Appendix A4

Guidelines for the use of geophysical methods in the assessment of glacial hazards

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A4.1 Introduction

In remote areas it is seldom feasible for ground investigations to be undertaken using drilling techniques due to the size, weight, and dimensions of the rigs, unless vehicular access is possible. Consequently, non-invasive methods represent a range of highly sophisticated and extremely portable tools that can be used to provide information about the sub-surface. Furthermore, different geophysical methods respond to different physical properties of the materials present and can thus provide complementary information about the sub-surface materials, structures, and indeed processes. Given the nature of modern geophysical equipment, surveys can be undertaken over both clean and debris-covered glaciers, moraines and lakes.

Geophysical methods for glacial hazard assessment were first reported to have been used in the Peruvian Andes in the 1970s (Lliboutry *et al*., 1977), the European Alps since the 1980s (Haeberli and Epifani, 1986), but were not used in the Himalayas until 1996 (Hanisch *et al*., 1998) since when they have been used regularly.

As part of the present DFID-funded project, geophysical methods were used at Imja Tsho in the Khumbu Himal, Nepal, in conjunction with surface geomorphological mapping and topographic surveying. Experiences with geophysics during these field programmes, in conjunction with previous experience of geophysical surveys at Thulagi Glacier Lake, Upper Marsyangdi, Nepal, in 1996 and at Tsho Rolpa, Rolwaling Himal, Nepal, in 1999 and 2000, have resulted in these recommendations for best practice.

A4.2 Geophysical methods in glaciology

Historically, a number of geophysical methods have been used in glaciological investigations, predominantly under research conditions and these are listed in Table 4.1. Detailed descriptions of the methods have been given by Reynolds (1997). BY far the oldest and most developed use of geophysics in glaciology has been Radio-Echo Sounding, particularly of polar ice sheets. However, since early 1990s, commercially-available Ground Penetrating Radar systems have become available (e.g. Sensors & Software's PulseEKKO; Mala Geoscience's RAMAC system) that are highly portable. Over the last few years, lower frequency bistatic antennae (25-100 MHz) have become available thereby increasing the potential benefit to glaciological users due to the greater depth penetration achievable.

While geophysical methods have long been used over clean glaciers (since the 1950s), their use over debris-covered glaciers has only really been attempted routinely over the last ten years of so. One of the impediments to using modern equipment in developing countries has been the lack of availability of equipment coupled with lack of expertise in its use and interpretation.

Table A4.1: Geophysical methods used in glaciological investigations.

METHOD	EXAMPLE REFERENCES
Seismic reflection and refraction	Baker *et al.*, 2003
Gravity	Grant & West, 1965; Herrod & Garrett,1986
Ground Penetrating Radar and Radio-Echo Sounding	Bogorodsky *et al.,* 1985; Hanisch *et al.*, 1998; Richardson & Reynolds, 2000; Murray *et al.*, 1997; Moran *et al.*, 2003
Electrical resistivity methods	Pant & Reynolds, 2000; Richardson & Reynolds, 2000

Italicised methods are those best used over debris-covered glaciers.

Seismic reflection and refraction profiling:- This has been used predominantly over clean glaciers and ice sheets to determine ice thickness and profiles of firnification. In order to achieve significant depth penetration (>100 m) explosives typically are required in order to generate sufficiently large signals. Melting shot holes in snow is relatively easy, but on debris-covered glaciers drilling shot holes and emplacing geophones is very difficult. Consequently, use over dirty glaciers is very restricted. Furthermore, the moraine cover/ice interface forms the principal refractor making achievement of any significant depth penetration beyond this interface extremely difficult. In order to map the moraine cover/ice interface over debris-covered glaciers requires a geophone interval of 1-2 m resulting in relatively short seismic refraction arrays even using a 48-channel system. This is inefficient in respect of ground coverage and also very limited in the type of information achievable. For these reasons seismic methods are not recommended over debris-covered glaciers.

Gravity profiling:- Historically, gravity methods have been used on large clean glaciers in order to obtain an indication as to ice thickness. The limitations on this method are the requirement to have very high resolution topographic surveying (vertically to ±2 mm; horizontally to ± 100 mm), a stable platform for each gravity station, ease of return to a base station within a 45 minute loop, and a low noise environment. In the case of noise, high mountain environments often are affected by strong winds that affect the gravimeter, which is in effect a very sensitive seismometer – any vibrations will detrimentally affect the measurement spring and cause degradation of data quality. Where glaciers are particularly active or have significant amounts of supraglacial stream activity, ambient noise levels can be even greater. Profiles over glaciers occur in very steep terrain, such as the Himalayas, making terrain corrections extremely difficult to calculate, so reducing the accuracy of the gravity readings. Where ice thickness profiles have been compared between those from seismic profiles and gravity sections, agreement tends to be no better than to within ±10%.

Radio-Echo Sounding (RES) and Ground Penetrating Radar (GPR):- Radio-Echo Sounding normally, but not exclusively, is restricted to polar ice sheets. In the 1980s sledge-mounted RES was attempted on glaciers in the Karakoram with some degree of success (e.g. Dong *et al.*, 1988). A low frequency radar system was deployed at Thulagi, Upper Marsyangdi, Nepal (Hanisch *et al.*, 1998) and used to determine buried ice thicknesses within a debris-covered stagnant ice body that effectively dams the glacial lake. Since then, GPR systems have been deployed at Tsho Rolpa, Rolwaling Himal (Mala Geosciences RAMAC system) in 1999-2000, and a Sensors and Software PulseEKKO 100 system was used at Imja Tsho, Khumbu Himal, Nepal, in 2001. These systems have been used to determine the depth to the debris cover over stagnant glacier ice within the moraine complexes, to locate structures within the buried ice and to provide estimates of ice thickness where adequate depth penetration could be achieved. Antennae with centre-frequencies of 25 MHz and 100 MHz have been used (Figure A4.1). If radar antennae are placed at the bottom of an inflatable boat with wooden floorboards (not metal), good quality data can be acquired over shallow parts of glacial lakes (e.g. water depths <20 m) (Figure A4.2). Digital data acquired with modern GPR systems can be viewed on laptop computers using software supplied with the equipment by the radar system manufacturers or using commercially available GPR processing software, such as RADAN 5 (GSSI) or in seismic reflection processing packages, although bespoke radar packages are preferred.

Fig. A4.1: Ground Penetrating Radar survey (Mala Geosciences RAMAC system) in use on moraines at Tsho Rolpa, Nepal.

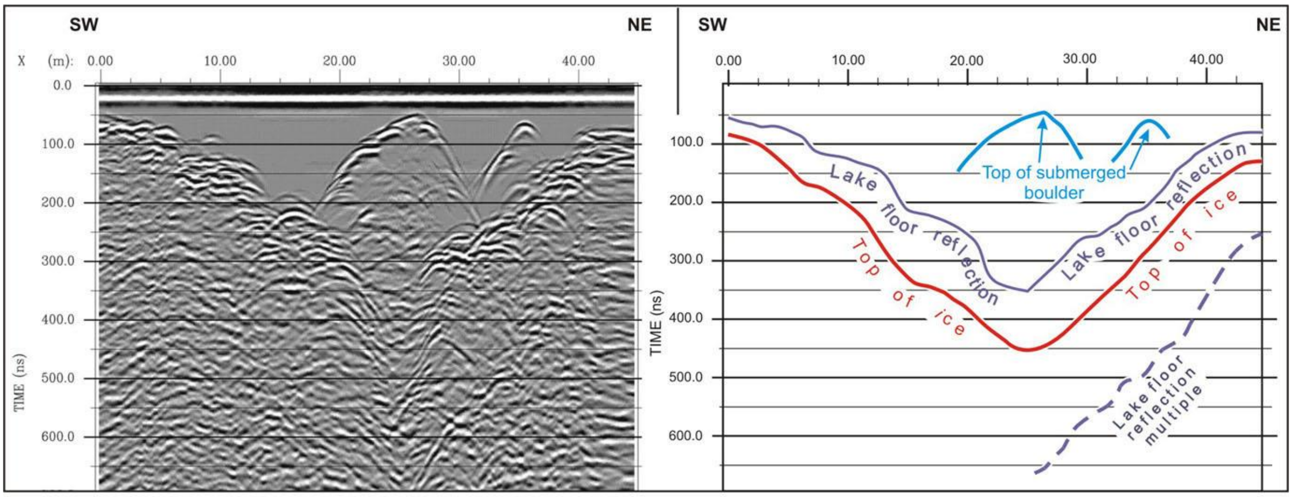


Fig. A4.2: Example radargram and interpretation obtained over Tsho Rolpa glacial lake, Nepal.

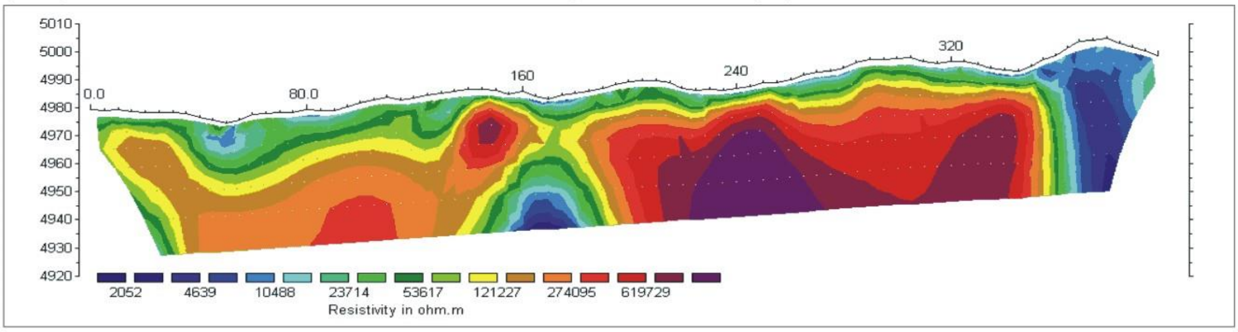
As with all GPR surveys, in addition to the need to acquire high-quality field data, appropriate and adequate data processing should be undertaken in order to produce the most robust interpretation. To this end, determination of *in situ* radiowave velocity should be undertaken using the Wide Angle Reflection and Refraction (WARR) method (see Reynolds, 1997). Once an indication as to relevant radiowave velocities through different local materials has been determined, radargrams can be interpreted in terms of estimates of depth. In morainic material at Imja Tsho, for example, depths of penetration in excess of 40 m have been obtained using 25 MHz and 100 MHz antennae, and even greater depths obtained when imaging into glacier ice.

Electrical resistivity tomography:- Röthlisberger (1967) used electrical resistivity sounding to investigate glaciers in Switzerland and the same approach was taken by Lliboutry *et al.* (1977) at Hatunraju in the Cordillera Blanca. However, interpretational methods available at these times limited the type of information that could be determined from these measurements. In the Himalayas, for example, electrical resistivity tomography has been used with great effect to locate buried ice masses beneath debris cover. In most cases it is possible to find areas of relatively fine-grained material in which to emplace electrodes, but it is still normal practice to have to water each electrode with salt solution in order to reduce the electrode contact resistances to acceptable levels (typically <2,500 Ω). If surveys take too long, the drying out of the salt solution will cause the contact resistance to increase and thus this must be carefully monitored. Electrical resistivity tomography data take the form of a 2-d section in which apparent electrical resistivity values are displayed. These data can be inverted using commercially available software (e.g. RES2DINV) to produce images of true resistivity that are physically diagnostic of material types present (e.g. Pant and Reynolds, 2000). It is important to note that contrasting electrical targets that lie off the line of a given profile, such as a nearby body of buried ice, may be sensed by the survey. Off-section features need to be identified by correlation with local geomorphology in order to aid the overall interpretation. As a further aid to interpretation, detailed 3-D modelling of sub-surface features should be undertaken in order to reduce ambiguity.

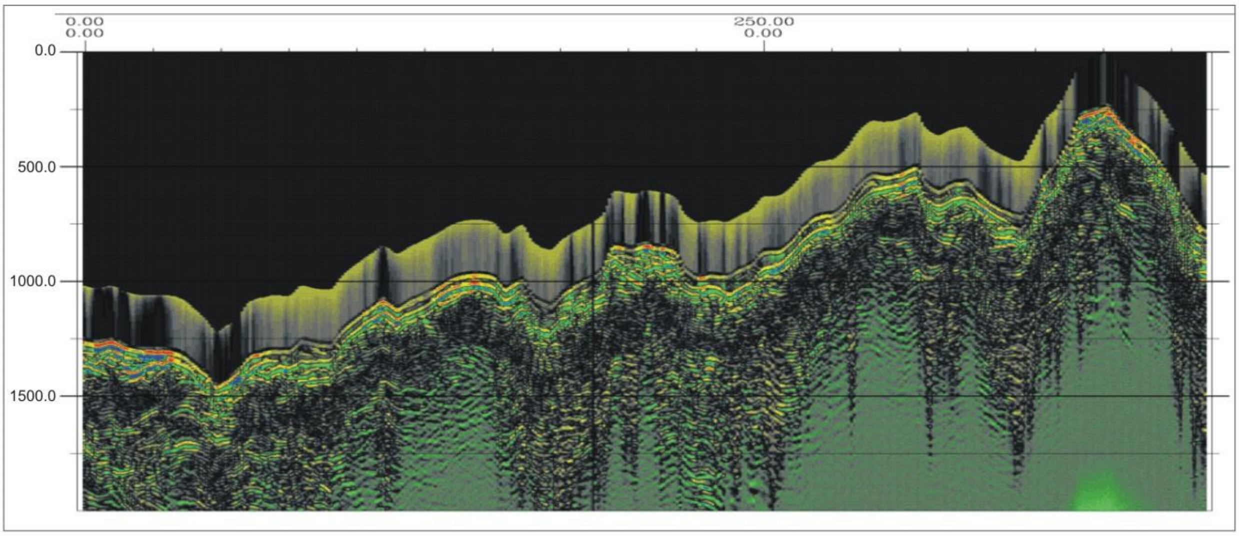
Where a moraine dam may exhibit seepages on the distal flank, it may be possible to locate internal water flow using Self Potential profiles along strike. This method has been demonstrated to be effective on man-made dams (e.g. Butler and Llopis, 1990) and has been used in an early trial at Tsho Rolpa, Rolwaling Himal, Nepal. The method has not been used sufficiently to detect internal flows of water within moraine dams to be recommended for general use in such applications. Further trial surveys should be undertaken to test the method.

Use of integrated methods:- Experience in the Himalayas suggests that the most efficient and most effective geophysical methods for glacial hazard work are when GPR and electrical resistivity tomography are used coincidentally. Furthermore, the best use of geophysical profiling is when transects are combined with other investigation methods such as geomorphological mapping and the results correlated with high- resolution images/photographs of the surface landforms. An example of the integration of an electrical resistivity image, a GPR profile, and its coincident geomorphological map, is provided in Figure A4.3.

A *Electrical resistivity profile (inverse model resistivity section), showing high resistivities (reds) in areas of buried ice, very low resistivities (blues) where the moraine sediments are saturated, and mid-range values for relatively dry sediments.*



B *Example radargram section from the same section as above.*



C *Morphological plan identifying active slope movement associated with melting buried ice. This basic field map is sufficiently detailed to identify the surface expression of internal features within the moraine identified in the 2 geophysics sections above.*

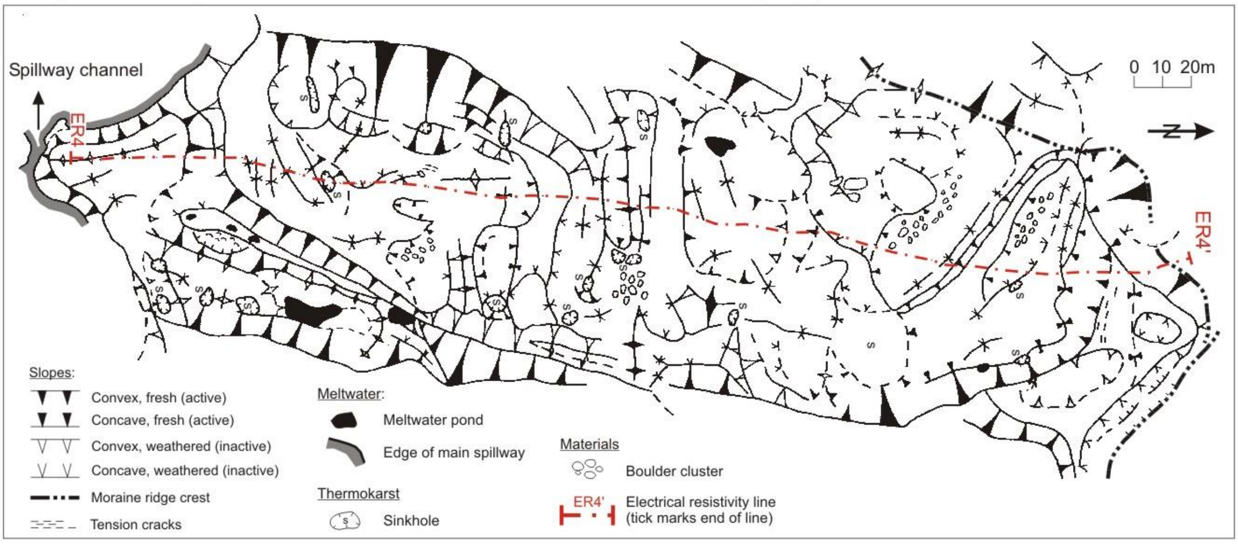


Fig. A4.3: Integration of various geophysical and geomorphological approaches to identify the location and thickness of buried ice, Imja Tsho, Nepal.

As with any geophysical investigation it is of paramount importance that accurate topographic surveying of each transect is undertaken so that topographic effects can be incorporated within the data processing and visualisation of the data.

A4.3 Conclusions

From experience within the Himalayas over debris-covered glaciers, the most effective geophysical methods, when used coincidentally, are Ground Penetrating Radar and Electrical Resistivity Tomography. These methods provide key information about the subsurface such as presence of buried ice, internal structures within ice, structures within moraines, and general material types. By deploying such methods strategically, it is possible to determine the extent of buried ice, location of former crevasses within buried ice masses (that may be subject to reactivation, differential melting, *etc*.), presence of shallow englacial drainage, and buried glacial channels within moraine complexes.

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