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Thermal State of Permafrost and Active-layer Monitoring in the Antarctic: Advances During the International Polar Year 2007–2009

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ABSTRACT

Results obtained during the International Polar Year (IPY) on the thermal state of permafrost and the active layer in the Antarctic are presented, forming part of ANTPAS (‘Antarctic Permafrost and Soils’), which was one of the key projects developed by the International Permafrost Association and the Scientific Committee for Antarctic Research for the IPY. The number of boreholes for permafrost and active-layer monitoring was increased from 21 to 73 during the IPY, while CALM-S sites to monitor the active layer were increased from 18 to 28. Permafrost temperatures during the IPY were slightly below 0°C in the South Shetlands near sea-level, showing that this area is near the climatic boundary of permafrost and has the highest sensitivity to climate change in the region. Permafrost temperatures were much lower in continental Antarctica: from the coast to the interior and with increasing elevation they ranged between −13.3°C and −18.6°C in Northern Victoria Land, from −17.4°C to −22.5°C in the McMurdo Dry Valleys, and down to −23.6°C at high elevation on Mount Fleming (Ross Island). Other monitored regions in continental Antarctica also showed cold permafrost: Queen Maud Land exhibited values down to −17.8°C on nunataks, while in Novolazarevskaya (Schirmacher Oasis) at 80 m a.s.l. the permafrost temperature was −8.3°C. The coastal stations of Molodeznaya at Enderby Land showed permafrost temperatures of −9.8°C, Larsemann Hills – Progress Station in the Vestfold Hills region – recorded −8.5°C, and Russkaya in Marie Byrd Land, −10.4°C. This snapshot obtained

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during the IPY shows that the range of ground temperatures in the Antarctic is greater than in the Arctic. Copyright © 2010 John Wiley & Sons, Ltd.

KEY WORDS: permafrost temperature; active layer; Antarctica; IPY; ANTPAS

INTRODUCTION

Antarctica contains 90% of the World's ice and exerts a predominant influence on the Southern Hemisphere and global atmospheric and cryospheric systems (Bockheim, 2004). Compared with other components of the cryosphere, our understanding of Antarctic permafrost is poor, especially in relation to its thermal state and evolution, its physical properties, links to pedogenesis, hydrology, geomorphic dynamics and response to global change (Bockheim, 1995, Bockheim *et al*., 2008). Because permafrost is one of the major controlling factors of the dynamics of Antarctic terrestrial ecosystems, its thorough characterization is of utmost importance. Despite occupying only 0.36% (49 800 km^2) of the Antarctic region, permafrost is present beneath virtually all ice-free terrain, except at the lowest elevations of the maritime Antarctic and sub-Antarctic islands. An understanding of the distribution and properties of Antarctic permafrost is essential for the cryospheric sciences, but also for life sciences, since it will be a major control on ecosystem modification following climate-induced changes.

The contribution of permafrost to the global biogeochemical cycle of carbon also needs elucidation (Schuur *et al*., 2008). In contrast to the Arctic, Antarctic permafrost is low in carbon content and its contribution to greenhouse gas fluxes is minor at a global scale (Turner *et al*., 2009). However, the contribution of Antarctic permafrost may be the opposite of that in the Arctic, because recently deglaciated terrain, or areas with a thickening active layer, may function in the intermediate- to long-term as carbon sinks, due to increased biomass from colonization by new plant species and microbial communities. A better understanding of climate-change effects on Antarctic permafrost will also be important for infrastructure, particularly in coastal areas with abundant ground ice. Of major concern is the effect of climate change on subsidence, since despite the small total area of infrastructure in Antarctica, financial investments are substantial.

The lack of information on permafrost is applicable to most of Antarctica, with the possible exception of the McMurdo Dry Valleys (MDV), where substantial research has taken place over the past several decades. Elsewhere in Antarctica, permafrost research has been less systematic. Additionally, there has not been a coordinated effort to monitor permafrost properties and active-layer dynamics, except by individual countries and researchers, mostly in the vicinity of their research stations.

The 'Antarctic and sub-Antarctic Permafrost, Periglacial and Soil Environments' (ANTPAS) project, coordinated by the International Permafrost Association's working group on Antarctic Permafrost and Periglacial Environments and the Scientific Committee on Antarctic Research Expert Group on Permafrost and Periglacial Environments, aims at addressing key issues of Antarctic permafrost science (see Bockheim, 2004). ANTPAS was approved as a core project of the IPY and among its objectives are: (a) integrating existing datasets on permafrost, ground ice, active-layer dynamics and soils; and (b) implementing borehole, active-layer, periglacial process and soils monitoring networks as the Antarctic component of the 'IPA-IPY Permafrost Observatory Project' (TSP) and of the Circumpolar Active Layer Monitoring programme (CALM).

This paper provides an overview on the ANTPAS coordinated effort, with a focus on permafrost temperatures and active-layer monitoring across the region, particularly during the IPY. Permafrost boreholes are also a product of the TSP project. More detailed regional results, as well as the results from other elements of ANTPAS, will be reported elsewhere.

NEW MONITORING SITES AND METHODS

An important ANTPAS objective was the development and implementation of a common methodology for observation, mapping and monitoring of permafrost and the active layer across Antarctica. In view of the size and paucity of ice-free areas, we divided the continent into eight major ice-free areas following Greene *et al*. (1967) (Figure 1). A set of common protocols for permafrost and active-layer monitoring, mapping and soil sampling, classification and mapping was developed (http://erth.waikato.ac.nz/antpas) and these have been generally followed by the participating teams.

Permafrost Monitoring Borehole Network

Ground temperatures have been measured for different purposes on many occasions since the 1960s, especially in Maritime Antarctica. However, generally monitoring was conducted for short periods, using non-standardized protocols and with a focus on the active layer (Bockheim, 1995, 2004; Turner *et al*., 2009). In 1999 a network of boreholes was implemented in the Antarctic with the objective of monitoring the effects of climate on permafrost over the long term. The network was located in the Transantarctic

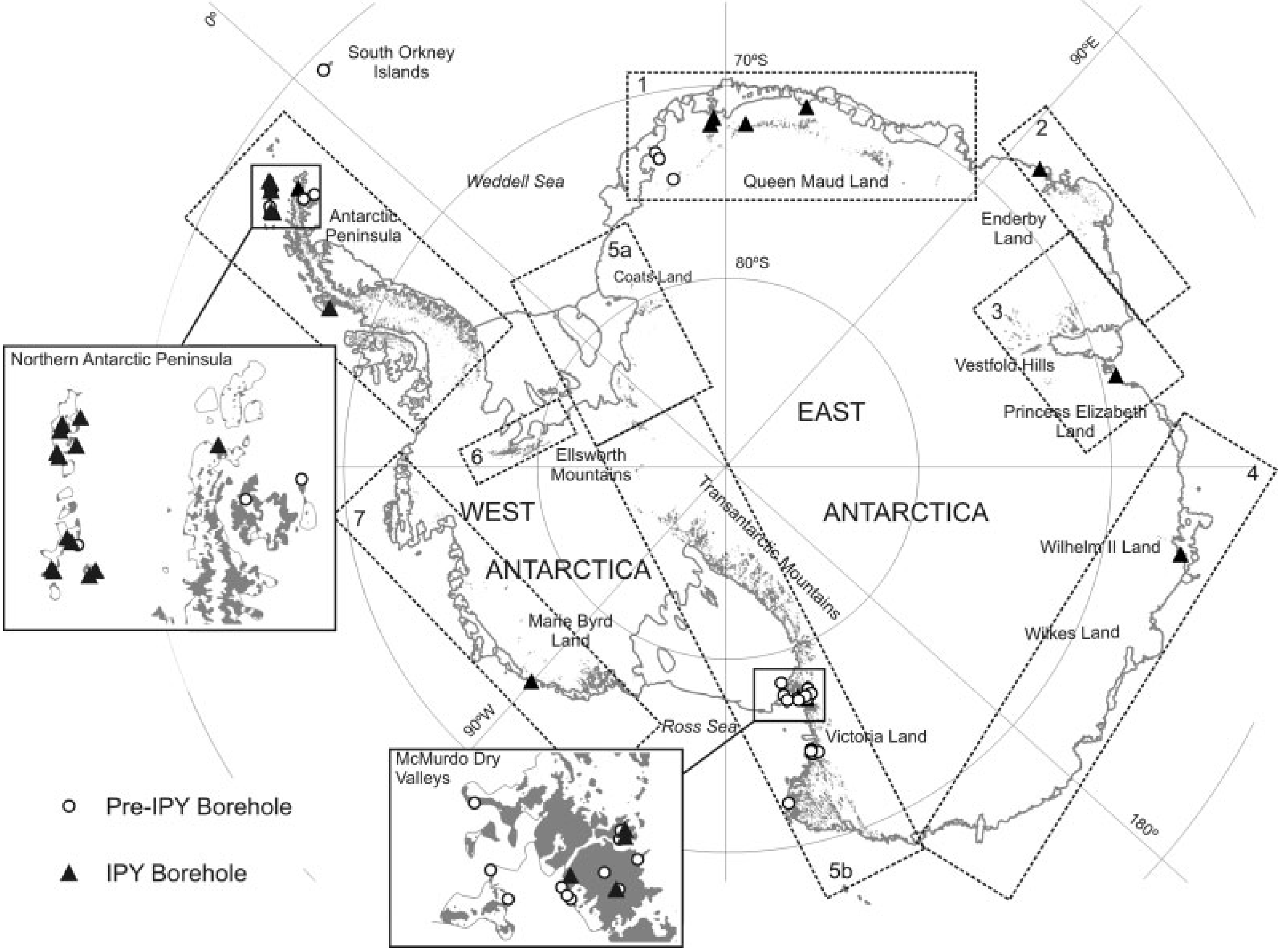

Figure 1 Antarctic permafrost monitoring boreholes (pre- and IPY installations) in relation to soil regions according to Greene *et al*. (1967): 1, Queen Maud Land; 2, Enderby Land; 3, Vestfold Hills; 4, Wilkes Land; 5a and b, Transantarctic Mountains; 6, Ellsworth Mountains; 7, Marie Byrd Land; 8, Antarctic Peninsula.

Mountains region in the framework of Italian, New Zealand and USA programmes.

In 2004, the Antarctic permafrost borehole network consisted of 21 sites with borehole depths ranging from 1 to 19 m. Nine of the sites were located in the MDV, five in Northern Victoria Land, four along the Antarctic Peninsula (AP), and three in Queen Maud Land (QML) (Bockheim, 2004). For permafrost monitoring, the main focus during the IPY was on increasing the spatial coverage of the existing network and installing boreholes deeper than the depth of zero annual amplitude. Because logistics in the Antarctic are especially complex for transporting drilling equipment, another option was the installation of shallow boreholes. The new boreholes were to have similar temperature measurement depths and casing systems, and wherever possible, to be drilled in bedrock at sites representative of the regional climate signal (Guglielmin, 2006). This would help avoid problems linked to latent heat fluxes in those areas near the climatic boundary of permafrost, where water contents in the ground change significantly with time. Boreholes are classified by depth as with Arctic boreholes: deep (>125 m, 1 borehole), intermediate (25 to 125 m, 6 boreholes), shallow (10 to 25 m, 3 boreholes), surface (2 to 10 m, 19 boreholes) and under 2 m (44 boreholes). Many of the latter are part of the CALM-S network. The total number of boreholes in the Antarctic increased from 21 in 2004 to 73 at the end of the IPY (Tables 1 and 2, and Figure 1).

Meteorological stations were installed close to the boreholes in order to evaluate ground–atmosphere coupling. Some teams also approached the problem of topographic controls on ground temperatures by developing a multiscale approach to monitoring. Intermediate boreholes were installed at key sites showing a regional climate signal, while shallow and surface boreholes were installed at different elevations and topographic settings showing local controls (Vieira *et al*., 2007; Ramos *et al*., 2009a,b). To improve the modelling of permafrost temperatures, Amaral *et al*. (2010), in the framework of ANTPAS, organized a ground thermophysical properties database. It contains data

Table 1 Development of the Antarctic borehole network during the International Polar Year

Location	Deep		Intermediate		Shallow		Surface		<2 m		Total	
	Pre-IPY	IPY	Pre-IPY	IPY	Pre-IPY	IPY	Pre-IPY	IPY	Pre-IPY	IPY	Pre-IPY	IPY
Antarctic Peninsula				2		1	4	7	1	24	5	34
Enderby Land										1	0	1
Queen Maud Land								2	3	2	3	4
Marie Byrd Land	1									1	1	1
Transantarctic Mountains			1	3	1	1	3	1	10	2	15	7
Vestfold Hills								1			0	1
Wilkes Land								1			0	1

Pre-IPY - Boreholes before 2007; IPY - New boreholes installed from 2007 to 2009.

from ground and bedrock cores from the South Shetland Islands (SSI), but the network is being expanded to other areas of the Antarctic.

The Antarctic Peninsula region received greater permafrost monitoring efforts during the IPY than in previous years. Several national projects and international consortia led to the installation of two intermediate, one shallow, 11 surface and 25 under 2 m deep ground temperature boreholes. These included activities by Argentina, Brazil, Bulgaria, Italy, Portugal, Russia, Spain, Switzerland and the UK (e.g. Ramos *et al*., 2009a,b; Ramos and Vieira, 2009; Vieira *et al*., 2007, 2008, 2009; Vieira 2009; de Pablo *et al*., 2010). Most of the activity was focused in the South Shetland Islands, but important boreholes were also installed on Signy Island and Adelaide Island. Ongoing and planned projects intend to expand the borehole network to other sites, such as Seymour, Brabant and Anvers Islands, as well as to sites on the Antarctic Peninsula (e.g. Hope Bay, O'Higgins, Paradise Bay, Sky Blu, Fossil Bluff and Mars Oasis). Sites on the eastern coast of the AP, as well as in the interior, however, are still lacking.

The Transantarctic Mountains are the region of the Antarctic where systematic permafrost research has been conducted for the longest time, beginning with the Dry Valley Drilling Project (DVDP) in the early 1970s. The region currently has one deep, four intermediate, two shallow, four surface and 12 under 2 m deep boreholes. Bockheim *et al*. (2007) provided maps showing permafrost distribution in the MDVs. The permafrost borehole network has developed especially since the late 1990's through the Italian, New Zealand, and US Antarctic Programmes (Guglielmin, 2006). Boreholes drilled in 2005 by the New Zealand and Italian programmes were instrumented in 2007, and activities within the IPY were mainly maintenance and data collection from existing boreholes, while some were also upgraded. New boreholes were drilled in the framework of the US Antarctic Program at the MDVs, including one intermediate, one shallow, one surface and two under 2 m deep boreholes in the Taylor and Beacon valleys. Most borehole data from the Transantarctic Mountains is archived at the USDA Soil Climate Analysis Network database (http://www.wcc.nrcs.usda.gov/scan/Antarctica/antarctica.html) making it an example that can be applied to the whole continent.

The main effort to install new boreholes outside the AP and TAM during the IPY was conducted by the Russian Antarctic Programme, with new sites in Enderby Land (Molodeznaya – Thala Hills), Queen Maud Land (Novolazarevskaya), Marie Byrd Land (Russkaya), Larsemann Hills (Progress Station) and Wilkes Land (Bunger Hills). In addition, a collaborative project by South Africa and Sweden led to three new boreholes in QML (two at Vesleskarvet and Flårjuven Bluff, and one at Troll Station). Altogether, these comprise two surface (2–10 m) and five under 2 m deep boreholes.

Temperature data used in this paper provide a snapshot for the IPY years of 2008 or 2009 and refer to the mean annual temperatures (ground surface or deepest permafrost temperature at each borehole), with the more recent data presented wherever it is available.

Circumpolar Active Layer Monitoring Network – Southern Hemisphere (CALM-S)

Eighteen active-layer monitoring sites existed in Antarctica in 2004 (Bockheim, 2004). However, these sites did not have a common protocol and there was a need to standardize methodologies. The implementation of the Circumpolar Active Layer Monitoring (CALM) protocol to Antarctica has been difficult, mainly due to the rocky terrain which limits mechanical probing and use of 100 × 100 m grids (Guglielmin, 2006). The protocol for active-layer monitoring in Antarctica, CALM-S, employs smaller grids and includes an array of shallow boreholes for monitoring ground temperatures in areas where probing is not possible. CALM-S sites emphasize spatial variations in depth and temperature of the active layer in relation to environmental parameters such as topography, soil texture, vegetation, hydrology and snow cover. The deeper boreholes are monitored for long-term permafrost temperatures. Frequently a CALM-S site includes a permafrost borehole site, but there are permafrost borehole sites which have no associated CALM-S grids. At some locations active-layer boreholes were installed but no other environmental parameters are monitored. These are not formal CALM-S

Table 2 Antarctic boreholes and CALM-S sites

Borehole classification	Borehole name	CALM-S *	Region	Reponsible Investigator(s)	Country	Drilling Year	Status	Latitude	Longitude	Elevation (m)
Deep (>125 m)	Commonwealth	No	TAM	Clow	USA	N/A	N/A	−77.58870	163.41607	20
Intermediate (25–125 m)	Rothera Point	No	AP	Guglielmin/Worland	IT/UK	2009	Active	−67.57195	−68.12068	31
	Oasi New	No	TAM	Guglielmin	IT	2005	Active	−74.70000	164.10000	80
	Beacon Valley – lower	No	TAM	Sletten	USA	2008	Active	−77.80318	160.71384	1000
	Marble Point	(Yes)	TAM	Guglielmin/Balks	IT/NZ	2005	Active	−77.40732	163.68083	85
	Bull Pass	(Yes)	TAM	Guglielmin/Balks	IT/NZ	2005	Active	−77.51700	161.85000	150
	Permamodel−Gulbenkian 1. Reina Sofia. Livingston Island	Yes	AP	Ramos/Vieira	SP/PT	2008	Active	−62.67028	−60.38222	272
Shallow (10–25 m)	Beacon Valley – middle	Yes	TAM	Sletten/Gilichinsky	USA/RU	N/A	N/A	−77.84864	160.60186	1273
	Permamodel−Gulbenkian 2. Reina Sofia. Livingston Island	No	AP	Ramos/Vieira	SP/PT	2008	Active	−62.67028	−60.38222	269
	Victoria Valley	No	TAM	Sletten	USA	2009	Active	−77.33095	161.601	399
Surface (2–10 m)	Bellingshausen Station. King George Island	Yes	AP	Abramov	RU	2008	Active	−62.19667	−58.96556	15
	James Ross Island	No	AP	Guglielmin/Strelin/Sone	IT/AR/JP	N/A	N/A	−63.90000	−57.66667	25
	Marambio Island	No	AP	Strelin/Sone	AR/JP	N/A	N/A	−64.23333	−56.61667	200
	Ohridski 3 – Station. Livingston Island	No	AP	Vieira/Ramos	PT/BU/SP	2009	Active	−62.64142	−60.36397	25
	Crater Lake 3. Deception Island	(Yes)	AP	Ramos/Vieira/Gilichinsky	SP/PT/RU	2009	Active	−62.98333	−60.66667	85
	Ohridski 2 – Papagal. Livingston Island	No	AP	Vieira/Ramos	PT/BU/SP	2008	Active	−62.64839	−60.36369	147
	Crater Lake 2. Deception Island	(Yes)	AP	Ramos/Vieira/Gilichinsky	SP/PT/RU	2009	Active	−62.98333	−60.66667	85
	Crater Lake 1. Deception Island	Yes	AP	Ramos/Vieira/Gilichinsky	SP/PT/RU	2009	Active	−62.98333	−60.66667	85
	Ohridski 1 – CALM. Livingston Island	Yes	AP	Vieira/Ramos	PT/BU/SP	2008	Active	−62.64681	−60.36231	136
	Signy Island	Yes	AP	Guglielmin/Ellis−Evans	IT/UK	2004	Active	−60.70000	−45.58333	90
	Incinerador Point. Livingston Island	No	AP	Ramos/Vieira	SP	2000	Active	−62.66472	−60.38556	30
	Novolazarevskaya	Yes	QML	Gilichinski	RU	2009	Active	−70.76278	11.79500	80
	Troll Station	No	QML	Meiklejohn	SA/SWE/NO	2007	Active	−72.01139	2.53306	1275
	Simpson Crags	Yes	TAM	Guglielmin	IT	1999	Inactive	−74.56667	162.75833	830
	Adelie Cove	Yes	TAM	Guglielmin	IT	2003	Inactive	−74.78333	163.96667	35
	Taylor Valley−New Harbor borehole	No	TAM	Sletten	USA	2008	Active	−77.57862	163.48769	18
	Boulder Clay	Yes	TAM	Guglielmin	IT	1996	Active	−74.74583	164.02139	205
	Larseman Hills Progress station	Yes	VH	Abramov	RU	2007	Active	−69.40389	76.34333	96
	Bunger hills	No	WL	Abramov	RU	2008	Active	−66.27528	100.76000	7
<2 m	Byers Peninsula 1. Livingston Island	Yes	AP	Ramos/de Pablo/Vieira	SP/PT	2009	Active	−62.65014	−61.10389	85
	Permamodel−Gulbenkian 0. Reina Sofia. Livingston Island	(Yes)	AP	Ramos/Vieira	SP/PT	2008	Inactive	−62.67028	−60.38222	274
	Crater Lake S2. Deception Island	(Yes)	AP	Ramos/Vieira	SP/PT	2007	Active	−62.98333	−60.66667	85
	Nuevo Incinerador. Livingston Island	No	AP	Ramos/Vieira	SP/PT	2007	Active	−62.66472	−60.38556	25
	Collado Ramos. Livingston Island	Yes	AP	Ramos/Vieira	SP/PT	2007	Active	−62.66778	−60.39194	110

Mount Reina Sofía. Livingston Island	(Yes)	AP	Ramos/Vieira	SP/PT	2000	Active	−62.67028	−60.38222	274
Hope Bay 1	No	AP	Schaefer	BR	2009	Active	−63.39871	−57.00881	50
Crater Lake S1. Deception Island	(Yes)	AP	Ramos/Vieira	SP/PT	2007	Active	−62.98333	−60.66667	85
Keller 8. King George Island	No	AP	Schaefer	BR	2008	Active	−62.08298	−58.39508	49
Keller 1. King George Island	No	AP	Schaefer	BR	2008	Active	−62.08486	−58.39508	28
Keller 2. King George Island	No	AP	Schaefer	BR	2008	Active	−62.08831	−58.40525	37
Keller 9. King George Island	No	AP	Schaefer	BR	2009	Active	−62.08584	−58.40669	113
Fildes 1. King George Island	No	AP	Schaefer	BR	2008	Active	−62.20363	−58.96038	60
Potter 1. King George Island	No	AP	Schaefer	BR	2008	Active	−62.25261	−58.65995	60
Irizar 1. Deception Island	Yes	AP	Vieira/Ramos/Caselli	PT/SP/AR	2009	Active	−62.98000	−60.71700	130
Irizar 2. Deception Island	(Yes)	AP	Vieira/Ramos/Caselli	PT/SP/AR	2009	Active	−62.98000	−60.71800	130
Byers Peninsula 2. Livingston Island	(Yes)	AP	Ramos/de Pablo/Vieira	SP/PT	2009	Active	−62.64992	−61.10419	85
Keller 4. King George Island	No	AP	Schaefer	BR	2008	Active	−62.07575	−58.40373	196
Keller 6. King George Island	No	AP	Schaefer	BR	2008	Active	−62.07821	−58.45322	31
Lions Rump 1. King George Island	No	AP	Schaefer	BR	2009	Active	−62.13778	−58.12843	86
Keller 7. King George Island	No	AP	Schaefer	BR	2008	Active	−62.08578	−58.41356	89
Fildes 2. King George Island	No	AP	Schaefer	BR	2009	Active	−62.18012	−58.94321	116
Byers Peninsula 3. Livingston Island	No	AP	Schaefer	BR	2009	Active	−62.63951	−61.07303	108
Keller 5. King George Island	No	AP	Schaefer	BR	2008	Active	−62.07246	−58.41619	45
Keller 3. King George Island	No	AP	Schaefer	BR	2008	Active	−62.08186	−58.40503	259
Molodeshnaya (Thala Hills)	No	EL	Gilichinski	RU	2007	Active	−67.66556	45.84194	45
Russkaya Station	No	MBL	Abramov	RU	2008	Active	−74.76333	−136.79639	76
Fossilryggen	No	QML	Boelhouwers	SA/SWE	2004	Inactive	−73.40000	−13.03333	550
Svea	No	QML	Boelhouwers	SA/SWE	N/A	Inactive	−74.56667	−11.21667	1286
Aboa Station (Wasa/Basen Nunatak)	No	QML	Boelhouwers	SA/SWE	2003	Active	−73.03333	−13.43333	450
Flårjuven Bluff	No	QML	Meiklejohn	SA/SWE	2008	Active	−72.01167	−3.38833	1220
Vesleskarvet (SANAE Base)	No	QML	Meiklejohn	SA/SWE	2008	Active	−71.68694	−2.84222	805
Beacon Valley−Bench	No	TAM	Sletten	USA	2008	Active	−77.85164	160.62598	1349
Taylor Valley−New Harbor active layer	No	TAM	Sletten	USA	2009	Active	−77.57862	163.48769	18
Marble Point	Yes	TAM	Seybold/Balks	NZ/USA	1999	Active	−77.41983	163.68083	60
Mount Keinath	Yes	TAM	Guglielmin	IT	N/A	N/A	−74.55833	164.00278	1100
Bull Pass	Yes	TAM	Seybold/Balks	NZ/USA	1999	Active	−77.51700	161.85000	150
Victoria Valley	Yes	TAM	Sletten/Seybold/Balks	NZ/USA	1999	Active	−77.33099	161.60052	415
Scott Base	Yes	TAM	Seybold/Balks	NZ/USA	1999	Active	−77.84917	166.75883	80
Cape Hallett	Yes	TAM	Antarctica NZ/Balks	NZ	2004	Active	−72.32000	170.22673	4
Minna Bluff	Yes	TAM	Seybold/Balks	NZ/USA	2003	Active	−78.51155	166.76617	35
Granite Harbour	Yes	TAM	Seybold/Balks	NZ/USA	2004	Active	−77.00000	162.51700	5
Mount Fleming	Yes	TAM	Seybold/Balks	NZ/USA	2002	Active	−77.54519	166.29017	1800
Beacon Valley lower	Yes	TAM	Sletten/Gilichinsky	USA/RU	N/A	N/A	−77.80319	160.71200	950

*- (yes) means that borehole includes a CALM-S site that is already counted on the main borehole at the site.

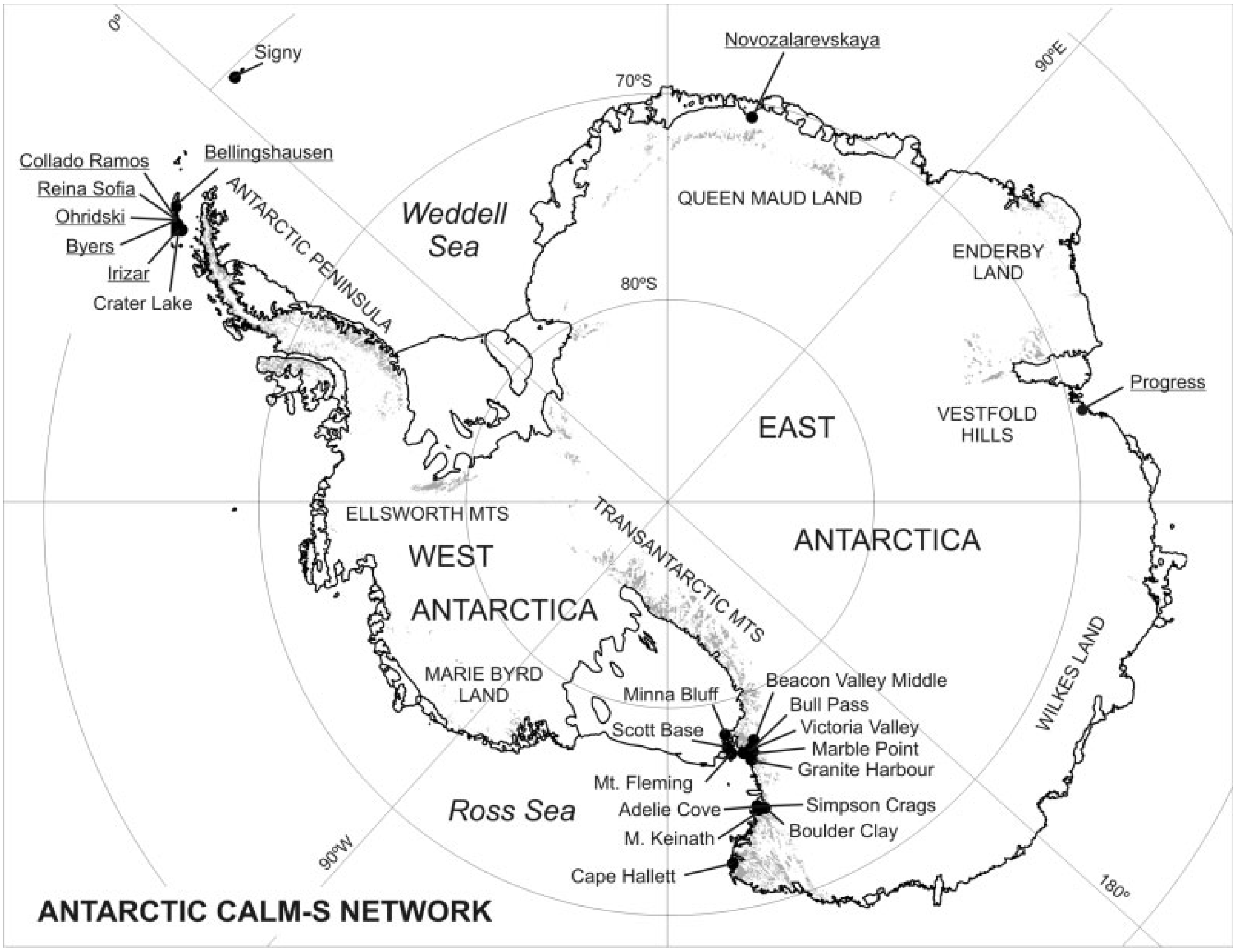

Figure 2 Antarctic Circumpolar Active Layer Monitoring Network (CALM-S). New sites installed during the IPY are underlined.

sites, but may be upgraded following an evaluation of post-IPY needs. There are currently 28 CALM-S sites, eight in the AP, 15 in TAM, four in QML and one in the Vestfold Hills (Figure 2).

In the Antarctic Peninsula most of the active-layer data are derived from shallow boreholes and mechanical probing has been implemented only in: (a) the pyroclastic terrain of the active volcanic Deception Island (where data should not be directly used for climate monitoring purposes); and (b) on sedimentary infills, generally present in basins constrained by topography. No CALM-S sites exist on the eastern side of the AP.

The Transantarctic Mountains have the largest number of CALM-S sites in Antarctica. These are pre-IPY sites and were the precursors of the enlargement of the CALM-S network to the rest of the Antarctic. Sites have been installed by the Italian, New Zealand and USA programmes and are monitored using ground temperatures to detect the position of the permafrost table. Comprehensive monitoring of other meteorological parameters such as air temperature, relative humidity, wind speed and direction is undertaken at all sites, while some are also equipped with solar radiation, soil moisture and snow thickness monitoring instrumentation (Adlam, 2009; Adlam *et al.*, 2009).

In QML ground temperatures have been monitored since 2004 at Basen Nunatak and since 2006 at Vesleskarvet in joint research by South Africa and Sweden. At Troll station, the same countries maintain CALM-S boreholes in collaboration with Norway. During the IPY, the Russian Antarctic Programme installed new CALM-S sites at Novolozarevskaya and in the Vestfold Hills (Larsemann Hills – Progress Station).

RESULTS

Antarctic Peninsula

The results from the IPY permafrost temperature monitoring show that the South Shetland Islands have permafrost temperatures slightly below 0°C at low elevations, with values decreasing to about −1.8°C at 270 m a.s.l. and 25 m depth (Figures 3 and 4). The lowest coastal terrain near sea-level is essentially permafrost free, but an altitudinal limit for continuous permafrost has not been identified with confidence. Field observations on the spatial distribution and characteristics of periglacial phenomena indicate that permafrost in the South Shetland Islands is very much controlled by local factors, such as marine disturbances or snow conditions and becomes widespread to continuous above ca. 30 m a.s.l. (Serrano *et al*., 2008).

Bedrock temperatures from Hurd Peninsula (Livingston Island) suggest that the continuous permafrost boundary is higher up, probably closer to ca. 150 m a.s.l. (Vieira *et al*., 2009). Active rock glaciers and ice-cored moraines are present down to sea-level (Serrano and López-Martínez 2000; Hauck *et al*., 2007; Vieira *et al*., 2008), accompanied by what are probably relict permafrost bodies. The distribution of permafrost is complex in the South Shetlands archipelago, and several low-elevation boreholes show the presence of permafrost with temperatures close to 0°C, especially beneath diamictons or in sedimentary materials. Such is the case at Bellingshausen, Byers Peninsula, Crater Lake amongst others (Figures 3 and 4).

On Deception Island, where the substratum is of volcano-sedimentary origin and dominated by pyroclastic and pumice deposits, the material shows extremely high insulation properties and ice-rich permafrost occurs almost down to sea-level. Thermophysical properties of the ground, therefore, are an important control on the spatial distribution of permafrost.

Further south in Rothera Station, at 31 m a.s.l. permafrost temperatures of −3.1°C have been measured at 21 m depth, with mean annual ground surface temperatures of −2.8°C for 2009.

On Signy Island, permafrost is colder than in the SSI at similar elevations, with values close to −2.5°C at 90 m a.s.l. (Guglielmin *et al*., 2008). This agrees with the lower mean annual air temperatures towards the eastern side of the Antarctic Peninsula along an eastwards air temperature gradient of ca. 6°C (Reynolds, 1981). Similarly, permafrost observations from James Ross Island reported by Fukuda *et al*. (1992) indicate temperatures of ca. −6°C.

Active-layer thicknesses are diverse in the Antarctic Peninsula with values measured at the boreholes generally between 0.8 and 2.0 m and very much controlled by ground characteristics (Figure 3). For example, in Deception Island at the Crater Lake CALM site (85 m a.s.l.) in pumice and ash deposits, active-layer thickness measured with probes is ca. 40 cm, but about 2.6 km away at 130 m a.s.l. the thickness doubles with values of ca. 0.7–0.8 m. These differences at short distances and even higher elevations show the complex influence of such factors as ground properties and snow cover.

The effects of microscale factors on active-layer temperatures are currently being studied in detail at two CALM sites on Deception Island (Crater Lake and Irizar) by the Spanish, Portuguese and Argentinean programmes. The main monitoring site at Crater Lake evaluates active-layer thickness by probing at the end of the summer, and has two boreholes with 1 and 1.5 m depth, three surface boreholes from 5 to 6 m depth, continuous temperature monitoring at the base of the active layer (0.45 m) in 16 nodes of the grid, continuous electrical resistivity monitoring, snow temperature poles, a time-lapse digital camera, a meteorological station, as well as monitoring of solifluction and thermokarst (Ramos *et al*., 2009b). Four years of active-layer thickness monitoring enabled detection of microscale variations in active-layer thickness, with an interannual repetition of the spatial pattern, showing similar controlling factors. Preliminary analysis of the patterns and a comparison with the time-lapse photos of 2008 shows the significance of the date of snowmelt in spring, allowing for a deeper thaw of the ground (Figure 5).

Transantarctic Mountains

Typically, the MDVs show a dry (water content of 2–3%) sandy active layer lacking ice-cement because of sublimation. Immediately beneath the active layer the sediments are generally poorly sorted sands with abundant pebbles firmly ice-cemented. However, ice-bonded permafrost, as well as buried ice, can also occur beneath the active layer or beneath a dry permafrost layer in the Transantarctic Mountains region (Campbell and Claridge, 2006). Recently, a Russia–USA–New Zealand team reviewed the 1995 (Friedmann *et al*. 1996; Wilson *et al*., 1996, 2002) and 1999 (Sletten *et al*., 2003) field studies of the MDV, which focused on permafrost physical and chemical characteristics at 5–20 m depth (Gilichinsky *et al*., 2007). An unexpected finding was that all permafrost cores had high ice contents, comparable to the more humid Arctic (25 to 50% by weight), therefore revising the earlier thesis of deep dry Antarctic permafrost (Gilichinsky, 2008).

Permafrost temperatures in Victoria Land are typically between −14°C and −24°C, with the highest temperatures in Northern Victoria Land and lowland coastal sites, and the lowest temperatures in the MDVs and the Ross Sea region (Figure 6). Mean annual ground surface temperatures are similar to permafrost temperatures in the MDV. Results from the DVDP show that permafrost thicknesses in the TAM range from 350 to 970 m (Decker and Bucher, 1977). A decade of temperature monitoring in the 20-m-deep Beacon borehole by the University of Washington indicates a stable regime without significant trend.

The thickness of the active layer in Victoria Land varies between 0.03 m at Mount Fleming (1800 m a.s.l.) to more than 0.9 m at Granite Harbour (5 m a.s.l.) (Figure 6). Values of 1.6 m were recorded in 2009 in Oasi in northern Victoria Land. This borehole is drilled in granite and due to thermal properties of the rock, the active layer is thicker than at sites with surficial materials. For the MDV and Ross Sea Region, high correlation coefficients have been obtained between elevation and active-layer thickness, as well as between latitude and active-layer thickness, showing that average active-layer thickness can be reasonably modelled using

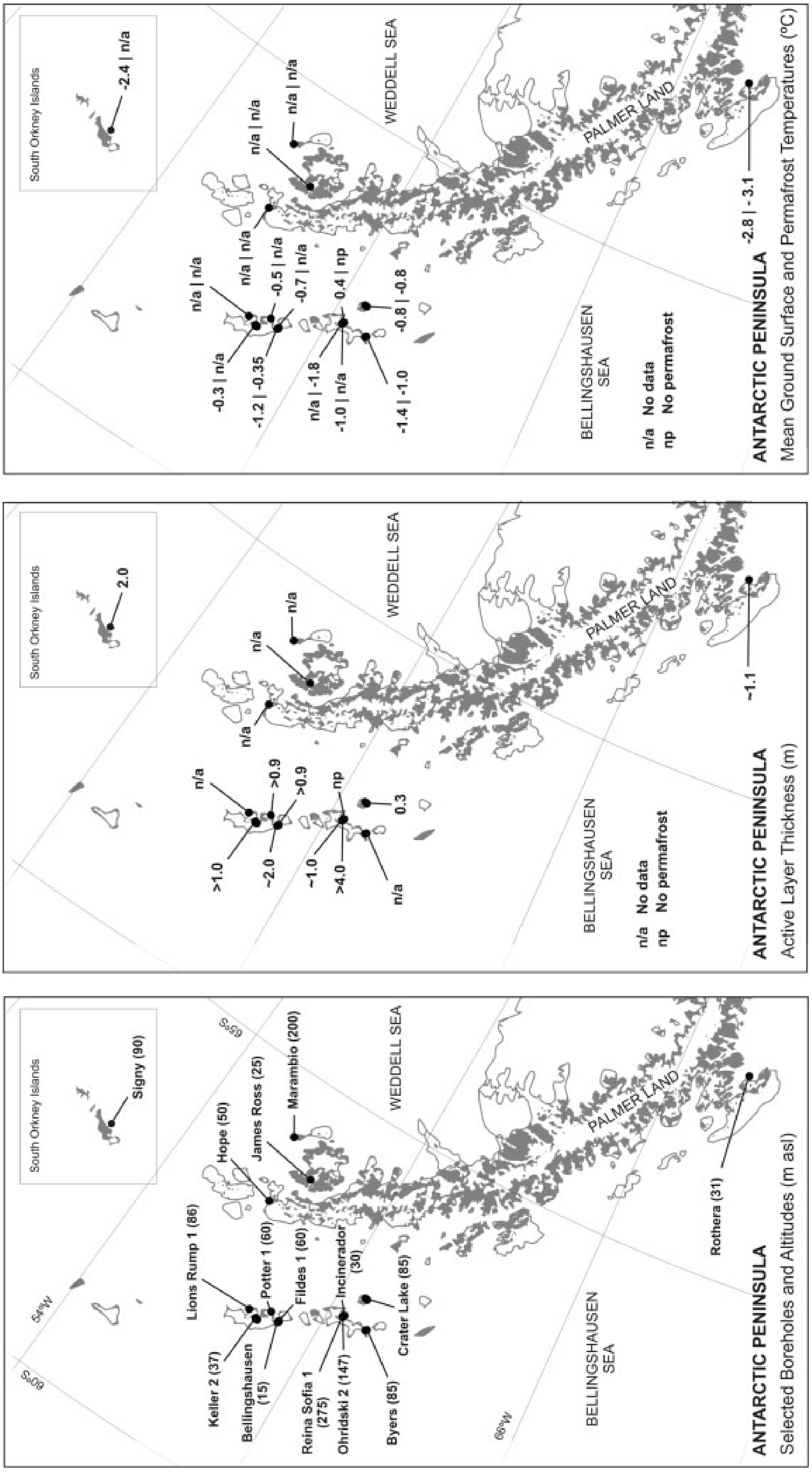

Figure 3 Antarctic Peninsula permafrost temperatures and active-layer thickness for selected boreholes.

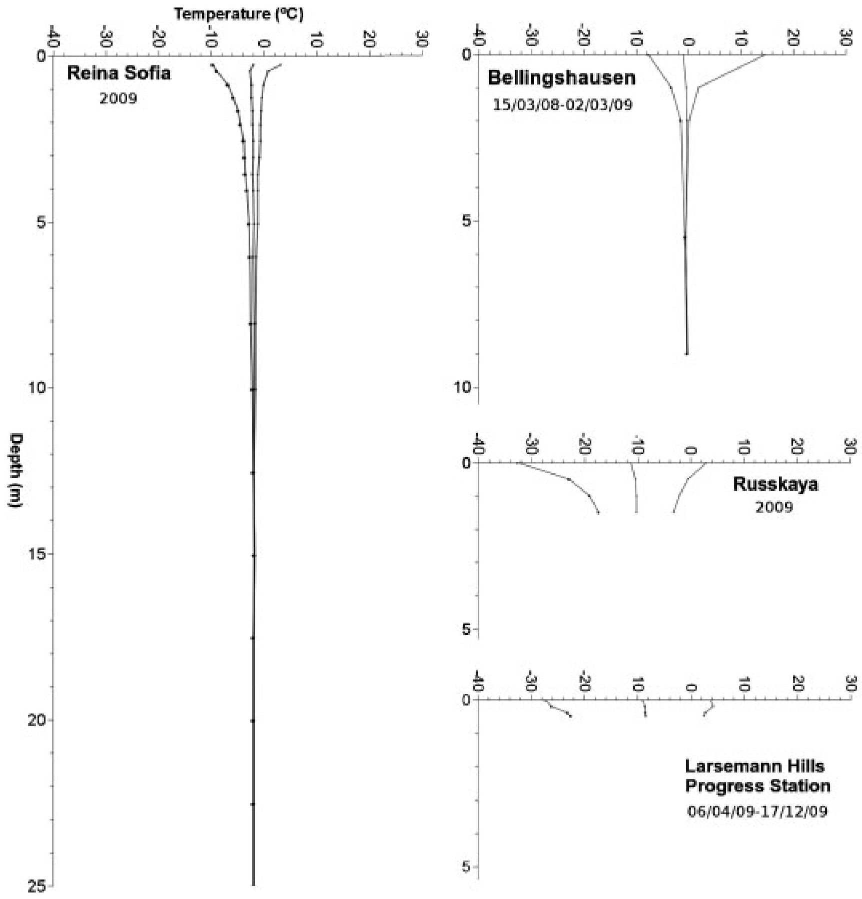

Figure 4 Temperature versus depth profiles for selected Antarctic IPY boreholes.

these two variables (Adlam, 2009, Adlam *et al*., 2010). Active-layer thicknesses in the MDV are also strongly dependent on summer temperatures and vary considerably from year to year. Guglielmin *et al*. (2003) and Cannone *et al*. (2008), however, have shown that surface conditions are the prevailing controls on active-layer thickness in Northern Victoria Land, rather than elevation or latitude.

Other Antarctic Regions

Regions outside the Transantarctic Mountains and the Antarctic Peninsula have sparser and shallower permafrost boreholes.

Mean annual permafrost temperatures in QML show values between −8.3°C at Novolazarevskaya and −17.8°C at Troll Station, with a strong influence of elevation on the decrease in temperature between the two (Figures 4 and 7). Mean annual ground surface temperatures show lower values at lower altitude. Active-layer thickness varies from 0.08 m at high elevation in Troll Station (1275 m a.s.l.) to 0.7 m at Novolazarevskaya (80 m a.s.l.) (Figure 7).

In Enderby Land, Molodeznaya (Thala Hills) recorded a mean ground surface temperature of −10.8°C and a permafrost temperature of −9.8°C. The annual ground temperature envelope shows minimum near-surface temperatures of −30°C and maxima of ca. 6°C with an active layer thicker than 1 m (Figure 4). At Progress Station, Larsemann Hills (Vestfold Hills region), permafrost temperatures at −8.5°C are comparable to coastal regions in Queen Maud Land, and the active-layer is 0.7 m (Figures 4 and 7).

In Marie Byrd Land, the borehole at Russkaya showed a permafrost temperature of −10.4°C and a very shallow active layer (0.1 m), with a thermal envelope showing near-surface temperatures between −32°C and 3°C (Figures 4 and 7).

DISCUSSION AND CONCLUSIONS

The Antarctic expansion of the Global Terrestrial Network for Permafrost (GTN-P) and the Circumpolar Active Layer Monitoring Network (CALM-S) represent major achievements for ANTPAS during the IPY. Due to the short data series for most boreholes, it is not yet possible to provide an overview of permafrost temperature trends in the Antarctic. However, an updated and continent-wide snapshot of the thermal state of permafrost and the active layer now exists.

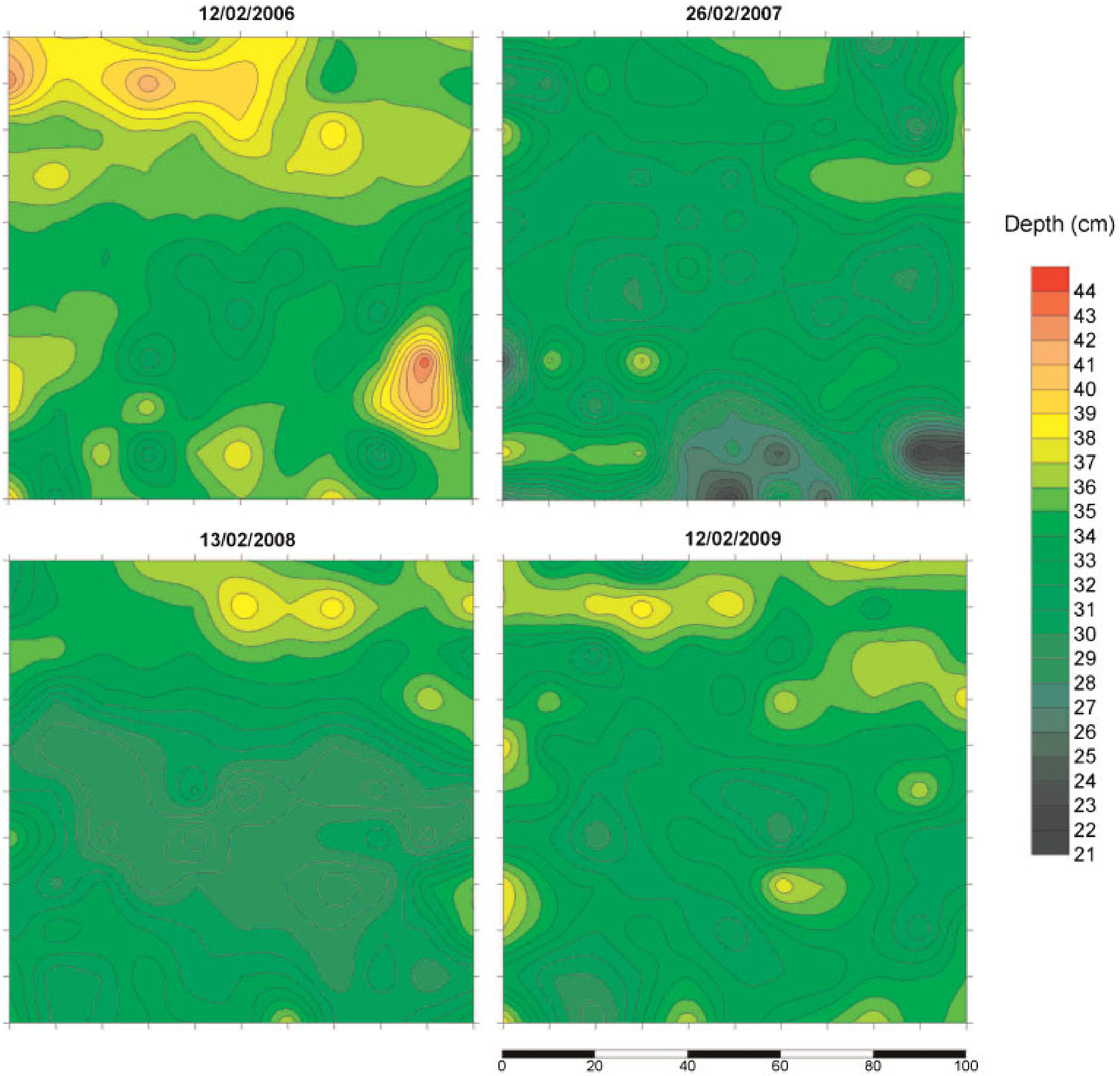

Figure 5 Active-layer thickness at Crater Lake CALM-S in the South Shetlands from 2006 to 2009. Note the relatively similar pattern of thaw every year, reflecting snow cover that lasts longer in the bottom part of the CALM-S grid. Data obtained by probing.

The number of permafrost monitoring boreholes increased from 21 to 73, with most coastal areas represented. The CALM-S network showed a smaller increase, but includes important new sites in the South Shetland Islands, Larsemann Hills (Progress Station) and Novolazarevskaya. Several new boreholes under 2 m depth are being considered as candidates for CALM-S sites.

Permafrost temperatures that were recorded reflect the climatic characteristics of the Antarctic with major controls of latitude, elevation and continentality. The Antarctic Peninsula is one of Earth's most rapidly warming regions with an increase in the mean annual air temperatures of 0.56°C per decade from 1950 to 2000 (Turner *et al*., 2005). Impacts on the glacial environment are relatively well-known, but the reaction of permafrost is only starting to be monitored systematically. Permafrost temperatures recorded during the IPY were slightly below 0°C at low elevation in the South Shetlands, an archipelago that marks the northwest boundary of permafrost in the Antarctic Peninsula region. This is, therefore, an extremely important area for detecting the impacts of climate change on permafrost and on the terrestrial environment. The rugged relief of the South Shetlands implies a transition from seasonal frost to permafrost over a short distance. This occurs along a

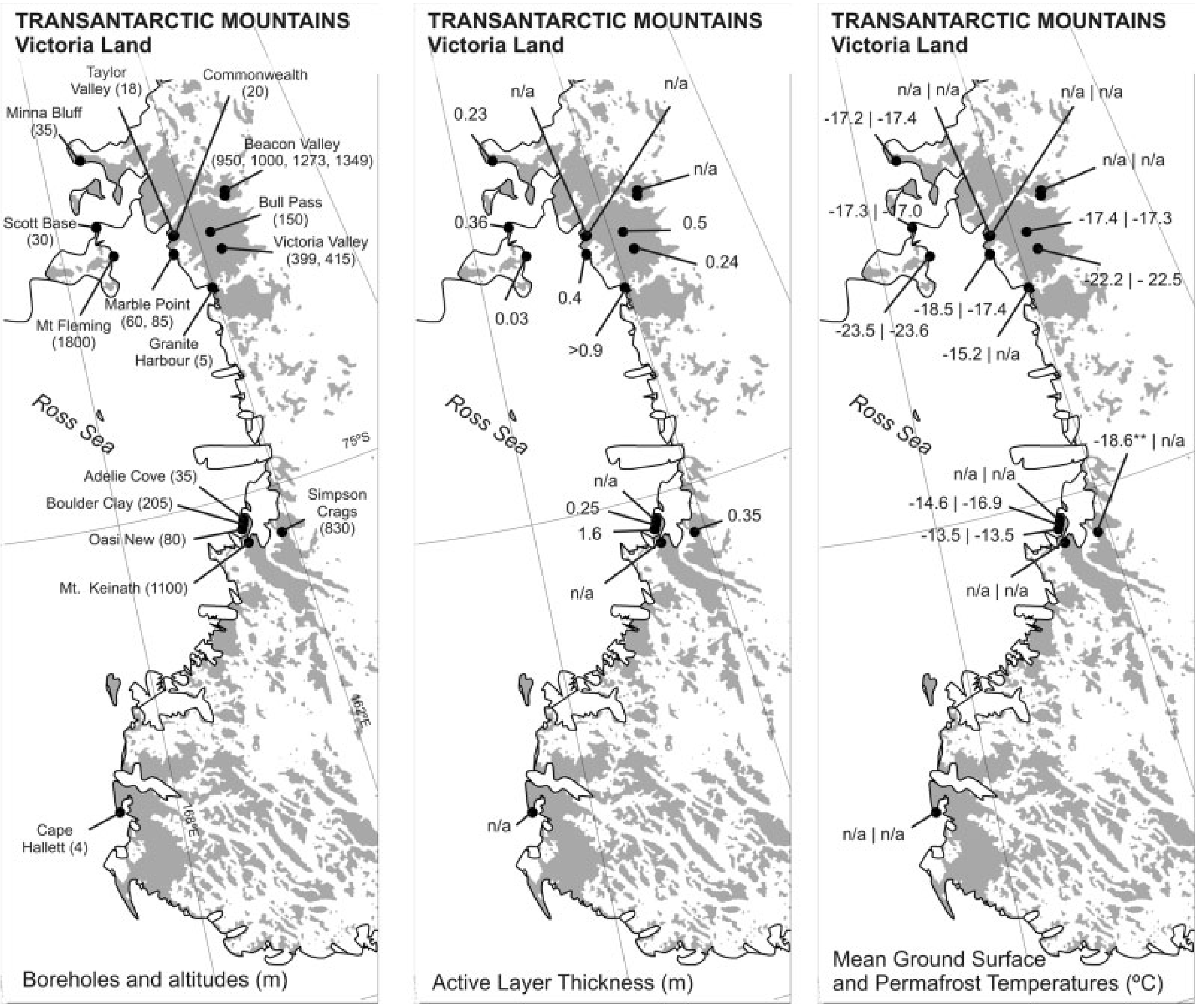

Figure 6 Transantarctic Mountains permafrost temperatures and active-layer thickness. Data from 2008 and 2009 except Simpson Crags (1999).

boundary that is still difficult to locate precisely, since site-specific conditions, such as ground material and snow are very variable and major influencing factors.

It is difficult to predict the response of terrain and landforms to rapidly warming ground in areas where monitoring is absent or at an early stage. This has implications for a geomorphology-based permafrost mapping along this transition zone, and investment to monitor both ground temperatures and climate, as well as key geomorphic features, is needed. This was one of the objectives of ANTPAS, and several geomorphic monitoring sites were installed and interdisciplinary activities involving geomorphological mapping are taking place in the South Shetlands (e.g. Koch *et al*., 2008; Serrano *et al*., 2008).

The Transantarctic Mountains are the Antarctic region where there is the best understanding of permafrost characteristics and temperatures. This region has been intensively studied for several decades by a number of researchers and a permafrost monitoring program was implemented in the late 1990s (see e.g. Campbell and Claridge, 2006; Guglielmin, 2006; Bockheim *et al*., 2007; Bockheim and McLeod, 2008; Gordon and Balks, 2008; Adlam *et al*., 2010). Given the low temperatures recorded during the IPY (Figure 6), permafrost in the Transantarctic Mountains is not as likely to thaw in the near future as the warm permafrost in the Antarctic Peninsula region. However, the mean data hide the seasonal variability and especially the sensitivity of the active layer that may alter hydrological and ecological conditions (Turner *et al*., 2009). An example is the anomalous summer conditions that have occurred in recent years in the MDVs, including the 'wet event' in December 2000 to January 2001 (Doran *et al*., 2008; Turner *et al*., 2009; Adlam *et al*., 2010).

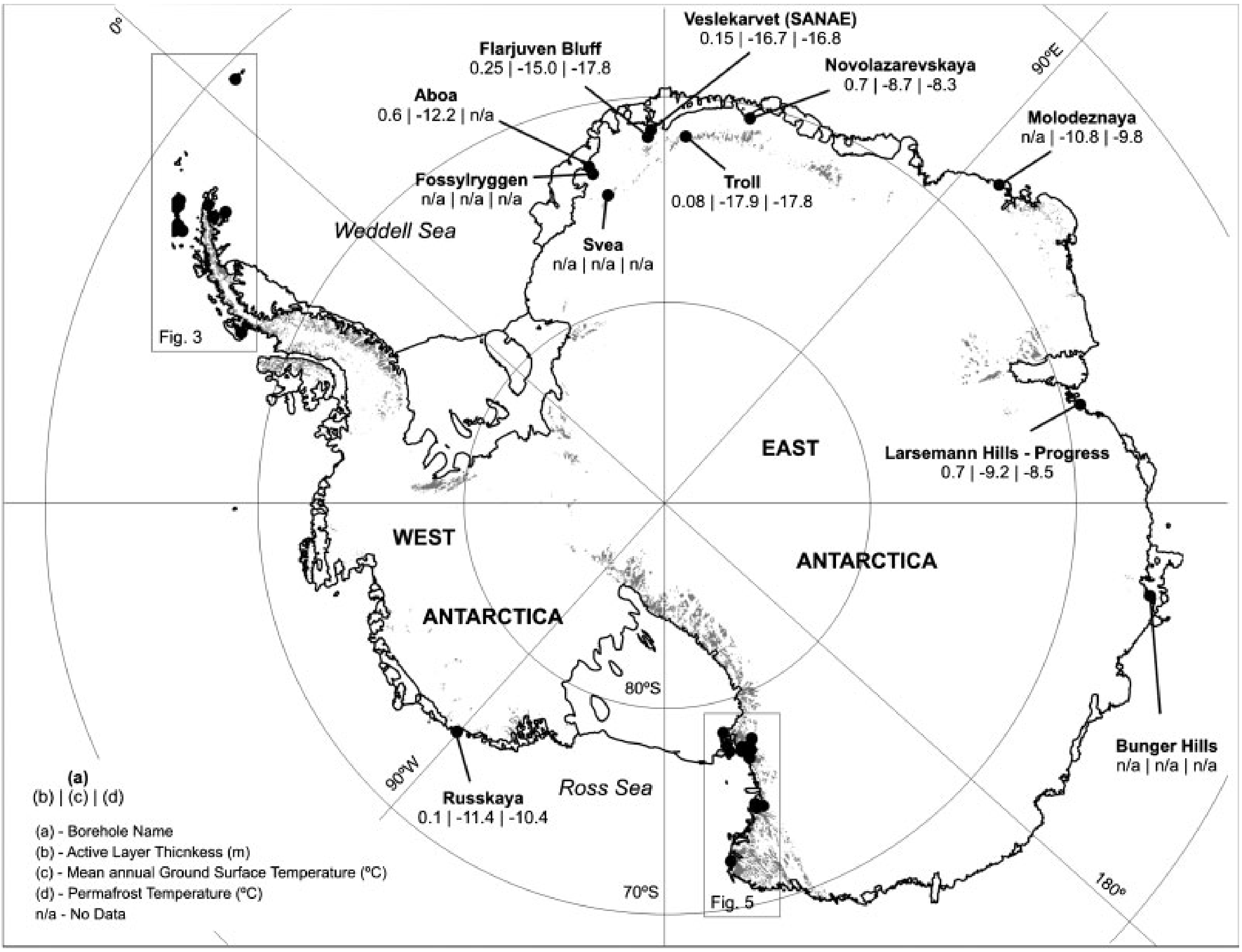

Figure 7 Permafrost and ground surface temperatures and active-layer thickness for Antarctic boreholes outside the Antarctic Peninsula and Transantarctic Mountains.

The other monitored regions in continental Antarctica also showed cold permafrost, with all measured mean ground temperatures below −8.3°C. Overall, the range of permafrost temperatures recorded in the Antarctic greatly exceeds that from the Arctic (e.g. Romanovsky *et al*., 2010; Smith *et al*., 2010) because of the very low values obtained at high elevations inland. In other words, the data indicate that Antarctica currently has the coldest mean permafrost temperatures on Earth, with the possible exception of those on high mountain ranges such as the Himalayas.

The active layer is typically greater than 0.9 m in thickness on monitored boreholes in the South Shetlands Islands, with the exception of sites in Deception Island where it is ca. 0.3 m. In continental Antarctica, values range generally from 0.2 to 0.7 m, occasionally with >0.9 m in coastal sites and with very shallow active layers (<0.1 m) at high elevation sites. In Victoria Land, at a borehole site in granite, active-layer thicknesses of 1.6 m have been measured. The large differences reflect ground thermo-physical properties and show the spatial complexities that occur even under cold conditions. It is expected that new CALM-S sites installed during the IPY will provide significant advances into the understanding of the active-layer dynamics and evolution, but a longer time-series is still needed.

The results presented here, together with the database organized in the framework of ANTPAS, allow for a continent-wide insight into the thermal state of Antarctic permafrost and provide the means for the future modelling and validation of ground temperatures. This was a major achievement of ANTPAS and an important IPY legacy. The permafrost boundary in the Antarctic is located in the South Shetlands archipelago in the Antarctic Peninsula region. The mountainous nature of the terrain and the changing ground conditions imply a complex spatial distribution, especially in the lower terrain, and different authors place the boundary of continuous permafrost between 30 and 150 m a.s.l. This corresponds to mean annual air temperatures of ca. −2°C, a higher value than for the boundary of continuous permafrost in the Arctic. It is not yet known whether the difference between Antarctic and Arctic conditions is due to the rapid atmospheric warming recorded in the Antarctic Peninsula region and a delay in permafrost reaction to change, or if it is caused by different coupling between air and ground to that in the Arctic (i.e. different moisture and vegetation conditions).

Finally, it is noteworthy that despite the significant development of the borehole and CALM-S networks, observational gaps still exist, with a need for key sites to be installed in Coats Land (Shackleton and Pensacola ranges), Wilkes Land, Oates Land, Marie Byrd Land, Ellsworth Mountains, Graham Land, Palmer Land and Alexander Island, and the Queen Maud Mountains. With the new technologies for sensors and with low-cost and low-power consumption dataloggers now available, a strategy for the full implementation of such a network should be envisaged, without the need for annual visits. However, the availability of continuous funding over the long term will remain critical in order to maintain the existing borehole and CALM-S networks, and to allow reactivation of some existing boreholes.

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