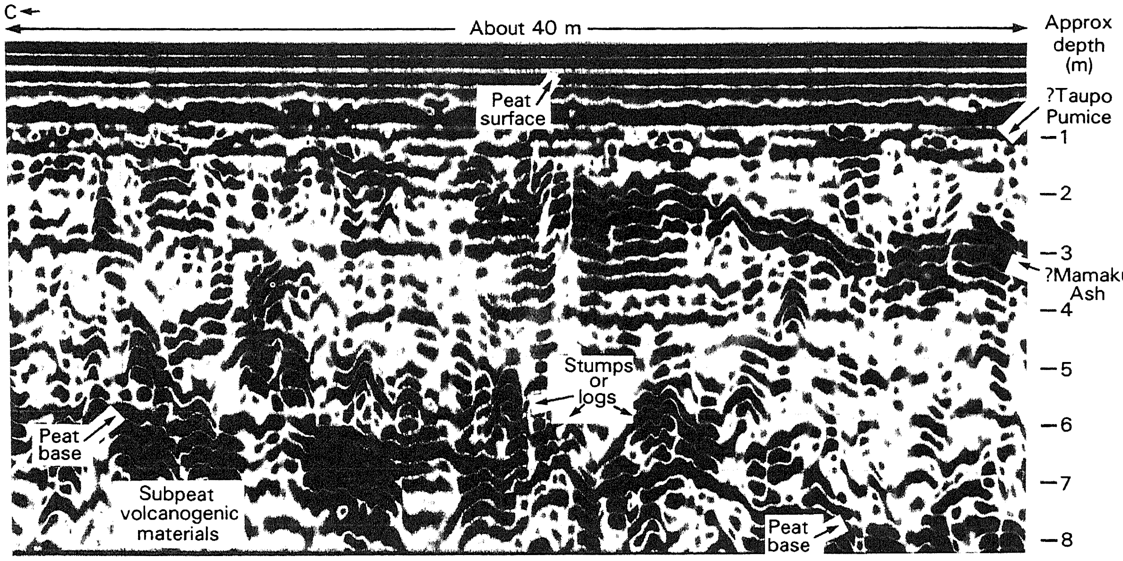

Fig. 5 Radar profile of part of transect C–C′ about midway across an arm of the Rukuhia peat bog at Lake Maratoto (vertical exaggeration approx. 2×). The interface-tephra correlations are tentative suggestions only. Taupo Pumice occurs just below the water table.

reflections in Fig. 4) (weathered tephric colluvium and volcanogenic materials). Each of these different units is visible in the sediment core, shown in Fig. 3, which was taken from the centre of the lake along transect A–A′ (core 4,lb of Green & Lowe 1985).

The total depth of penetration achieved was about 10 m (including up to 7 m of water plus 3 m of lake sediment); the depths closely matched those determined by Green & Lowe (1985). It was evident from scale expansion of the lake sediment parts of the profiles (as in the lower part of Fig. 4) that the tephra layers are often uneven in thickness but generally follow the shape of the basin topography. Not all of the tephras are represented right across the lake basin (cf. fig. 8 of Green & Lowe 1985). This is because the lake area contracted to about half its present size at c. 13 000 years ago due to marginal peat development (Green & Lowe 1985). Also, the depth of water in the lake (hence thickness of lake sediment) remained low (c. 2 m in the deepest part) until the Rukuhia bog began expanding rapidly from about 11 000 years ago. A series of accurately positioned SIR surveys would enable such features as paleoshorelines of the lake to be rapidly plotted using the spatial distributions of the identified tephras as chronologic markers (as achieved to a certain extent, but with far greater effort, by Green & Lowe 1985).

Peat transects

Peat profiles obtained by SIR (Fig. 5) were less clear than the lake ones, but enabled the peat-substratum interface to be readily mapped. Some gross stratification within the subpeat materials (i.e., tephric colluvium and older volcanogenic deposits) was also evident in the radargrams. The hyperbolic-shaped reflections on the subpeat surface are interpreted as stumps (possibly *in situ*) or logs. (Because of their form they are evidently exposed to the radar beam for a relatively long time and hence look bigger on the radargrams than they are in reality—Bjelm 1980; Ulriksen 1980.) Emergent stumps and logs are abundant on the Rukuhia bog in areas that have been drained and developed (cf. Cranwell 1939), and wood was frequently encountered at the base of the peat during the probing and coring around Lake Maratoto. One such large piece of wood, embedded in the uppermost subpeat materials at c. 6 m depth in a drillhole close to point C (Fig. 1B; Green & Lowe 1985), has been identified as rimu root wood, *Dacrydium cupressinum* (L. Donaldson, Forest Research Institute, pers. comm. 1983). It has an age of (Wk508) 12 550 $\pm$ 110 years B.P. (old half-life), determined by the University of Waikato Radiocarbon Dating Laboratory (Hogg 1982). Within the peat column itself are several broad interfaces (spaced at 2 m or so depth intervals) that may correspond to changes in the degree of peat humification (cf. Bjelm 1980) and/or water content. The diffuse tephra layers in the peat were not able to be made out with certainty, apart from two possible layers as indicated in Fig. 5. This may be due in part to considerable noise on the radargrams because of the coarse, occasionally fibrous and woody nature of the peat. Also, the tephras in the peat are more disseminated and have greater depth variability than their counterparts preserved in the fine lake sediments. Evidently, computer processing techniques that improve the signal-to-noise ratio and help in data interpretation have been developed by the SIR manufacturer (Morey 1974), but they were not available for this study.

The total depth of penetration achieved on the peat transects was about 8 m (including up to 8 m of peat) and corresponded closely with the depths obtained by probing. Repetitive profiling along the same transects gave consistent results.

CONCLUSIONS

This pilot study at Lake Maratoto, the first of its kind in New Zealand, was limited in scope, and the interpretations should properly be viewed cautiously. Nevertheless, the results confirmed many of the previously claimed attributes of the SIR system. SIR is very fast and precise, is reasonably accurate when compared with conventional techniques, and provides an instant, continuous subsurface profile. At Lake Maratoto, a total depth penetration of 10 m was achieved through a variety of materials including fresh water, peat, lake sediments, tephras, and water-saturated sediments ranging in texture from clays to gravelly sands. Apart from the clays, these materials are apparently well suited to SIR because their low conductivities cause minimal attenuation of the electromagnetic pulses; other materials may be less amenable to investigation by SIR (Morey 1974; Arcone & Delaney 1984).

Resolution of the SIR system was good enough to identify several different units making up the subsurface materials. It was particularly easy to map the lake bottom and to distinguish between the lake sediments and the coarser underlying materials. The depth of peat and the positions of stumps or logs on the subpeat surface were also readily determined. The apparent delineation by SIR of thin ash-grade tephra layers, of only a few centimetres thickness, in the fine-grained lake sediment is particularly impressive. The system could thus be very effective in various studies involving tephrostratigraphy, especially in mapping limnic and peat deposits for paleoenvironmental reconstructions, and in studies on buried wood.

As with most geophysical tools, data interpretation of SIR requires experience and at least some knowledge of the subsurface terrain under investigation. Hence, confident interpretations of the radargrams need good stratigraphic control, as was available in this study. With further refinements, such as the incorporation of computer processors (noise filters) and in-line 3-D block diagram plotters, the SIR system appears to offer considerable potential as a valuable tool for shallow subsurface exploration in New Zealand.

ACKNOWLEDGMENTS

I thank Dr J. D. Green, Mr K. Thompson, and Professor J. D. McCraw (University of Waikato) for their useful discussions and support in this study, and an anonymous reviewer for helpful comments on the manuscript. Mr L. Donaldson (Forest Research Institute, Rotorua) and Dr A. G. Hogg (Waikato Radiocarbon Dating Laboratory) are thanked for respectively identifying and dating wood sample Wk508. I acknowledge also the assistance of Strata Geophysics Ltd (Wellington) in obtaining the SIR profiles, and am especially grateful to Mr B. Davies for providing access to Lake Maratoto.

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