Radio-Echo Sounding Over Polar Ice Masses

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ABSTRACT

Radio-echo sounding (RES) constitutes the principal means by which glaciologists investigate the subsurface properties of the polar ice sheets and ice caps. Developed in the 1960s as a method for locating and mapping the subglacial interface beneath extensive regions of ice-covered terrain, thereby to constrain ice volume and morphology, it was quickly discovered that RES supplies numerous additional cryospheric parameters, including strong reflectors derived from subglacial lakes, and isochronous internal reflectors derived from burial of snow deposition events. Soon after its establishment, RES was integrated into long-range aircraft primarily to image the bed across Antarctica and Greenland (1960s/1970s). More recent airborne campaigns (1980s/1990s), while supplementing this coverage and extending to the ice caps of the High Arctic, have utilised only short-range aircraft, and were designed explicitly to support specific scientific studies, such as locating optimal sites for deep ice-coring, constraining the dimensions of subglacial lakes, or resolving internal layers for studies of ice sheet mass balance, form and flow. In parallel with these developments, ground-based (over-snow) RES equipment has also been used to investigate the englacial and subglacial conditions at a number of key locations across the polar ice sheets. This article discusses the many scientific advances which have resulted from these efforts, and offers recommendations for future developments in terms of (i) reanalysis of existing data and (ii) suggestions for future RES campaigns.

Introduction

Radio-echo sounding (RES) is a technique through which scientists investigate the subsurface properties of polar ice masses. RES, also known as ice-penetrating radar (IPR) or radar sounding, primarily exploits electromagnetic (EM) waves in the HF/VHF (megahertz) bands, to which, it was discovered in the late 1950s, cold ice is largely transparent. Prior to this discovery, glaciological calculations reliant upon such basic quantities as ice thickness and volume were based on a very limited and widely-spaced set of active seismic measurements, which were highly labor-intensive to obtain; and the englacial properties of ice sheets and ice caps remained enigmatic. Today, RES comprises an efficient method for the collection of a wide range of fundamental subglacial and englacial data from polar ice masses, complementing the extensive array of observations on surface elevation and flow that are now obtained using satellite remote sensing methods (Bindschadler, 1998). To constrain these boundary conditions is important, because it is widely recognised that ice sheets and ice caps fluctuate in response to climate change, thereby impacting significantly on sea levels; and our ability to predict future behaviour is fundamentally dependent upon the accurate determination of past and present ice volumes, subglacial morphology, accumulation and melting rates, and rates of ice flow.

RES equipment comprises a transmitter that emits EM waves and a receiver that records their reflections (or 'echoes') from any surfaces where there is a contrast in dielectric properties. Over ice sheets and ice caps, the most common reflectors constitute the ice surface, the basal interface, and englacial (internal) layers; although additional features such as subglacial lakes, subsurface crevasses and thermal boundaries can also be discerned.

RES apparatus can be mounted either on to airborne or ground-based (over-snow) platforms. For comprehensive studies of ice sheets and ice caps over scales of 10 s to 100 s of km, airborne RES constitutes the most logistically feasible and efficient mechanism for gathering subsurface data. In particular, airborne RES programmes conducted over Antarctica and Greenland since the 1960s have revolutionised our understanding of the englacial and subglacial conditions beneath the surfaces of these vast polar ice sheets. For some investigations however, for example in smaller-scale (km to 10 s of km) studies, surveys in regions of complex subglacial topography (*i.e.*, outlet glaciers), or simply in an attempt to reduce costs associated with the expensive deployment of aircraft, ground-based RES (a.k.a., Ground-Penetrating Radar, GPR) has been preferred.

In this article, we build upon recent reviews of RES in glaciology (Plewes and Hubbard, 2001; Dowdeswell and Evans, 2004) by focusing on the current state of the field in RES over *polar* ice masses, *i.e.*, the Antarctic and Greenland Ice Sheets, and the large ice caps of the Canadian and Eurasian High Arctic. Over these vast ice masses the majority of RES has been conducted from airborne platforms, hence this review will tend to focus on airborne studies; however, we will also reference significant results and findings that have arisen from associated ground-based studies. In particular, we consider the types of data that have been generated by RES and the issues to which they have been applied to date; and based on these discussions we propose some future directions for RES surveying over the polar ice sheets and ice caps.

Subglacial Exploration and Investigations

Subglacial Topography and Ice-Mass Morphology

Airborne RES techniques were initially developed to locate the bed reflector beneath continental-scale areas of ice-covered terrain, thereby to constrain subglacial topography for the determination of ice-mass morphology (Evans and Robin, 1966). The first wide-ranging, comprehensive and systematic airborne RES surveys designed for this purpose were conducted between 1967 and 1979 over the 12.4 million km^2 Antarctic Ice Sheet by a consortium of the University of Cambridge's Scott Polar Research Institute (SPRI), the U.S. National Science Foundation (NSF) and the Technical University of Denmark (TUD). These "SPRI-NSF-TUD" surveys used a 60 MHz pulsed instrument, designed for optimal ice penetration and bed detection beneath several km of ice, mounted onto a U.S. C130 Hercules long-range aircraft, which facilitated surveying deep in the ice-sheet interior 100 s of km from the nearest scientific support camps (Bailey *et al.*, 1964; Gudmandsen, 1969; Robin *et al.*, 1977; Siegert, 1999).

The SPRI-NSF-TUD Antarctic RES surveys proved seminal; covering much of the continental ice sheet at a grid spacing of 50–100 km, imaging the bed along 86% of the 400,000 km of tracks flown, and achieving an areal coverage which has never subsequently been matched (Siegert, 1999). The 70,000 bed echoes gathered in the campaign were used to produce the first map of Antarctic subglacial topography (Drewry, 1983), and showed for the first time that the ice was, on average, 2.5 km thick, reached a maximum depth of 4.7 km, and had a volume of ~30 million km^3 which, if melted completely, would raise global sea level by ~60 m (Dowdeswell and Evans, 2004). The survey findings were also instrumental in the conceptual division of the ice sheet into two components: the 'continental' East Antarctic Ice Sheet (EAIS), found to be grounded mainly above modern sea level and therefore considered relatively stable, and the 'marine' West Antarctic Ice Sheet (WAIS), found to be grounded mainly below modern sea level, and therefore considered potentially prone to rapid flotation and collapse in response to rising sea levels and/or thinning (Mercer, 1978). Twenty-seven years after the SPRI-NSF-TUD RES campaigns were discontinued in 1979, many sectors of the continental ice sheet that it surveyed have never been revisited. The data gathered remains commonly exploited in contemporary studies, and the scientific hypothesis of WAIS instability that it instituted remains at the heart of many scientific programmes in Antarctica.

Subsequent airborne RES campaigns in Antarctica, while implicitly incrementally supplementing the continental coverage of subglacial topography, have all explicitly been directed to support specific scientific activities, such as searching for optimal sites to locate deep ice cores, or obtaining high resolution records of internal layering which can be used to investigate ice dynamics and ice sheet evolution (a theme we investigate in more detail later in this paper). Examples include detailed site surveys associated with the European Project for Ice Coring (EPICA) deep ice-core sites at Dome C (Tabacco *et al.*, 1999; Remy and Tabacco, 2000; Forieri *et al.*, 2004) and Dronning Maud Land (Steinhage *et al.*, 1999; Steinhage *et al.*, 2001), East Antarctica; and extensive surveys of the Siple Coast ice streams (Retzlaff *et al.*, 1993; Blankenship *et al.*, 2001; Peters *et al.*, 2005), Ellsworth Land, Marie Byrd Land, and the Antarctic Peninsula (see Lythe *et al.*, 2001, and references therein), designed to obtain detailed input for numerical modelling investigations of ice streams and potential WAIS instability. These surveys have all utilized smaller, more economical, short and medium-range aircraft (*e.g.*, DeHavilland Twin Otter, Dornier Do228-101, Lockheed P-3); and, in addition to 'filling in' some of the 'gaps' left by the SPRI-NSF-TUD surveys, have delivered high-resolution records of subglacial topography across a number of key sites in Antarctica.

In 2001, RES records of ice thickness in Antarctica were collated and incorporated into a new database (BEDMAP; Bedrock Mapping Project) held at the British Antarctic Survey. This database combined determinations of the bed reflector from airborne RES with those from various ground-based RES surveys (*e.g.*, Tabacco *et al.*, 1998; Gades *et al.*, 2000) as well as additional measurements from seismics, gravimetry and ice coring (Lythe *et al.*, 2001). Containing over 2 million ice thickness measurements, BEDMAP was used to generate an updated digital elevation model (DEM) of Antarctic subglacial topography over a grid resolution of 5 km^2 (Lythe *et al.*, 2001). This latest version of Antarctic subglacial topography, when combined with surface elevation data yielded by satellite altimetry, suggests that Antarctica presently supports 25.7 million km^3 of ice, and the DEM constitutes an integral boundary condition for recent estimates of satellite-derived mass balance change across Antarctica (Arthern and Hindmarsh, 2003; Rignot *et al.*, 2004).

Nevertheless, in many regions of Antarctica, most notably in remote, interior regions of the EAIS, the basal reflector remains very poorly constrained by empirical observations, often restricting the ability of numerical models to reproduce significant facets of ice sheet form and flow in response to climatic stimuli. RES efforts since 2001, and the generation of the first iteration of BEDMAP, have therefore continued to image the bed in regions of particular data paucity, gradually enhancing our knowledge of the subglacial topography beneath hitherto non-surveyed regions. Significant airborne surveys which have added to our knowledge of basal topography since 2001 therefore include: (i) investigations over Coats Land, East Antarctica, from which the Bailey and Slessor Ice Streams contribute significant mass to the Filchner-Ronne Ice Shelf from a highly-overdeepened basin (Rippin *et al.*, 2003a; Rippin *et al.*, 2004); (ii) surveys over the Amundsen Sea sector of West Antarctica containing the rapidly thinning Thwaites and Pine Island basins (Thomas *et al.*, 2004; Holt *et al.*, 2006; Vaughan *et al.*, 2006); (iii) traverses from the Transantarctic Mountains into interior East Antarctica, including the South Pole region (Davis *et al.*, 2004; Studinger *et al.*, 2004a); and (iv) expanded coverage over Dronning Maud Land in the vicinity of the EPICA Kohnen ice-coring site (Steinhage *et al.*, 2001; Ferraccioli *et al.*, 2005). Coordinated over-snow RES surveys conducted as part of the International Trans-Antarctic Scientific Expedition (ITASE) are also adding to our knowledge of subglacial conditions across Antarctica (Welch and Jacobel, 2003). The contemporary RES coverage of Antarctica is shown in Fig. 1a.

Over Greenland, airborne RES surveys conducted throughout the 1970s by the Technical University of Denmark, again using a 60 MHz system, covered ~30,000 km of flight track, and revealed that the ice sheet had a mean ice thickness of 1.4 km, a maximum depth of ~3 km, and a total ice volume of ~2.83 million km^3 (Gudmandsen, 1969; Bogorodskiy *et al.*, 1985; Létreguilly *et al.*, 1991). Subsequent surveys, as in Antarctica, were more regionally concentrated, and largely associated with the search for optimal deep ice-coring sites (Hodge *et al.*, 1990; Jacobel and Hodge, 1995; Dahl-Jensen *et al.*, 1997; Hvidberg *et al.*, 1997; Hempel *et al.*, 2000). However, since 1993, a wide-ranging airborne RES survey of the Greenland Ice Sheet, using a 150 MHz system designed and operated by researchers at the University of Kansas, under the auspices of the US NASA PARCA (Program for Arctic Regional Climate Assessment) initiative, has taken in over 105,000 km of flight track, surveying ~80% of the ice sheet with an average along-track spacing of 150 m (Gogineni *et al.*, 2001) (Fig. 1b–c). This extremely high-quality and comprehensive dataset has been used to generate updated DEMs of the subglacial topography beneath the Greenland Ice Sheet which, when combined with satellite altimetry measurements, yields an ice volume of 2.85 million km^3, whose wholesale melting could cause global sea level to rise by ~7 m (Bamber *et al.*, 2001, 2003). There do, however, remain regions of Greenland, particularly across many of its outlet glaciers, where thick, warm ice tends to scatter the radar signal and the bed remains obscured, and efforts are ongoing to develop methods to image the bed in these most challenging sectors of the ice sheet (Braaten *et al.*, 2002). This is especially important in the light of recent satellite observations of significant accelerations of many of Greenland's outlet glaciers (Rignot and Kanagaratnam, 2006).

Elsewhere in the Arctic, RES has also been used to image the bed and map the subglacial topography of selected ice caps in the Canadian Arctic islands (Evans and Robin, 1966; O'Neil and Jones, 1975; Narod *et al.*, 1988; Dowdeswell *et al.*, 2004) and the Eurasian archipelagos of Svalbard (Drewry *et al.*, 1980; Macheret and Zhuravlev, 1982; Dowdeswell *et al.*, 1984), Franz Josef Land (Dowdeswell *et al.*, 1999) and Severnaya Zemlya (Bogorodskiy *et al.*, 1985; Dowdeswell *et al.*, 2002) (Fig. 1). These surveys provide vital morphological boundary conditions for modelling cryosphere-climate interactions across the High Arctic, where the smaller, and therefore more rapidly responsive, ice masses may contribute more mass to sea level rise over the next century than the major ice sheets. However, RES surveys have not, to date, been conducted over all of the Canadian Arctic ice caps, nor over the 23,600 km^2 North Ice Cap, Novaya Zemlya.

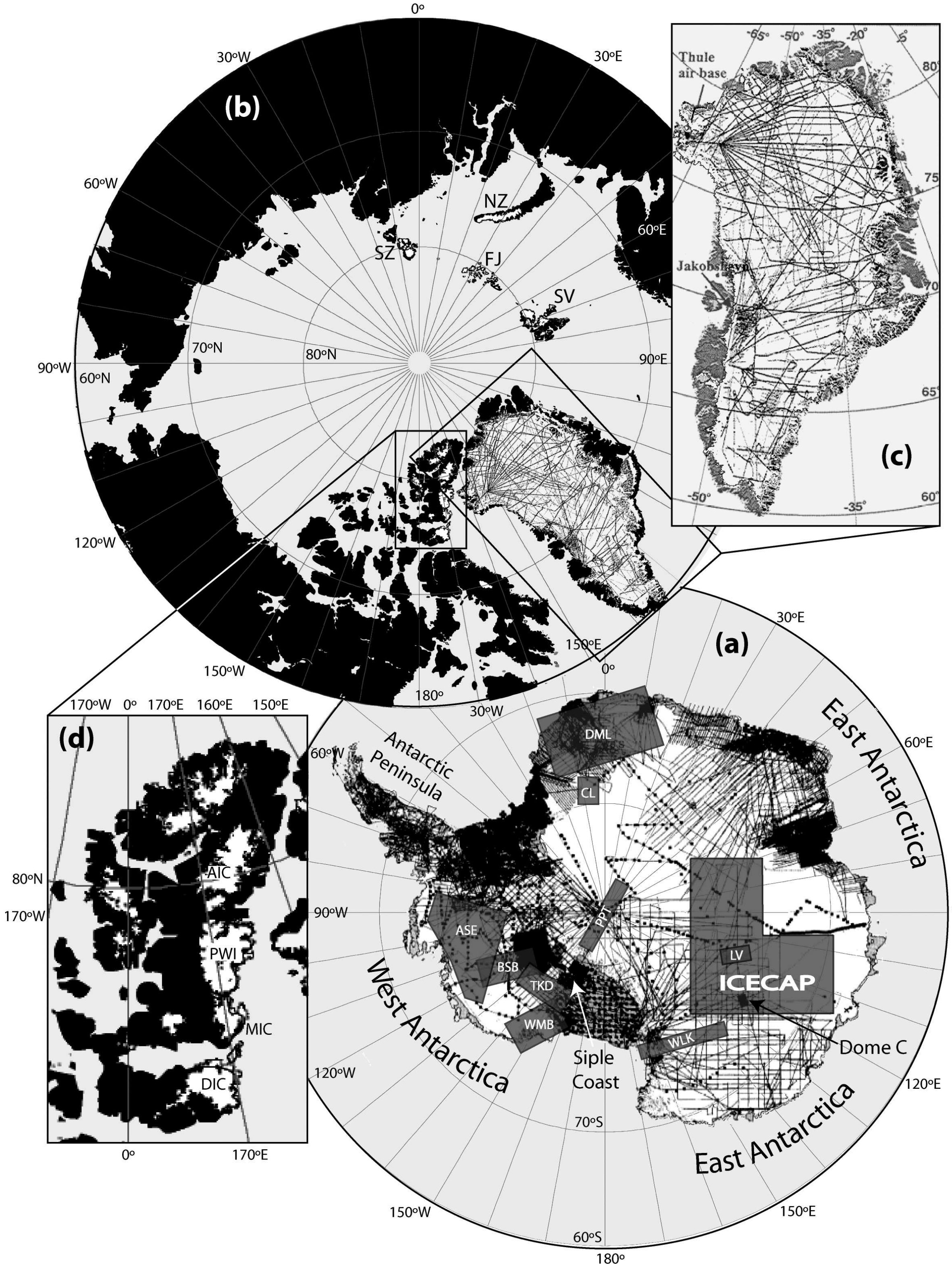

Figure 1. RES coverage over the polar regions. (a) Newly surveyed regions of Antarctica (shaded in grey) overlaid over the existing coverage according to BEDMAP (black lines; after Lythe *et al.*, 2001). DML = Dronning Maud Land; CL = Coats Land; ASE = Amundsen Sea Embayment; BSB = Byrd Subglacial Embayment; TKD = Trunk of Bindschadler Ice Stream (formerly Ice Stream D); WMB = Western Marie Byrd Land; PPT = Pensacola-Pole Transect; LV = Lake

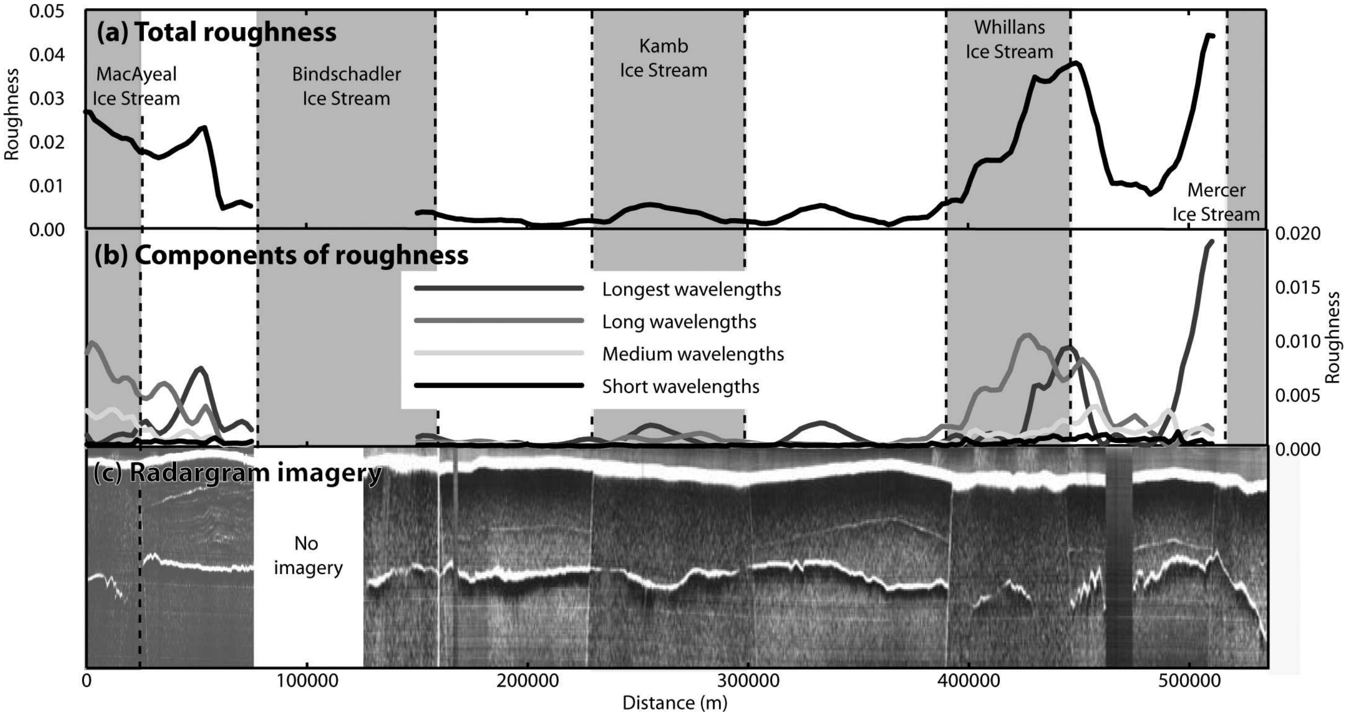

Figure 2. (a) Total roughness, (b) wavelength components of roughness, and (c) raw Z-scope RES data along a profile transecting five principal ice streams draining the Siple Coast region of Antarctica. In (b) wavelengths are as follows: longest >40 km; long 20–40 km; medium 10–20 km; and short 5–10 km. Adapted from Siegert *et al.* (2004b).

Subglacial Roughness and Subglacial Geology

Variations in the roughness and reflection coefficients of the bed reflector impart significant information for glacier geophysicists, in particular relating to rates of subglacial erosion and deposition, mapping of subglacial geology, and the detection of water at the base. We return to the last point in the following section.

A major recent development in the analysis of subglacial topography from airborne RES has been the quantitative regional characterisation of subglacial roughness, the wavelength-related variation of subglacial bedrock elevation with horizontal distance (Hubbard and Hubbard, 1998; Hubbard *et al.*, 2000; Taylor *et al.*, 2004). Bed roughness represents an important first-order measurement for understanding the potential effects of the bed in determining variations in ice dynamics over scales >10^2 km. This is because: (i) a bed that is smoother, and/or softer, than in surrounding areas may promote faster ice flow by proffering less frictional resistance to ice flow; and (ii) faster ice flow may, in turn, facilitate greater erosion at the base and therefore further smoothening of subglacial topography.

Such considerations have motivated analyses of subglacial roughness beneath both the WAIS and the EAIS. Beneath the Siple Coast region of West Antarctica, Siegert *et al.* (2004b) found that ice streams are generally associated with low bed roughness values while intervening ridges are generally underlain by rough basal topography. This has been taken to imply a subglacial topographic control on ice stream positions, while smooth subglacial topography beneath the ice streams is consistent with their being underlain by a thick layer of deforming subglacial sediments. An exception is provided by Kamb Ice Stream (formerly Ice Stream C), whose flanking ice ridges are also underlain by remarkably smooth subglacial topography which could facilitate (and/or reflect) lateral migration of that ice stream (Fig. 2). Subglacial roughness has also been

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Vostok; WLK = Wilkes Land. The area labelled ICECAP has been endorsed as a new region for surveying during the International Polar Year, 2007–09. (b) Overview of RES coverage across Arctic ice sheets and ice caps. SZ = Severnaya Zemlya; NZ = Novaya Zemlya; FJ = Franz Josef Land; SV = Svalbard. (c) Inset of Greenland RES coverage (black lines), after Bamber *et al.* (2003). (d) Inset showing locations of Canadian Arctic ice caps surveyed by RES. DIC = Devon Ice Cap; MIC = Manson Ice Cap; PWI = Prince of Wales Icefield; AIC = Agassiz Ice Cap.

analysed over East Antarctica, showing that whilst the ice divides at Ridge B and Dome A are underlain by rough basal topography, the subglacial interface beneath Dome C is surprisingly smooth. An explanation proposed for this apparent anomaly is that the subglacial morphology beneath Dome C is likely to predate the present ice-sheet configuration, and probably reflects substantial erosion under warm-based conditions (Siegert *et al.*, 2005b).

Analyses of subglacial roughness therefore provide valuable insights concerning rates of subglacial erosion and/or deposition and geology (which we discuss shortly), and there is much potential for further roughness analyses using already available datasets. In Antarctica, for example, attempts to discern the influence of subglacial topography on the flow of the ice streams draining into the Filchner-Ronne Ice Shelf could benefit significantly from an analysis of subglacial roughness; and airborne RES data have already been collected over many of these ice streams (Siegert, 1999; Rippin *et al.*, 2003a; Rippin *et al.*, 2004). Throughout Greenland, the extensive surveys of the University of Kansas PARCA consortium (Gogineni *et al.*, 2001) have provided the data which would facilitate widespread determination of subglacial roughness beneath the Greenland Ice Sheet. Airborne RES surveys over the Canadian and Eurasian Arctic ice caps (Dowdeswell *et al.*, 1984, 1999, 2002, 2004) also provide the wide-ranging data required to investigate subglacial roughness, but as yet such analyses have not yet been conducted.

Airborne RES, in combination with additional aeromagnetic surveying, also constitutes one of the principal methods used to map subglacial geology beneath the major ice sheets. This is especially the case over Antarctica, where options to view the bedrock directly, via subaerial outcrops or using coring methods, are scarce. Typically, variations in subglacial roughness, the bed reflection coefficient, and the distribution of aeromagnetic anomalies are all used in combination to characterise variations in subglacial geology. Notable early studies to use these methods included Drewry's (1976) geological division of the Aurora and Wilkes basins, East Antarctica; and characterisation of the subglacial West Antarctic Rift system by Behrendt *et al.* (1980) and Jankowski and Drewry (1981). The use of RES methods to map subglacial geology has snowballed since the 1990s as a series of targeted airborne programmes has simultaneously imaged the bed and collected gravity measurements over several key regions of Antarctica. Such surveys have exposed, for example, widespread, thick, unconsolidated sediments beneath a number of ice streams, interpreted as a vital control on their initiation and dynamics (Bell *et al.*, 1998; Blankenship *et al.*, 2001; Studinger *et al.*, 2001; Bamber *et al.*, 2006); and the presence of an active rift system beneath the West Antarctic Ice Sheet (Blankenship *et al.*, 1993; Behrendt, 1999, and references therein).

Subglacial Water and Subglacial Lakes

A particularly significant property of variations in RES bed echoes over polar ice masses is their use to infer whether water is present at the base, either overlying or within subglacial sediments. Significant early work in this regard was reported by Shabtaie *et al.* (1987), who examined airborne RES data collected over the Mercer, Whillans and Kamb Ice Streams (formerly Ice Streams A–C) and argued that relative reflection strengths (after correction for variations in subglacial geology and ice thickness) varied inversely with freezing at the bed. Bentley *et al.* (1998) developed this scheme further, arguing that high bed reflection strengths beneath Kamb Ice Stream evinced the existence of liquid water at its base, while low relative reflection strengths under Engelhardt Ice Ridge (Ridge BC) were taken to evidence underlying frozen till.

Ground-based RES techniques have also been developed to infer whether liquid water is present at the subglacial interface beneath polar ice. Notably, Gades (1998) developed a range of bed reflection powers (BRP) for subglacial materials ranging from frozen permafrost to a film of liquid water, and applied this categorisation to the subglacial interface from a RES profile transecting Siple Dome (Gades *et al.*, 2000). The study highlighted that while the dome itself is underlain by frozen material, the *dormant* ice streams flanking the dome appear to be underlain by water-saturated material. This was interpreted as suggesting that the presence of liquid water at the basal interface *alone* does not enable active streaming to take place (Gades *et al.*, 2000); rather additional conditions conducive to basal flow (*e.g.*, weak subglacial sediments, ice stream piracy) must apply to activate streaming. The BRP method for detecting subglacial water was further extended by Catania *et al.* (2003), who calibrated additional RES-derived measures of BRP with observations of water content in nearby boreholes. This calibration enabled Catania *et al.* (2003) to classify regions of low basal reflectivity as frozen at the bed, regions of high basal reflectivity as wet-based, and regions of intermediate reflectivity as a mix of the two. Applying this scheme to several further ground-based RES surveys across the Siple Coast region, Catania *et al.* (2003) confirmed the earlier contention of Bentley *et al.* (1998) that ice streams (both active *and* dormant) are predominantly wet-based, while the intervening ridges are frozen to the bed. Most recently, these findings have been supported by Peters *et al.* (2005), who developed a similar subglacial reflector classification scheme and applied it to

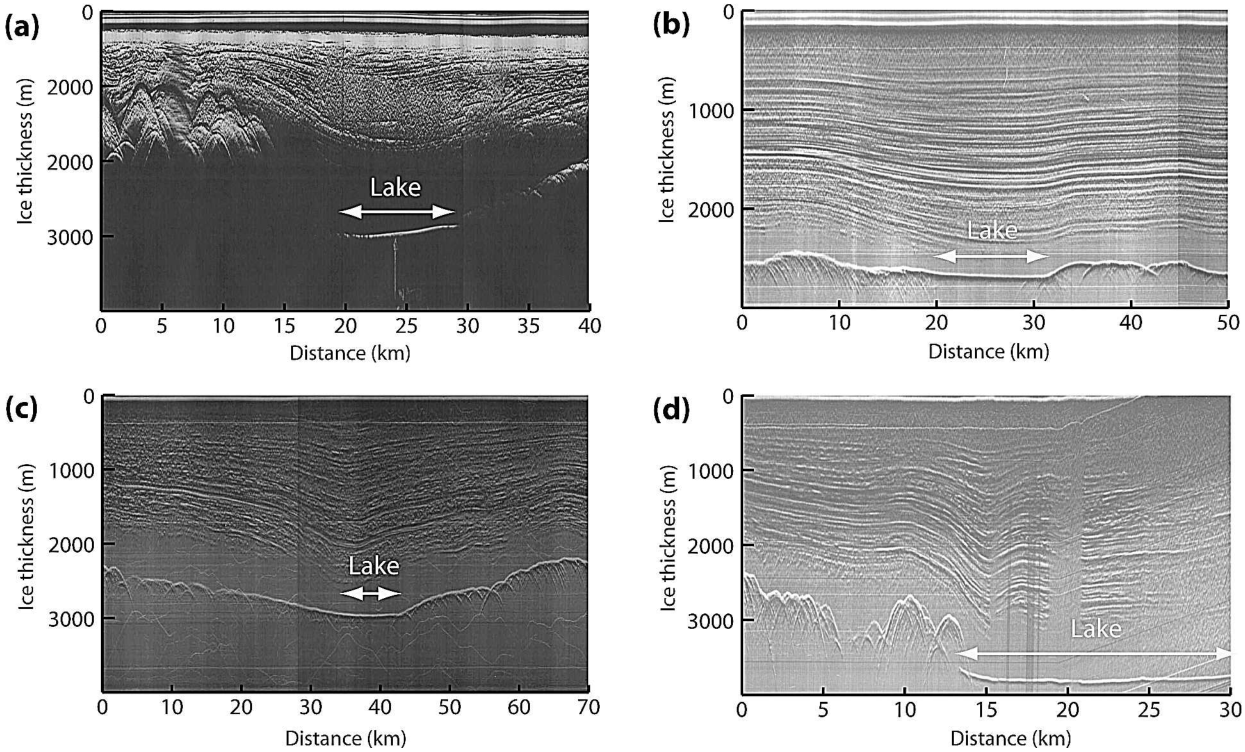

Figure 3. Examples of subglacial lakes identified from RES data collected during the SPRI-NSF-TUD campaigns 1974–79, and listed in Siegert *et al.* (2005a). (a) Lake no. 70, "Subglacial Lake Ellsworth," West Antarctica, (b) Lake no. 31, "Subglacial Lake Aurora," close to Dome C, East Antarctica, (c) Lake no. 16, in the Adventure Trench, East Antarctica, and (d) Lake. No. 2, "Lake Vostok," Antarctica's largest known subglacial lake, which continues off the right of the window imaged here.

investigate comprehensive airborne RES survey data collected over a large proportion of the Siple Coast region.

Where sufficient water is generated at the base of an ice sheet, it gathers into depressions in hydraulic potential, forming distinct bodies of subglacial water commonly termed 'subglacial lakes'. The existence of subglacial lakes, and the utility of airborne RES records in identifying them, was first discovered by observations of unusually strong and flat basal reflectors present within the SPRI-NSF-TUD airborne RES records collected across the Antarctic Ice Sheet in the late 1960s (Robin *et al.*, 1970, 1977). Subsequently, analysing all airborne RES records collected in Antarctica up until 1971/2, Oswald and Robin (1973) inventoried 17 subglacial lakes beneath the East Antarctic Ice Sheet, identifying such features wherever: (i) bed echoes were strong, bright and typically 10–20 dB greater in strength than surrounding bed echoes; (ii) bed echoes had constant strength along track, indicating a surface that is smooth with respect to the 60 MHz system wavelength; and (iii) bed echoes were especially flat compared with surrounding topography. The bed topography was also observed to have a reverse slope around 10 times that of the ice surface slope, consistent with a water body in hydrostatic equilibrium. 'Subglacial-lake' reflectors are therefore readily discernible from airborne RES data (*e.g.*, Fig. 3), and the above criteria have been used to compile and update catalogues of subglacial lake locations and dimensions beneath the Antarctic Ice Sheet as new surveys have been conducted (Siegert *et al.*, 1996; Siegert *et al.*, 2005a).

Investigations of Antarctic subglacial lakes using airborne RES techniques have been further boosted by the discovery, initially from the SPRI-NSF-TUD records (Fig. 3d), of the vast subglacial Lake Vostok beneath East Antarctica (Oswald and Robin, 1973; Kapitsa *et al.*, 1996). This lake fills a 230-km trough up to a depth of 1 km, has a surface area of ~14,000 km^2, and has an estimated maximum water-storage volume of >5,000 km^3 (Siegert, 2005). The suggestion that it may harbour unique forms of bacterial life and/or compounds isolated by ice cover 10^5–10^6 million yr ago, and which may therefore be analogous to extraterrestrial phenomena, has precipitated a range of efforts to drill through the ice and into this, and other, subglacial lakes in order to collect water and sediment samples for scientific analyses (Priscu *et al.*, 2003; Siegert *et al.*, 2004a; Inman, 2005; Tikku *et al.*, 2005). Such investigations have been aided considerably by the use of airborne RES in constraining more accurately subglacial lake morphology in order to inform modelling investigations and to provide detailed information for future drilling projects (Tabacco *et al.*, 2002; Studinger *et al.*, 2004b; Cafarella *et al.*, 2006).

The latest airborne-RES-derived inventory of Antarctic subglacial lakes, informed by the entire SPRI-NSF-TUD dataset and airborne surveys conducted over East Antarctica by Italian, Russian, and U.S. teams, now lists 145 lake-type reflectors beneath the ice sheet (Siegert *et al.*, 2005a). Cumulatively these are estimated to contain between 4,000–12,000 km^3 of water, which equates to a potential rise in global sea level of 10–35 mm. Individually, these 'lakes' probably lie along a continuum from the vast liquid body of Lake Vostok to substantial masses of water-saturated sediments.

It has recently been argued that a number of subglacial lakes, rather than being isolated, may in fact be interconnected, facilitating drainage from up-gradient to down-gradient locations, and ultimately to the ice-sheet margin (Dowdeswell and Siegert, 2003; Wingham *et al.*, 2006). If and/or where such connected drainage does take place, it is likely to occur as a series of rapid drainage events between basins, potentially accounting for observations of rare floods (Goodwin, 1988) and spectacular water-carved landforms (*e.g.*, Sawagaki and Hirakawa, 1997; Denton and Sugden, 2005; Margerison *et al.*, 2005) at the margins of the ice sheet. At present, however, there remain insufficient airborne RES data over many regions of Antarctica to state definitively whether the majority of subglacial lakes are connected.

In stark contrast to the Antarctic Ice Sheet, to date no distinctive subglacial lake reflectors have been observed from RES data collected across the Greenland Ice Sheet nor the polar ice caps of the Canadian and Eurasian High Arctic.

Detection and Application of Englacial Layers

Englacial, or internal, layers (a.k.a. Internal Reflecting Horizons, IRHs)—weakly-reflecting englacial horizons that commonly extend for several 10 s (and sometimes 100 s) of km across ice sheets (*e.g.*, Fig. 4)—were first identified as a fortuitous by-product of the extensive airborne RES programmes conducted over the Antarctic and Greenland Ice Sheets in the 1960s (Bailey *et al.*, 1964). Such layers represent echoes off any boundary where there is a contrast in the dielectric properties of the ice, resulting, variously, from contrasts in ice density, electrical conductivity, and/or ice crystal fabrics. Near the surface, density variations, exemplified by contrasts between firn and occasional ice lenses, probably account for most internal reflections (Moore, 1988). Below 1 km of ice, however, where compression negates density contrasts, most internal layers probably manifest variations in conductivity, resulting from fluctuations in the acidity of volcanically-derived aerosols incorporated into the ice when it was first laid down during discrete snow deposition events (Millar, 1981; Paren, 1981; Hempel *et al.*, 2000). In very deep ice (>3 km), subject to very large englacial stresses, changes in ice permittivity, related to the development of anisotropic or preferred crystal fabric orientations, may also be discernible as discrete internal layers (Harrison, 1973; Fujita *et al.*, 1999; Matsuoka *et al.*, 2003). Regardless of their origins, most internal layers picked out on RES radargrams are thought to represent constructive interference formed by radiowave reflections off several parallel and closely-spaced layers; thus the apparent thickness of individual layers observed in RES data is a function not only of its physical origins, but also the radiowave pulse length and frequencies used (Siegert, 1999; Miners *et al.*, 2002).

Internal layers have two significant attributes which make their detection and analysis invaluable. Firstly, they most likely represent discrete, or very closely-spaced, past deposits of snow, subsequently buried by firn compaction and converted to ice layers. Internal layers may therefore be treated as isochrones; palaeosurfaces of similar age. Secondly, and following on from this, the stratigraphy of internal layers, or isochrones, results from a combination of their burial rate (or surface accumulation) and the internal flow field. These considerations have precipitated the extensive use of internal layers in analysing a broad array of glacial geophysical problems.

Mass Balance

Cross-referencing internal layers with ice cores has gained considerable currency owing to the potential for extrapolating the one-dimensional climate records held in cores to two and three dimensions. Wherever an internal layer intersects an ice core, it is possible to assign to that layer an age based on the core record (Siegert *et al.*, 1998b; Hempel *et al.*, 2000; Baldwin *et al.*, 2003). This yields a spatially extensive stratigraphic control for calculations of surface accumulation along the entire length of the internal horizon being used (Nereson *et al.*, 2000; Morse *et al.*, 2002; Siegert and Payne, 2004). Occasionally, continuous internal layers have been traced between two or more ice cores; in which case not only do they provide a powerful means of synchronising ice core records, but they can also be used to determine accumulation rates, and their spatial

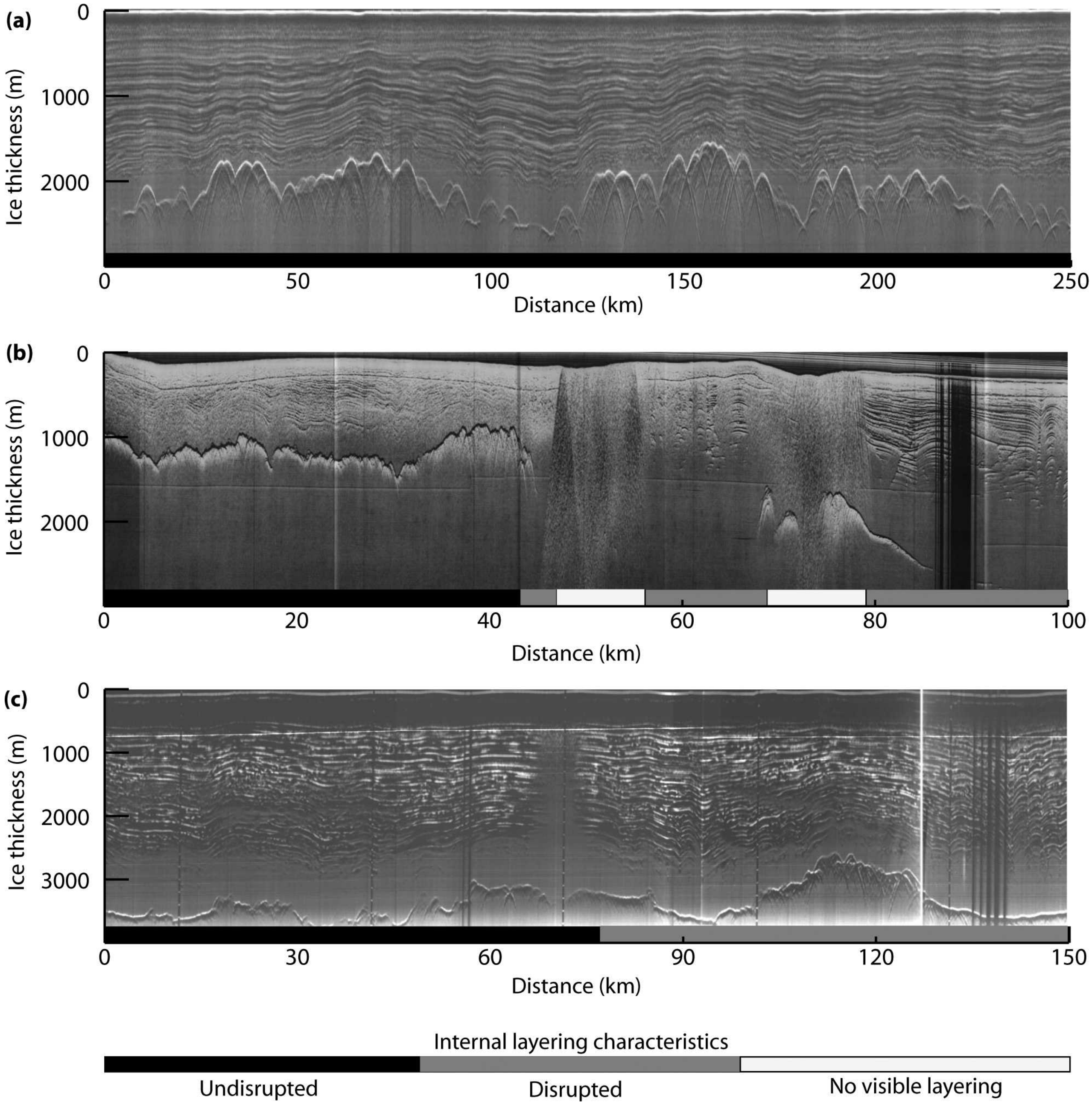

Figure 4. (a)–(c) Examples of internal layers imaged in Antarctica RES data collected during the SPRI-NSF-TUD campaigns of the 1970s, showing distinctive classes of internal layering, *i.e.*, continuous, buckled and absent, as discussed in text.

and temporal variability, between the separate core locations (Dahl-Jensen *et al.*, 1997; Hvidberg *et al.*, 1997; Siegert *et al.*, 1998a, 1998b). Within this context, continuous internal layers resolved from airborne RES surveys have proved particularly valuable, as surveys yielding unbroken records of internal horizons have been conducted over distances of several 100 km.

Furthermore, it is now standard practice, when exploring a putative ice-coring site, to conduct RES surveys over the area in a closely-spaced grid (Steinhage *et al.*, 2001; Morse *et al.*, 2002; Bianchi *et al.*, 2003; Frezzotti *et al.*, 2004; Jacobel *et al.*, 2005). This is driven by the requirement to select a site where the internal stratigraphy of the ice remains as undisturbed by flow as possible; thus the frequencies deployed are often designed as much to resolve internal layers as they are to image the bed. For example, detailed airborne RES surveys over the EPICA Dome C site have been used to derive several regional palaeosurfaces from internal horizons, providing particularly detailed, and temporally constrained, information for the derivation of regional variations in surface accumulation across the Dome C region (Siegert *et al.*, 2001).

In addition to calculating mass gain at the surface through accumulation, internal layers can also be used to determine mass loss at the base through melting (Fahnestock *et al.*, 2001a; Dahl-Jensen *et al.*, 2003). Any calculation of ice-sheet mass balance utilising internal layers as calibration must, however, account for the possible influences of vertical compression with depth, and also the potential impacts of ice flow, on internal layer stratigraphy. Beneath many ice divides, where most deep-ice cores are situated, vertical compression is stronger than elsewhere, but layer stratigraphy is typically least disturbed by lateral ice flow, thus a depth-age chronology is relatively simple to derive (Fahnestock *et al.*, 2001b). However, deep beneath some divides ice is so slow-flowing and stiff that upper layers tend to become draped over it, leading to an apparent upwarping of internal layers around it (Raymond, 1983). Such 'Raymond Bump' phenomena may disrupt simple layer stratigraphy and complicate the derivation of depth-age relationships. Furthermore, if the divide has migrated over time, the vertical axis of the Raymond Bump may become skewed in the direction of the divide shift, further complicating depth-age relationships (Raymond, 1983; Vaughan *et al.*, 1999; Pettit *et al.*, 2003; Martin *et al.*, 2006). With increasing distance away from ice divides, lateral ice flow imparts increasing disruption to internal layer stratigraphy, and the derivation of depth-age relationships becomes reliant upon relatively sophisticated ice-flow modelling (Hvidberg *et al.*, 1997; Mayer and Siegert, 2000).

Internal layer stratigraphy thus often reflects rates of surface accumulation and basal melting, but vertical compression and three-dimensional ice flow must be incorporated into mass-balance models which use internal layers as calibration.

Ice Dynamics and Ice Sheet Evolution

Although internal layers are often more or less bed-parallel and spatially continuous over distances of several 100 km, in some regions layer orientations diverge significantly from the bed and/or surface, and layers may become broken or indistinct. Various terms have been used to describe such disruption to englacial stratigraphy (*e.g.*, warping, folding, buckling, distortion), but it is generally agreed that, where accumulation and melting are relatively uniform, any disruption to bed-parallel internal layering must result predominantly from ice flow. In particular, it has been observed that internal layers experience severe disruption across ice-stream margins, which may be attributed to past and present variations in the internal strain field across strain boundaries (Jacobel *et al.*, 1993; Jacobel *et al.*, 1996; Bell *et al.*, 1998; Siegert *et al.*, 2003). In the particularly well-imaged Siple Coast region of West Antarctica, disruption of internal layering demonstrably originates upstream from regions of streaming flow, and the resultant folds advect into the ice streams, where the degree of distortion may be used to constrain the accumulated shear strain since they were produced (Jacobel and Bindschadler, 1993; Ng and Conway, 2004). Downstream, significant flow-induced disruption to internal layers may, in extreme cases, extinguish internal layers completely (Jacobel *et al.*, 1993). Disrupted internal layering is also widely observed across and within ice stream tributaries (Rippin *et al.*, 2003b; Siegert *et al.*, 2003), suggesting that wherever there is a contrast in flow conditions and strain, perhaps as a consequence of changes in basal boundary conditions at the onset of streaming, significant disruption to internal layers can occur.

The above considerations have expedited the application of airborne-RES-derived internal layers to analysing ice flow across the major ice sheets. In particular, RES data can supplement measurements of ice flow gained by satellite remote sensing methods in two ways. Firstly, whereas satellites can perceive only *surface* flow variations, internal layers provide time-transgressive records of past variations in ice flow extending deep beneath the surface. Secondly, in a number of regions where satellite constraints on ice flow are currently lacking, internal layers provide the only empirical evidence for variations in ice flow across wide expanses of ice sheets. Thus, several studies (Rippin *et al.*, 2003b; Siegert *et al.*, 2003; Bingham *et al.*, *in press*) have divided the Antarctic Ice Sheet into distinct regions in which internal layers are either: (i) continuous/undisrupted, in that they are easily identifiable and relatively flat over large distances; or (ii) buckled/disrupted, *i.e.*, internal layers diverge significantly from the wavelengths of the underlying subglacial topography (*e.g.*, Fig. 4). Regions in which internal layers are absent are generally excluded from this type of analysis as it is often difficult to determine whether layers genuinely do not exist or the RES equipment has failed to capture them.

In applying this classification scheme to extensive airborne RES data, Siegert *et al.* (2003) showed that the margins and tributaries of Bindschadler Ice Stream (formerly Ice Stream D) were characterised by disrupted internal layering, whilst layering in the ridges to each side stayed largely undisrupted. That this remained true deep beneath the ice surface was taken as an indication that this ice stream and its tributaries have not migrated recently—in stark contrast to the neighbouring Kamb Ice Stream, which is thought to have experienced several switches in its configuration, evidenced by disrupted internal layering within both it and its current bounding ridges (Catania *et al.*, 2006). Examining airborne RES records over the much larger region of Wilkes Land, East Antarctica, Rippin *et al.* (2003b) further confirmed that disrupted internal layering is widely diagnostic of ice-flow tributaries as identified from interferometric synthetic aperture radar (InSAR). Therefore, regions of disrupted internal layering may be used to identify past and present ice streams and tributaries where no satellite-derived measurements of surface ice flow are available. This is particularly so in central East Antarctica, south of 86°S, the current latitudinal limit of ICESat, where Bingham *et al.* (*in press*) used disrupted internal layers to remap the distribution of tributaries around the South Pole, thereby providing an empirical constraint to previous ice flow distributions yielded by balance-flux modelling (Bamber *et al.*, 2000; Wu and Jezek, 2004). In all studies using disruption to internal layers as an indicator of fast or tributary flow, however, it is important also to account for possible disruptions to internal layering caused by other factors, such as variations in subglacial topography, accumulation and melt rates, for example. Only by reasonably discounting these non-flow induced causes of layer disruption can internal layering variations truly be attributed to variations in ice flow alone.

Internal layers, and their three-dimensional architecture, therefore offer myriad information concerning mass balance and ice flow properties over vast spatial extents of the polar ice sheets and ice caps; information which could not be gathered with such ease by any other means. However, to date, the analysis of these growing datasets has remained largely restricted to two dimensions. As additional airborne RES datasets are gathered, especially from previously unexplored sectors of the polar ice sheets and ice caps, and our capacity to view the interior of the ice sheet in three dimensions consequently grows, the challenge lying ahead will be to develop increasingly sophisticated methods for visualising and interpreting internal layers and three-dimensional palaeosurfaces in line with developments in the three-dimensional modelling of ice sheet evolution.

Summary and Future Recommendations for Airborne RES

RES provides a powerful, non-invasive and wide-ranging means of imaging the subsurface properties of ice sheets and ice caps. It can be operated from both airborne and ground-based (over-snow) platforms—although both essentially measure the same properties, airborne surveys offer the easiest means of obtaining wide, regional-scale coverages, and have therefore predominated over ice sheets and ice caps, while ground-based surveys can provide finer detail and afford greater control in areas of more complex topography and may be used simply where aircraft are unavailable. Originally developed as a method for locating and mapping the subglacial interface over extensive regions of ice-covered terrain, thereby to calculate the total volume of ice on the Earth, it was quickly discovered that RES offers a great deal of further information concerning englacial and subglacial environments, including the ability to identify subglacial lakes and to resolve isochronous internal reflectors. Thus, four decades since major airborne RES programmes were initiated over Antarctica and Greenland, numerous campaigns have sought to:

(i) map subglacial topography beneath the Earth's ice sheets and ice caps at an ever-increasing resolution;
(ii) characterise bed returns in terms of subglacial roughness, bed geology and the presence or absence of liquid water;
(iii) constrain the locations and geometry of subglacial lakes; and
(iv) resolve englacial stratigraphy, for a variety of purposes including siting deep-ice cores, constraining mass balance (surface accumulation and basal melting) over spatially extensive regions; and analysing three-dimensional ice flow through comparison with existing internal layer architecture.

The datasets gathered, and the increasingly sophisticated, complex and high-resolution numerical models into which these data are being incorporated, have yielded significant advances in our knowledge of cryosphere/climate/sea-level interactions across the high latitudes, demonstrating the incomparable value of RES to glacial geophysical research. Yet many polar ice-covered areas remain unexplored, many have not been revisited since significant improvements in data acquisition and processing have been made, and many existing datasets have not been analysed fully in line with theoretical advances in the interpretation and applications of RES data. Thus, in terms of future developments in the acquisition and analysis of airborne RES data over the polar ice sheets and ice caps, we make the following recommendations:

(i) Subglacial topography must be surveyed over ice-covered terrain which, to date, has not been imaged. For example, there remain significant gaps in the RES coverage of Antarctica over which, consequently, we have no knowledge of subglacial topography nor englacial stratigraphy. In particular, subglacial topography beneath the interior of much of the East Antarctic Ice Sheet has never been measured, severely hampering efforts to model the response of this 12.4 million km^2 ice mass to climate change. To conduct these surveys will require RES equipment to be mounted on long-range aircraft for the first time since the SPRI-NSF-TUD surveys were discontinued in 1979. Over Greenland, while much of the ice sheet has been comprehensively surveyed by the PARCA programme, subglacial topography has still not been adequately surveyed beneath the major ice streams, hindering attempts to model the future of this ice sheet. This is largely due to inadequate penetration of the RES signal through the ice where scattering is dominant and the ice is thick and warm, and to overcome this problem will require both the construction of new radar equipment with greater power and more focus, and new processing algorithms capable of accounting for scattering and strong attenuation. Elsewhere, examples of significant unsurveyed ice caps include North Ice Cap, Novaya Zemlya (23,600 km^2), and the ice caps of Canada's Ellesmere (80,500 km^2) and Axel Heiberg Islands (11,700 km^2). RES surveys of all these regions/ice caps can provide the information that is necessary for an accurate assessment of their potential responses to climate change.

(ii) As gaps in the existing coverage continue to be filled incrementally, and airborne RES acquisition and processing techniques continue to be refined, a shift in emphasis should take place from RES programs directed predominantly towards surveying the basal reflector in unexplored regions to campaigns targeted towards investigating specific 'ice sheet evolution' hypotheses through the co-ordinated gathering of data on both the basal interface *and* internal layers. Because numerical models increasingly require higher resolution data both on basal topography and englacial layering, and because we are now able to image the bed beneath deeper ice and resolve more internal layers than ever before, this should involve resurveying key regions of the polar ice sheets and ice caps at a higher resolution than has previously been achieved.

(iii) In line with the acquisition of new RES data and concurrent advances in remote sensing and numerical modelling techniques, significant efforts need to be made to coordinate and combine existing datasets, and to improve their three-dimensional visualisation and incorporation into glaciological models. Such developments will lead to significant new insights into the critical role that land ice plays in responding to climate change and contributing to changes in sea level.

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