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Science and exploration in the high interior of East Antarctica in the twentieth century

Irina Gan[1], David Drewry[2], Ian Allison[1*] & Vladimir Kotlyakov[3]

[1] Antarctic Climate and Ecosystems Cooperative Research Centre, Hobart, Australia;
[2] University of Hull, Hull, UK;
[3] Institute of Geography, Russian Academy of Sciences, Moscow, Russia

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Abstract The highest part of the East Antarctic Ice Sheet, more than 4000 m above sea level, has been an area that has seen a considerable scientific research effort undertaken by the Chinese National Antarctic Research Expedition, and its international collaborators, since January 2005. That includes the establishment of the most remote of the Chinese Antarctic stations, Kunlun, at Dome A in 2009. However, the exploration and mapping of this region had been commenced many decades earlier, most notably by inland traverses of the Union of Soviet Socialist Republics during the 1957–1958 International Geophysical Year (IGY) and later; and the extensive surveys of Antarctic surface and sub-ice topography by airborne radio-echo sounding made by the US National Science Foundation–Scott Polar Research Institute–Technical University of Denmark (NSF-SPRI-TUD) in the late-1960s and the 1970s. Here we provide a history of the activities and achievements of these earlier programs. Recent topographic maps of the ice sheet surface in the Dome A region, produced using Chinese GPS data and satellite altimetry, have shown the maps compiled from the earlier data were remarkably accurate.

Keywords **East Antarctica, Dome A, Gamburtsev Mountains, traverse, sub-glacial mapping, seismic, radio-echo sounding (RES)**

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1 Introduction

On 18 January 2005, the 12-man “Inland Detachment” of the twenty-first Chinese National Antarctic Research Expedition (21st CHINARE) reached the highest point on the Antarctic Ice Sheet by tractor traverse, after 25 days travel from the Chinese coastal station, Zhongshan, 1228 km to the north. This was the culmination of a number of earlier CHINARE scientific traverses southward from Zhongshan which commenced in 1996–1997. These initially followed the route of the Australian 1990s traverses around the Lambert Glacier Basin[1], but then pushed increasingly further south and higher up the ice sheet towards the highest point called Dome A (or Dome Argus). The precise location and height of this highest point of the ice sheet, which was determined by a detailed Chinese GPS survey, are 80°22′S, 77°21′E and 4091 m above sea level[2].

CHINARE has traversed to Dome A during most summer seasons since 2005, and in 2009 established Kunlun Station (named after the Kunlun Mountains on the northern edge of the Tibetan Plateau and among the longest mountain chains in Asia) at 80°25′S, 77°07′E. Kunlun Station is only 7 km from the highest point of Dome A and is the most remote of the Chinese Antarctic stations[3]. The exploration and scientific research undertaken on the Dome A traverse and at Kunlun Station demonstrate that the People’s Republic of China is an important polar power in the 21st century with a comprehensive Antarctic program. The research results from a decade of these Dome A activities are summarised in the papers in this volume.

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* Corresponding author, E-mail: Ian.Allison@utas.edu.au

But earlier Antarctic mapping and research programs had determined the location and elevation of the highest point on the ice sheet more than 30 years before the CHINARE traverse reached there. These were the East Antarctic inland traverses of the Union of Soviet Socialist Republics (USSR, or Soviet) during the 1957–1958 International Geophysical Year (IGY) and later; and the extensive surveys of Antarctic surface and sub-ice topography by airborne radio-echo sounding made by the US National Science Foundation–Scott Polar Research Institute–Technical University of Denmark (NSF-SPRI-TUD) in the late-1960s and the 1970s. In the following sections, the activities and achievements of these two programs are discussed in detail.

2 The earliest scientific estimate of the height of the Antarctic ice sheet

In 1909, long before the Soviet IGY traverses or subsequent airborne measurements and even before any surface measurements had been made in the interior of the East Antarctic Ice Sheet, the German meteorologist/geographer Wilhelm Meinardus estimated the average height of the ice sheet from atmospheric pressure measurements made elsewhere in the globe[4]. Meinardus observed that there was a small difference between the January and July mean surface pressures averaged over the total globe, excluding the Antarctic ice sheet. To preserve the total atmospheric mass, Meinardus postulated that the mean surface pressure over the ice sheet was 23 hPa higher in January than in July, while the mean pressure at sea level around the Antarctic coast remained approximately the same in both months.

This postulate is supported by subsequent observations that show a marked semi-annual oscillation in surface pressure around the Antarctic coast, with equinoctial minima and similar maxima in January and July. This semi-annual oscillation dominates Southern Hemisphere mid-latitude surface pressures. It was first reported by Schwerdtfeger and Prohaska[5] and has since then been widely described and discussed[6]. Inland over the ice sheet however, the annual pressure variation is dominated by an annual oscillation, asymmetrically shaped around a summer solstice peak. One interpretation of this variability is that the inland pressure rise in late spring is caused by warming which permits some of the tropospheric air, previously blocked by the ice sheet, to spread out across it. During the remainder of the year, synoptic systems and katabatic surface layer drainage gradually remove the excess summer air mass from the ice sheet[7].

The atmospheric pressure-height relationship is described by the barometric formula:

$$\partial p = -g\rho\partial z = -\frac{g}{R}\frac{p}{T}\partial z \qquad (1)$$

where p is the pressure, ρ is the air density, T(°K) is the temperature, z is the elevation above sea level; g is the acceleration of gravity and R is the specific gas constant.

Integration of (1) over the atmospheric layer between sea level ($z=0$, $p=p_0$) and the unknown mean ice sheet elevation ($z=h$, $p=p_1$) with mean temperatures T_{Jul} for July and T_{Jan} for January yields:

$$\ln p_0 - \ln p_1 = -\frac{g}{R}\frac{h}{T_{\mathrm{Jul}}} \qquad (2a)$$

and

$$\ln p_0 - \ln(p_0 + \Delta p) = -\frac{g}{R}\frac{h}{T_{\mathrm{Jan}}} \qquad (2b)$$

where Δp is the pressure difference of 23 hPa.

Subtracting equation (2a) from equation (2b) gives the solution for the mean elevation:

$$h = \frac{\left(\frac{R}{g}\right)(T_{\mathrm{Jul}}T_{\mathrm{Jan}})}{(T_{\mathrm{Jan}} - T_{\mathrm{Jul}})}\ \ln(1 + \Delta p/p_1) \qquad (3)$$

A matching pair of the two unknown quantities h and p_1 can be found by iteratively estimating between equation (3) and (2a).

Using the values assumed by Meinardus[4] for the layer mean temperatures of 235°K in July (T_{Jul}), 258°K in January (T_{Jan}) and sea level pressure (p_0) of 993 hPa, yields an estimate for the mean elevation of the ice sheet of 2464 m, and the mean pressure at that elevation of 695 hPa. For an ice sheet with a parabolic surface shape (as for perfectly-plastic ice flow) and a radius of over 1000 km, the highest point will be nearly twice as high as the average elevation. Hence, for the Antarctic Ice Sheet, using Meinardus' method for estimating mean elevation, then the summit will be over 4000 m above sea level.

The average elevation of Antarctica, excluding ice shelves, estimated from the BEDMAP2 compilation is 2209 m[64], and from a recent high resolution DEM[65] it is 2204 m (J. Bamber, pers. comm.).

3 Soviet traverses to the Antarctic Pole of Relative Inaccessibility: the last unconquered pole on Earth

Up until the 1950s, the deep interior region of the East Antarctic ice sheet was yet unexplored. It was only during the International Geophysical Year (IGY) of 1957–1958 that man first set foot in this remotest of regions of planet Earth. The USSR, as part of its commitments to the International Geophysical Year (IGY) program of 1957–1958 took up the challenge of conducting research in this area. This was considered by some to be a near impossible exercise due to the extremely hostile physical environment and climatic conditions, but the desire for scientific knowledge and consequent international prestige was a powerful stimulus for the Soviet scientists[8].

This account, based in the main on Russian and English language publications and archival material, focuses on general logistic issues and the pioneering observations and research conducted by the Soviet Antarctic expeditioners during the three traverses through this area that preceded the current Chinese activities. These were during the Third SAE of 1957–1959; the Ninth SAE of 1963–1965 and the Twelfth SAE of 1966–1968. These expeditions were originally called "Composite Antarctic Expeditions" (CAE) because they were made up of both a marine and a continental component, but after the Third CAE they were renamed "Soviet Antarctic Expeditions" (also CAE in Russian, but transliterated to SAE in English).

Although the People's Republic of China did not participate in the IGY due to international political reasons, it nonetheless had an interest in the research being conducted during that time. Prior to the IGY, China had attended international conferences and gave financial support to the Chinese Academy of Sciences for IGY activities. After withdrawing from the IGY, it still continued with its planned geophysical program and exchanged data with the USSR, but not under the IGY banner[9].

Chinese cooperation with Soviet scientists continued even after the conclusion of the IGY. For example, in 1958 and 1959, according to an agreement between the Academies of Sciences of the USSR and China, a participant of the First SAE of 1955–1957, Leonid Dolgushin (1911–2012) was sent to China as scientific leader of the First Expedition of the Chinese Academy of Sciences to study ice and snow in the mountains of Nan Shan, Central Tien Shan and Kunlun. His activities in China in 1958 and 1959 were instrumental in helping train Chinese glaciologists, who in turn were to establish the Lanzhou Institute of Glaciology and Geocryology[10-13].

3.1 Third SAE, 1957–1959

About a year before Dolgushin's involvement in the research expedition in China, the leader of the Third SAE Evgeniy Tolstikov (1913–1987) had commenced preparations for an expedition on the Antarctic continent. The Soviet scientists had decided on a near impossible feat: to secure a foothold and establish a research station on the most inaccessible site of the continent, the Pole of Inaccessibility, that point on the Antarctic continent most distant from the Southern Ocean. A previous reconnaissance flight in late December 1957 had identified a route for the overland expedition and had dropped a Soviet flag at the proposed site for the station[14].

On 26 December 1957, the overland expedition set out from the main Soviet base, Mirny (66°33′S, 93° 01′E), to supply the previously established year-round inner continental stations Pionerskaya (69°44′S, 95° 30′E), Komsomolskaya (74°06′S, 97°30′E), and Vostok 1 (78°27′S, 106°50′E). On returning to Komsomolskaya they turned westward and continued across the Antarctic plateau [which the expeditioners named Plateau Sovetskoye (Soviet Plateau)], towards the proposed new site for an intermediate station en route to the Pole of Inaccessibility[15-16]. The traverse, which was to last 69 days till March 1958, and to cover over 4000 km in total[17], was considered to be a 'dress rehearsal' for the future planned traverse to the Pole of Inaccessibility[18] (Figure 1).

Fortunately, this exercise was able to build on the knowledge acquired by the first two SAEs. The valuable lessons and experiences of the previous expeditions stimulated the development of new technology and tactics. Personnel went through rigorous health screening and equipment more suited to Antarctic conditions was developed[15-16]. The tractors were modernized with wider tracks for better cohesion with the snow cover, increased ground clearance and with turbo superchargers fitted to the engines for work in the thinner atmosphere at high altitudes without a reduction in power and giving increased fuel economy[19].

Aircraft served as a vital auxiliary means of transport. The aviation department of the Third SAE consisted of a record number of twelve airplanes and a helicopter which were of great assistance in supporting all aspects of the expedition. Aviation support during this (and other traverses) played a key role, although flights could be very dangerous in Antarctic conditions. A common problem was the small airborne ice crystals which scattered the light, creating a 'curtain of light' which dramatically reduced visibility[20].

Although planning and preparation had seemingly accounted for all contingencies, on the ground the progress was very slow. Temperatures below −50°C and the effects of high altitudes led to mechanical failure as the tractors sank into the loose snow (sub-surface hoar frost) to a depth of up to 1.5 m and 'swam in it like sea turtles'. The 'Queen of Cold' had also posted her 'frontline warriors', the sastrugi, to block the expeditioners' way, preventing them from reaching the 'wide cold open spaces of her snowy wilderness'[21].

A maximum speed of a mere five kilometre per hour was common. The frequent lurches of the tractors as they went over the sastrugi weakened the stability of the cargo. The rugged terrain and frigid conditions took their toll on fuel consumption, which was an unexpected ten litres per one kilometre. Supplementary fuel (and supplies) had to be air dropped by the aviation team[18]. In the area of Komsomolskaya Station, the traverse found itself in the zone of katabatic winds and blizzards; the powdery snow and the exhaust fumes affected visibility to such an extent that the leading tractor had to rely solely on its navigational instruments in order to move forward. The drivers of the following tractors had to stand and look out of the emergency hatch while operating the machine with their feet[18]. It is interesting to note that the driver/mechanics of the tractors, who largely determined the success of the expedition, were actually former army personnel from the tank forces. 'In conditions of lack of oxygen and severe cold they withstood extreme physical and moral loads', wrote Tolstikov, who remembered them fondly[14].

Despite the hardships and ordeals, the traverse reached a point 1550 km from Mirny Station, but could not find an appropriate site for a station. It returned to a point 1420 km from Mirny, where a new interior continental station was opened on 16 February 1958 and named Sovetskaya (78°23’S, 87°32’E)(Figure 1). It was an intermediate half way station within range of a Lisunov LI-2 aircraft flying out of Komsomolskaya Station. The approaching winter and very deep and soft snow prevented any further progress. Sovetskaya was to become a base from which to launch the assault on the Pole of Inaccessibility when winter was over. Meantime, five expeditioners among them an aerologist, a meteorologist, two seismologists and a gravimetrist were left to spend winter at Sovetskaya with temperatures falling to as low as −86.7°C in early August 1958[20]. At such low temperatures, when outdoors, the wintering party had to use special protective masks and goggles connected to an oxygen supply placed under their overalls[22].

The traverse with the other members returned to Mirny where it stayed till the end of October. Tractors underwent maintenance; new sledge couplings were made; tens of thousands of pelmeni (Russian dumplings) were prepared: these were easiest to cook during the traverses at high altitudes, where water boils at 70°C and cooking times become much longer. A structure including living quarters, a power plant, radio station and upgraded drilling apparatus, which was to become the future station at the Pole of Inaccessibility, was erected on a steel sledge[18].

After completing preparations, a new traverse left Mirny on 23 October 1958, headed for the Pole of Inaccessibility. On 29 November 1958 it reached Sovetskaya Station, where the leader of the final assault on the Pole of Inaccessibility, Tolstikov, had previously arrived by plane from Mirny. Eighteen expeditioners on four tractors with sledges left Sovetskaya on 3 December 1958 [E. Tolstikov (head of the traverse), A. Nikolaev (head of the ground transport unit), V. Babarykin (leader, Sovetskaya station and future Pole of Inaccessibility station), Yu. Avsyuk (navigator), Kh. Zakiev (glaciologist), O. Sorokhtin and V. Koptev (seismologists), S. Shleifer (doctor), E. Vetrov (radio operator), and driver/mechanics: V. Yakimchuk, L. Donon, A. Erokhin, V. Zadvornikov, A. Parshin, A. Stepanenko, A. Ivanov and V. Gumenyuk] [14].

Seismic sounding, glaciological studies and other observations were conducted every 20–25 km along the traverse route[18]. A sub-glacial mountain range was

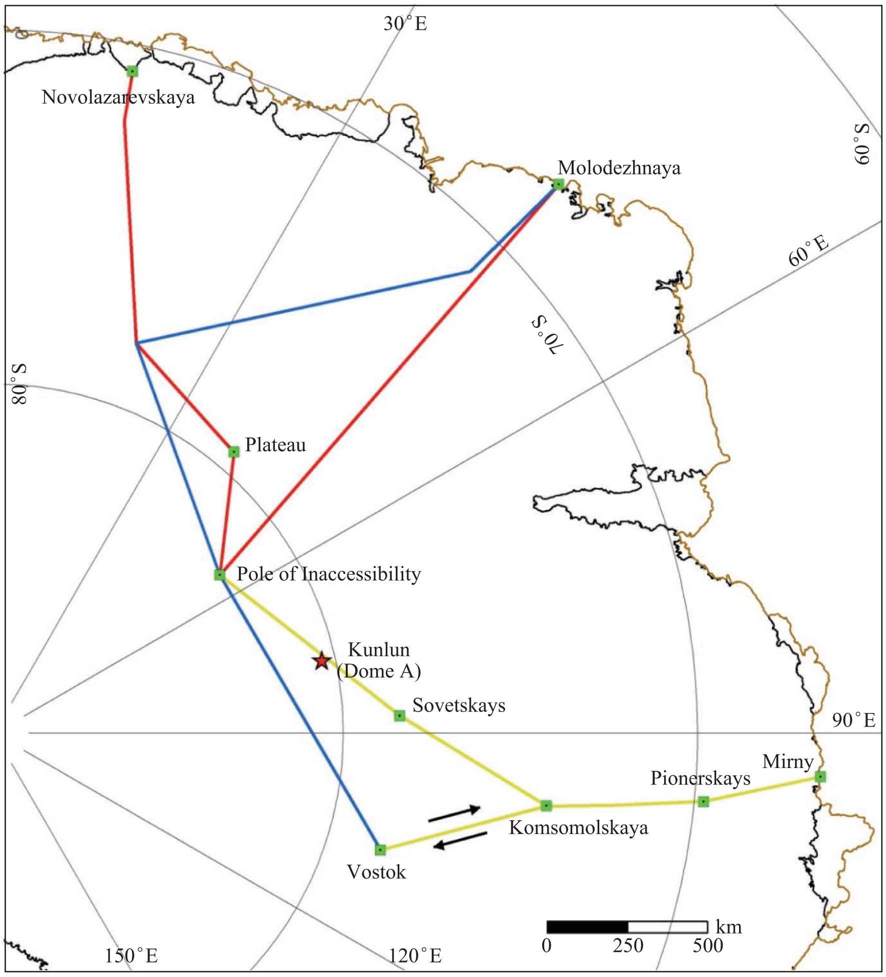

Figure 1 SAE East Antarctic traverse routes: Third SAE, 1958, Mirny–Pole of Inaccessibility (yellow); Ninth SAE, 1964, Vostok–Pole of Inaccessibility–Molodezhnaya (blue); Twelfth SAE, 1966–67, Molodezhnaya–Pole of Inaccessibility–Plateau–Novolazarevskaya (red).

discovered and named after the Soviet geophysicist Grigory Gamburtsev (1903–1955). This was a totally unexpected discovery for the scientific world at that time, as the prevailing opinion was that Antarctica was flat under its 2.5 km blanket of ice[22]. Since the International Polar Year of 2007–2009[23], this mysterious range has been under the watchful scientific eye of the international scientific community, eager to understand the last unexplored mountain on Earth[24- 25]. Sorokhtin, Koptev and Avsyuk also determined that East Antarctica is most likely a continent rather than an archipelago[21].

Despite harsh weather and low temperatures, they made steady advance to their destination, which they finally reached in the middle of December. Upon arrival, the group celebrated by launching flares and raising the Soviet flag. A runway was prepared and on 17 December an LI-2 airplane arrived, bringing supplies and to changeover some of the personnel.

By opening the Pole of Inaccessibility Station (82°06′ S, 54°58′E; Leader Babarykin) the Soviet Union fulfilled its IGY commitment. Although it only consisted of a few temporary structures and a small cabin for four persons mounted on a sledge, it became the seventh Soviet station in Antarctica opened during the IGY; albeit only for the short period of time, the last two weeks of the IGY. Meteorological and actinometric observations were conducted at the station[14].

When less than half way along the route between Sovetskaya Station and the site of Pole of Inaccessibility Station, the 1958 traverse passed only about 80 km to the north of the now known highest point on the Antarctic Ice Sheet (80°22′S, 77°21′E, 4091 m), near where the Chinese Kunlun Station is now located. Today, with accurate satellite-derived mapping of the Antarctic coastline, the location of the Pole of Inaccessibility, as determined by the British Antarctic Survey, is at 82°53′14″S 55°4′30″E (if only the grounded ice sheet is considered in defining the coastline) or at 83°50′37″S 65°43′30″E (if the floating ice shelves are also considered). These locations are some 700 km away from where the Soviet station was established in 1958. But this does not at all detract from the Soviet achievements during the IGY.

3.2 Ninth SAE, 1963–1965

The next expedition when research was to be conducted in this area could only be organized several years later. During the Ninth SAE (1963–1965), a traverse from Vostok Station at the South Geomagnetic Pole to the Pole of Inaccessibility and on to the newly opened coastal Molodezhnaya Station (67°40′S, 45°51′E) in Enderby Land was undertaken. The purpose of this traverse was to investigate the unexplored area of Central Antarctica between the Pole of Inaccessibility Station and Molodezhnaya Station.

The main scientific staff arrived at Mirny Station on an IIlyushin IL-18 aircraft in late November 1963 to prepare for the long traverse. Among them were A. Kapitsa (head of the traverse, seismology, thermal physics), A. Lebedev (deputy head, transport engineer and a driver), O. Sorokhtin(seismology, thermal physics), Yu. Bugaev (gravimetry, geodesy), E. Safomov (navigator, geodesy, astronomy), V. Nozdryuhin (glaciology, meteorology), G. Sakunov (actinometry, meteorology), V. Kazarin (actinometry, meteorology), N. Kazarin (drilling engineer), S. Koftanyuk (radio geomagnetism) and N. Saveliev (doctor and cook). There were five drivers: N. Borovskoy, A. Kunderev, I. Ushakov, P. Shulenin and A. Temlyakov[26].

All participants of the traverse had gone through thorough medical screening including time spent in a decompression chamber, which tested their response to extreme altitudes. Most of them had previously participated in traverses and many had spent a year in Antarctica, which had provided them with valuable experience[27].

The difficulties with the tractors on the previous traverses had stimulated the design of new tractors more suitable for use in Antarctic conditions, which were first used in a traverse to the South Pole in 1959. These 35 tonne Kharkovchanka tractors (Figure 2) were built in the city of Kharkov, Ukraine, on the base of the AT-T heavy artillery tractor. They had wide caterpillar tracks and could develop 550 hp. The heated cabins had complete living quarters and were fitted with scientific laboratories to conduct geodetic, gravimetric, aerological, glaciological, magnetic, and seismological observations. Geodetic apparatus was mounted on to the roof of the Kharkovchankas in a special protection unit made from a metal frame in the form of a hexahedron prism covered with canvas. The Kharkovchankas were equipped with a shortwave radio station, as well as gyro, magnetic, astronomical and radio compasses enabling the driver to navigate the machine with zero visibility during frequent whiteouts[27].

Figure 2 Soviet Antarctic Expedition Kharkovchanka tractor

Two Kharkovchankas and one heavy duty tractor fitted with an electric galley left Vostok Station on 3 January 1964. Travel was slow, and even the wide tracks of the Kharkovchankas got stuck in the loose snow. Fuel consumption was up to eight litres per one kilometre. At an altitude close to 4000 m above sea level it was difficult to breathe. Mean annual temperature there reaches −60°C, while the lowest winter temperatures can be as low as −90°C. Measurements of Earth’s magnetic field, gravitational field, height above sea level, and density of the snow cover were conducted every 20 km[28]. Cairns built of empty fuel drums were erected every 100 km and coordinates were measured by astronomical methods[26]. Two kinds of measurement of height (levelling) were used: geodetic and barometric. Despite the fact that geodetic levelling is especially difficult to conduct in Antarctica due to the harsh climate conditions, it was done on this traverse along the Vostok–Pole of Inaccessibility route of 1100 km with the aid of electronic distance measurements. From these measurements, the 1964 party found that the previously erected Pole of Inaccessibility Station was located at 3718 m above sea level (Figure 3). Seismic methods were used to measure the thickness of ice at that location, which was found to be 2980 m[29]. The highest point measured by the party was 3997 m above sea level[26].

Figure 3 Pole of Inaccessibility Station (in December 1965 during the visit of the United States Queen Maud Land [QML] traverse) with bust of Lenin atop the chimney (photo: QML traverse II)

Arriving at the Pole of Inaccessibility Station, they found the 1958 buildings intact. The expeditioners spent five days there conducting scientific observations and repairing equipment. After refilling their fuel tanks from stocks left by their predecessors in 1958, the traverse continued on to the unexplored section of the more westerly region of East Antarctica (around 78°S, 20°E) and then, on 14 February 1964, turned towards Molodezhnaya Station. In his radio reports to the popular Soviet newspaper Izvestiya directly from Antarctica, Sorokhtin stated that 'again and again the powerful Kharkovchankas battled their way in the boundless cold desert. Again and again we see the familiar monotonous landscape—a white plain covered with small sastrugi, a snow veiled sky, which is light blue in fine weather but milky white most of the time" [30].

As the traverse approached the coastal area, a crevassed region was encountered. An aircraft and tractor were sent from Molodezhnaya Station to meet them. Cairns were constructed every two kilometre by Maltsev's hydrographic team, showing a safe passage through a narrow corridor between the crevasses[29]. On 21 March 1964, after a 78-day journey, the traverse reached Molodezhnaya Station, having covered a distance of 3323 km. The scientific results of the traverse included the discovery of a subglacial ridge 2500 km in length, named Podlyednye Gory Vernadskogo after the Soviet geologist Vladimir Vernadsky (1863–1945), which divided East Antarctica into two parts. (The Gamburtsev Subglacial Mountains were initially similarly named as 'Gory Podlyednye Gamburtseva', until 1975 when the Advisory Committee on Antarctic Names (ACAN) accepted the English interpretation of this geographical feature). Data on snow, ice, and relief of the previously unexplored area were obtained, as well as seismic soundings and geodetic, meteorological, gravimetric, glaciological, and magnetic observations[26,31].

A profile of the subglacial topography and of the surface of the glacier was created. The thickness of the ice at some points reached 3800 m. It was found, based on modelling the measured vertical temperature profile within the ice, that in the past, thousands of years ago, temperatures here had been even lower (around −100°C) and that the ice cover might then have been thicker. The Earth's crust would now be slowly rising due to a reduction in the weight of the thinning ice cover[31].

3.3 Twelfth SAE, 1966–1968

A third Soviet traverse to the area, from Molodezhnaya Station to the Pole of Inaccessibility, Plateau Station (USA) (79°25'S, 40°30'E) and on to Novolazarevskaya Station (70°46'S, 11°50'E) was undertaken during the Twelfth SAE (1966–1968).

In the interim, the Pole of Inaccessibility Station had been visited by the United States Queen Maud Land Traverse. The Queen Maud Land Traverse was conducted in three phases in the austral summers of 1964–1965, 1965–1966, and 1967–1968 along a nearly 4200 km zig-zag route across the Antarctic plateau, starting from South Pole. Participants included scientists from Belgium and Norway as well as the United States. They made measurements along the route of surface elevation, ice thickness, snow accumulation, the geomagnetic field and gravity, and collected snow samples and ice cores[32]. The Pole of Inaccessibility Station served as a staging point for 3 weeks between Phase I and Phase II of that traverse in November-December 1965.

Seventeen expeditioners participated in the Twelfth SAE traverse: I. Petrov (head of the traverse); V. Petrov (glaciologist); V. Shlapunov (driver); A. Kogan (engineer, geophysicist); N. Melehin (driver); V. Chudakov (geodesy); L. Shevchenko (glaciologist); A. Maslennikov (geodesy); G. Egorov (levelling); V. Astanin (geodesy); V. Shirshov (geodezy); E. Morozov (magnitology); A. Borisov; P. Shulenin; S. Chertok; S. Kovtanyuk; and A.Kozlov. Half of these had never previously been to Antarctica. They left Molodezhnaya on 18 December 1966 and arrived at the Pole of Inaccessibility Station on 22 February 1967. From there, they continued on to the American station Plateau on March 3 and finally reached their destination, Novolazarevskaya Station, on 26 March 1967, having covered a distance of 3411 km.

The Molodezhnaya—Pole of Inaccessibility leg of this traverse approximately followed the 50 degrees east of Greenwich meridian. Ice temperature measurements were taken between the coast and the centre of the ice sheet in 8 places, at distances of 50 to 250 km from each other, within bore holes of diameter 190 mm and a depth of 33–45 m. The lowest temperature measured was −59.2°C[33]. The first 200 km from Molodezhnaya followed a route which had already been marked with cairns by the Maltsev team in 1964. Geodetic and barometric levelling on this leg was conducted simultaneously.

Two Kharkovchankas, a smaller tractor and sledges were used. After the previous traverse, the Kharkovchankas were completely covered with soot from the exhaust fumes: the inside walls, tables and shelves had to be washed with caustic soda and repainted. A new thermal insulation layer was placed on the floor and ceiling. Traversing in the Kharkovchankas, however, was a real challenge: the roar of the engine in the interior space of 20 m^2 was much like that of an aircraft, making sleep impossible. While going over the hard sastrugi and huge snowdrifts, the machines careened and swayed, with the expeditioners having to hold on to the walls so as not to lose their balance[29].

The fifteen day climb towards Central Antarctica allowed the expeditioners to slowly acclimatise to the high altitude. However, many of them still complained of headache and almost all had shortness of breath due to the lack of oxygen when moving quickly or doing strenuous work. Temperatures during the day were often above zero which melted the snow: one of the Kharkovchankas found itself in water up to the level of the cabin.

Owing to the fact that a full time cook was included in the team, three hot meals per day were served. As a consequence, unlike in previous years where the expeditioners lost from 7 to over 14 kg in weight during the traverse, their body weight remained practically unchanged. Protective measures against frostbite and mechanical injuries were also taken. Nevertheless, the conditions left a lot to be desired[34].

Observations and research conducted during the traverse included seismology, radar soundings, geodesy, gravimetry, meteorology, glaciology, atmospheric physics, and radio communication. A medical check-up of the personnel was conducted weekly to further understanding of the acclimatisation and behaviour of man in Antarctica[35].

4 Airborne radio echo surface profiling of the Dome A region, Antarctica: 1967–1983

4.1 Background to the 1969–1983 airborne radio echo sounding program

Long-range airborne radio echo sounding (RES) of the Antarctic ice sheet commenced in the 1967–68 austral summer with a joint international program between the Scott Polar Research Institute (SPRI) of Cambridge University in the United Kingdom and the United States National Science Foundation. The radar developed at the SPRI used a pulse-modulated system operating in the VHF range (MHz)[36] and had been tested successfully from over-snow vehicles in Greenland in 1964[37] and in light aircraft in the Canadian Arctic and the Antarctic Peninsula[38-39]. At an early stage it was recognised that detailed surface elevation profiles could be obtained from the RES output (i.e. equivalent to an aircraft altimeter) especially if the aircraft was flown at a steady pressure altitude and tied into or "fixed" at points of elevation from geodetic or other reliable surveys. Robin et al. 1970a[40] used this surface profiling feature of the RES, for example, to delineate the five major ice streams discharging into the Ross Ice Shelf along the Siple Coast. It should be recalled that this was an era of geophysical exploration just before the dawn of satellite radar and laser altimetry which would within the following decade transform data gathering and provide unimaginable detail of the surface of the great ice sheets.

The objective in 1967 was to test the ability of the RES system to sound continuously through a range of ice conditions in Antarctica and evaluate performance—deep cold ice in East Antarctica, warmer and deep ice in West Antarctica, over ice shelves, ice rises as well as large outlet glaciers cutting through the Transantarctic Mountains. Flying in a US Navy Super Constellation C-121 aircraft the season of ice thickness sounding out of the US air facility at McMurdo Sound/Williams Field was very productive and resulted in a number of publications and improvements to the RES performance[41]. A RES profile, obtained in 1967, is reproduced in Figure 4 which shows a strong sub-ice reflector close to Sovetskaya Station at a depth of 4200 m. The strong return was, "attributed to a thick layer of water beneath the ice" [41]. This was the first time that geophysical evidence had indicated directly the presence of extensive water bodies beneath the Antarctic Ice Sheet. In the 1960s Zotikov[42], following Robin[43], had calculated that the temperature at the base of the ice sheet was at the pressure melting point over extensive areas and could, therefore, be resting on a layer of water. In a future Antarctic RES season this proposition was proven with the identification of numerous sub-ice "lakes". These positive outcomes led to the development of a longer-term joint program of RES (which later involved the Technical University of Denmark [TUD] that had been conducting similar surveys in Greenland with NSF support) and became an important contribution to the International Antarctic Glaciological Project (IAGP) with its focus on understanding the dynamics and climate-related history of the East Antarctic ice sheet[44].

In 1969–1970, the second RES season, the program was supported by the use of a ski-equipped Hercules C-130 aircraft of the US Navy operating out of McMurdo (Figure 5). Problems with the tail-mounted antenna reduced the maximum thickness of ice that could be sounded but flights were made into the central regions of East Antarctica, to

Vostok, Sovetskaya, Pole of Relative Inaccessibility and across the main ice dome (Dome A).

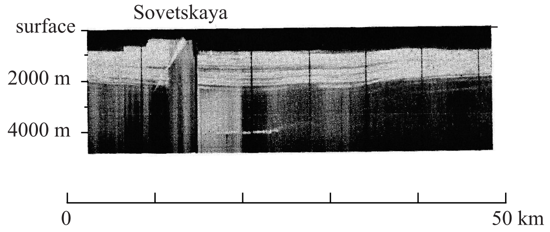

Figure 4 An early airborne RES profile from central East Antarctica in the vicinity of Sovetskaya Station recorded in December 1967 using the SPRI MkII sounder (operating at a centre frequency of 35 MHz and with a system performance of ~160 dB). The principal features are: a slanting echo from surface artifacts at Sovetskaya Station, internal layers to a depth of 2200 m and a strong, continuous and near-horizontal return from the base of the ice, interpreted as thick water layer. The figure is reproduced from Robin et al [41].

Figure 5 Hercules ski-equipped aircraft (LC-130R) in 1978 with 60 MHz ice radar antennae (comprising four half-wave dipoles) fitted beneath the starboard wing. The 300 MHz antenna is mounted beneath the port wing (unseen).

It was not until the 1971–1972 Antarctic field season that improved navigation facilities onboard the C-130 and a new SPRI radar sounder operating at a centre frequency of 60 MHz enabled a systematic survey of ice sheet surface elevations, ice thickness and sub-ice bedrock relief to be undertaken[45]. The season's activity comprised, inter alia, conducting a grid of flight lines at 100 km spacing across East Antarctica to obtain surface topography in order to delimit the principal drainage basins and main ice flowlines. In addition to the all-important ice thickness data, this would be of considerable value in selecting locations for deep ice core drilling and interpreting the history of the ice down-core. The season produced an exceptional quantity and quality of data including the first systematic identification of sub-ice lakes[46]. The elevation data were compiled into a series of topographic maps of the IAGP sector of Antarctica and published in 1975[47].

4.2 Mapping of East Antarctica 1971-1972

The 50,000 km of radio echo flight lines acquired in 1971–1972 required much attention to turn them into useful data. The navigational reduction was revolutionised by the use of Inertial Navigation Systems (INS). The instrumental drift of the INS was determined from numerous missions to range between 0.5 $\mathrm{m{\cdot}s^{-1}}$ to as little as 0. 07 $\mathrm{m{\cdot}s^{-1}}$, the average being 0.2 $\mathrm{m{\cdot}s^{-1}}$[47]. Aerial photographs continued to be used for making precise fixes and closure errors could be re-distributed along the flight track so that the position error was considered not to exceed 5 km anywhere and in many areas considerably less. When the flight lines were plotted on a map at a scale of 1:5,000,000 their thickness (0.5 mm) was equivalent to 2.5 km on the ground — corresponding to the modal value of the navigation errors.

4.3 The ice sheet surface

With the network of flight lines over East Antarctica it was possible to map the surface with a greater degree of accuracy and consistency than hitherto. It was also possible to add some of the data from the 1967–1968 and the 1969–1970 RES seasons where it was judged the navigation was sufficiently comparable. The principal source of error in ice sheet altitudes from the RES was determination of the height of the aircraft. The raw altitude data were, however, very coarse due to instrumental inaccuracies, large scale changes in the pressure surfaces over Antarctica over the duration of a flight and complications from the aircraft altitude changes. It was considered that the errors could be up to 100 m! This was unacceptable. To reduce the errors, elevations along the flight lines were fixed to sea level at both ends (e.g. at McMurdo) and, wherever it was possible, to accurately determined surface elevations from ground traverses; the only problem being that the latter were very sparse. Two computational methods were adopted to adjust the height differences at the cross-over points on the extensive grid of flight lines which would minimise the errors. The first, and more rigorous of these methods, was a random walk routine in which the elevation at any one crossing point was, after many thousands of "visits" (during random walks that began and ended at a control point) converged on a stable solution as errors were redistributed over the entire grid. The data reduction process is shown in Figure 6. These results were very closely replicated by the second method, a least-squares adjustment, and thus gave confidence that the uncertainties in the surface elevations had been reduced significantly to no more than 30 m over the area mapped[47].

The contouring for the published maps was undertaken principally by Alan Clayton and David Drewry from the adjusted data using colour-coded flight line plots of elevation at a scale of 1:2,188,800 and then reduced to 1:5,000,000. This latter scale made it compatible with some of the existing maps of the continent. The features that emerged provided much greater detail. In particular it was exciting to see three high regions within the interior emerging from the analysis—

called by the unexciting names of Domes “A”, “B” and “C”! These are centres of outflow of the ice from the interior to the ice sheet margins. Dome “A” in the very centre of East Antarctica was the highest part of the whole of the Antarctic ice sheet at about 4100 m above sea level (asl) (Figure 7), Dome “B”, at 3800 m asl, turned out later to be more of a long flat ridge many hundreds of kilometres in length descending from Dome “A”. Dome “A” and much of Dome “B” were located over the irregular highland region of the Gamburtsev Mountains. Dome “C” at over 3200 m asl lay further north along the 130ºE meridian at about 75ºS.

These findings were distributed in advance of publication in manuscript form to other participants in the IAGP in order to assist them with their planned activities. Whilst the area of RES coverage did not extend greatly into the region being investigated by the Soviet Antarctic Expedition, especially towards the coast and the station at Mirny, the new maps were nevertheless of considerable interest for the interior around Vostok and the sub-glacial Gamburtsev Mountains. It was clear that the completed grid revealed the East Antarctic Ice Sheet in unparalleled detail but the coverage needed to be extended in future seasons to be able to answer increasing questions on the form and flow of this great ice mass.

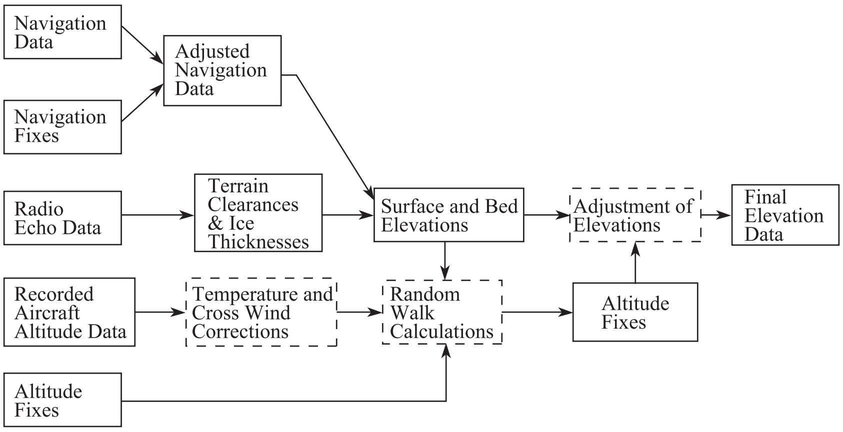

Figure 6 Radio echo sounding data reduction process (after Steed,1980[48])

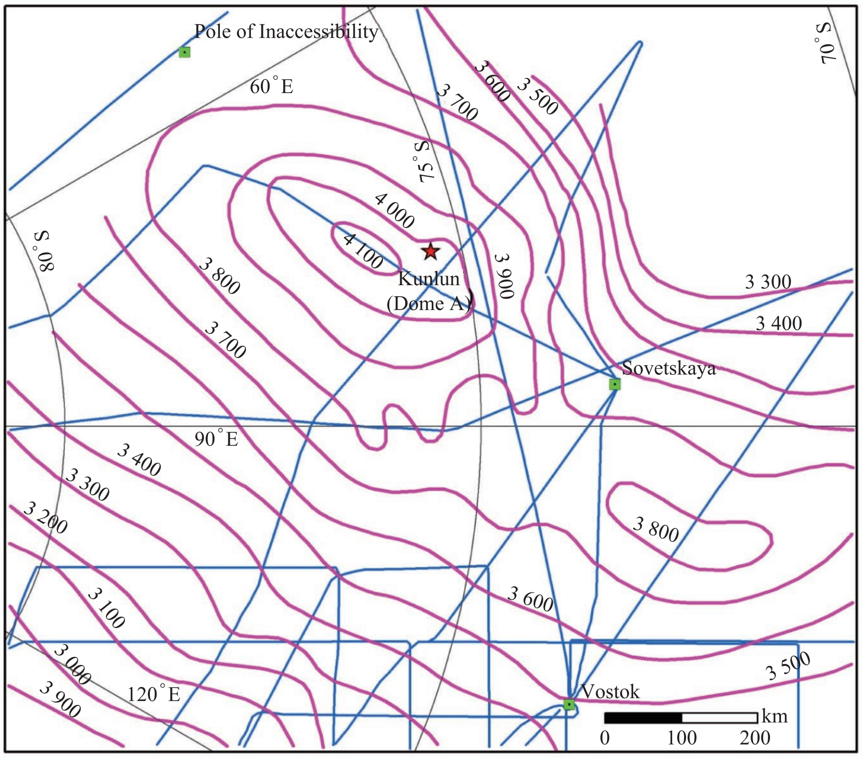

Figure 7 Dome A area as depicted on the 1975 SPRI RES Map[47]. Ice sheet surface contours are shown in pink and the RES flight lines are shown in blue. Additional data from ground traverses were also used, but are not shown in this figure.

4.4 Later seasons

The RES program continued in East Antarctica as well as West Antarctica and the Ross Ice Shelf in the 1974–1975, 1977–1978 and 1978–1979 seasons when the SPRI team was joined by colleagues from TUD with a new generation of improved radar sounders[49]. During the last two seasons a new C-130 R-model was employed with greatly improved navigational and avionics systems thus improving the consistency, quality and accuracy of the data. In central East Antarctica additional lines were flown. None of the flights during these three seasons, however, were programmed to gather further data over the region of Dome A. Much attention was focused on investigating the flow regime and sub-ice geophysical characteristics of West Antarctica and its adjacent large ice shelves[50]. In East Antarctica there was concentration on (1) “Ridge” B, (2) the Vostok area, (3) Dome C to provide detailed surface thickness and bed data for the international ice core drilling program, and (4) the coastal areas from about 118ºE to 160ºE.

4.5 SPRI Folio

At the termination of the airborne campaigns of the Antarctic RES program in 1979 considerable resource went into compiling the results of all the five major field seasons into a comprehensive series of large scale maps depicting measured and derived parameters of the ice sheet. A significant discovery in the1974–1975 season was the extensive and practically continuous body of water—a sub-ice lake—beneath and to the NNW of Vostok Station[51]. It was possible to indicated approximate dimensions and to speculate on its origin. Lake Vostok became the focus of later and more intensive airborne, satellite and ground based investigations[52-53]. The opportunity was taken to combine all available data on ice surface elevations and ice thicknesses gathered over the previous two decades which were of equivalent or acceptable accuracy. The elevation map comprised, in addition to the RES airborne data, barometric determinations and geodetic levelling conducted on over-snow traverses, some 5000 values from constant-density balloons and ground-based satellite doppler survey altimetry. The methods and details of the compilation have been given by Drewry (1983)[54] and Drewry et al (1982)[55]. In summary all the reduced data were plotted at a scale of 1:3,000,000 and contouring was undertaken with an interval of 100 m combining both manual and computer techniques.

The resulting continental-wide map yielded surface elevation data in the region of Dome A of improved accuracy and detail compared with the 1975 compilation (Figure 8). The 4100 m contour disappeared; the highest point was determined to lie above 4050 m but less than 4100 m. The shape of the wider Dome A region was also refined considerably, somewhat offset on an extensive and relatively shallow arcuate ridge the inner part of which focused ice flow into the enormous drainage basin of the Lambert Glacier. In the direction of the Pole of Inaccessibility and beyond this shallow ridge dropped to a wide col (in the vicinity of Plateau

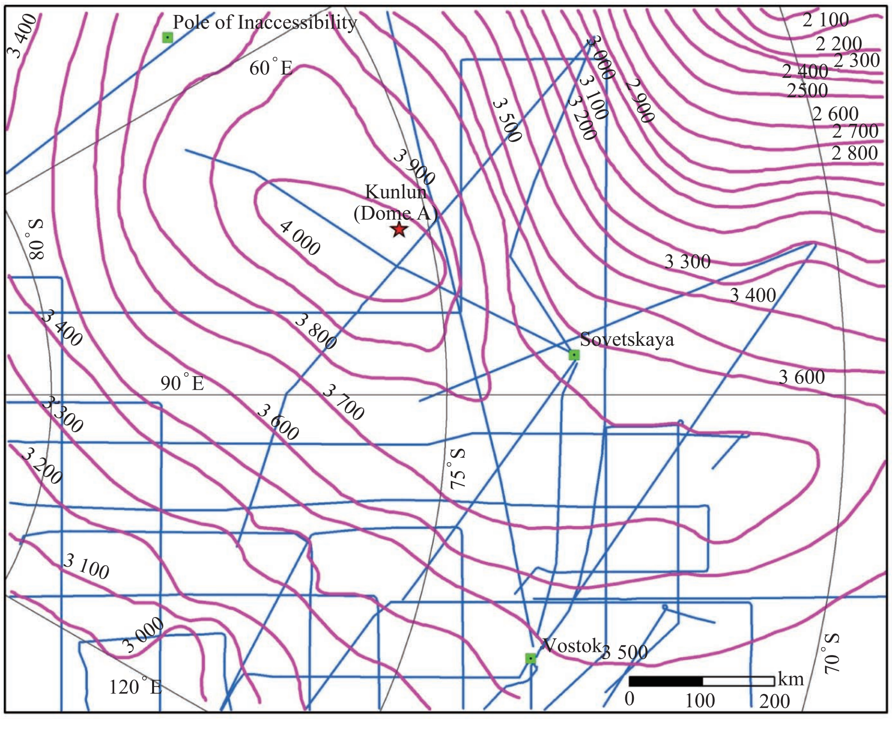

Figure 8 Dome A area as depicted on the SPRI Antarctic Folio, Sheet 2[54]. Ice sheet surface contours are shown in pink and the RES flight lines are shown in blue. Additional data from ground traverses, the high-elevation TWERLE balloon experiment and satellite Doppler determinations were also used, but are not shown in this figure.

Station; 79°215'S, 40°30'E) and thereafter rose to another broad dome in excess of 3700 m ("Valkyrjedomen" on the SPRI Map). Away from Dome A, in the other direction, the new contouring indicated a long, gentle slope but steepening gradually towards Komsomolskaya. The slight dome at 3800 m shown in the 1975 compilation and which was termed Dome B evaporated! It was now a well defined ridge which was renamed, unsurprisingly, Ridge B. In the opposite direction to the Lambert Glacier basin the ice sheet surface from Dome A is shown to fall away steadily towards the barrier of the Transantarctic Mountains where ice commences to be channelled into the major outlet glaciers and thence into the Ross Ice Shelf.

4.6 Sub-ice topography in the Dome A region

Ice thickness data comprised the primary objective of the RES airborne campaigns. A map at equivalent scale (1:3,000,000) was produced in the SPRI Folio of the bedrock surface of Antarctic from all known existing data[56]. The Third SAE Traverse from Soveteskaya to the Pole of Inaccessibility revealed, from seismic shooting and gravity observations, the presence of a substantial sub-ice mountain chain—the Gamburtsev Mountains. One of the 1967–1968 Season reconnaissance flights extended over these newly discovered ranges confirming their presence by an independent technique although Robin et al. [41] considered the seismic ice depths to be significant underestimates. In later years another four flight lines crossed the Gamburtsev Mountains in and around the Dome A area. To the east between Vostok Station and Dome A many more lines provided detail of the Vostok Sub-Glacial Highlands. This adjacent mountainous area displays less rugged terrain and would appear to be a separate geological province[57]. From these early and rather sparse soundings it was clear that the highest point of the East Antarctic Ice Sheet was currently positioned very closely to these high sub-ice regions whose elevation at that time was considered to be largely above 2000 m asl and with peaks rising to greater that 3000 m asl and covered by barely 1000 m of ice. It was also speculated at this time that the Gamburtsev Mountains (as well as the rising Transantarctic Mountains) most probably acted as one of the primary centres for the development of the East Antarctic Ice Sheet in the mid-Cenozoic[58]. More recent intensive RES has now defined the Gamburtsev Mountains in exceptional detail and also speculated at their role in the early origins of the ice sheet[59].

5 Concluding remarks

Scientifically and geographically, the three Soviet traverses to the Pole of Inaccessibility undertaken during the 3rd, 9th and 12th SAEs, in 1958, 1964 and 1966–1967 respectively, had been a huge success. By taking calculated risks and braving uncertainty, the Soviets penetrated to the coldest, highest and furthest point in Antarctica, tested new techniques and human endurance in the severest Antarctic conditions, and pushed the limits of scientific exploration. The scientific material obtained was incorporated in two volumes of the Soviet Atlas of Antarctica published in 1966 (Volume I) [60] and in 1969 (Volume II)[61]. When the then Director of the Australian Antarctic Division, Phillip Law was in Leningrad in 1964 he had the opportunity to check some of the finished proof sheets on subjects with which he was familiar and found that the work was of a high standard and meticulously done. He considered that 'the magnitude of the undertaking is impressive' and that the Soviet Atlas of Antarctica was to be a 'great contribution to Antarctic knowledge'[62].

Some of this knowledge was shared with the Chinese scientific community. Several leading Chinese geocryology, glaciology and permafrost scientists, including Xie Zichu, who was the second director of the Lanzhou Institute of Glaciology and Geocryology, were trained either at the Faculty of Geography or the Faculty of Geology at Moscow State University; Soviet studies formed the basis of upon which much Chinese science and engineering subsequently evolved from the 1960s to the 1980s[63]. At the present time, scientific endeavours in the Antarctic are continued by Chinese scientists who were trained by some of the graduates of Moscow State University.

The NSF-SPRI-TUD airborne radio-echo sounding measurements of the 1960s and 1970s provided comprehensive data confirming the position and elevation of the highest point of the ice sheet and of the existence of the Gamburtsev Mountains beneath it. The SPRI Glaciological and Geophysical Folio was for several decades the primary source for continent-wide data on ice sheet parameters. Subsequent modern satellite and ground based measurements have shown its ice sheet surface topography in the Dome A region to be remarkably accurate.

Today high resolution digital elevation models (DEMs) of the entire ice sheet, with decimetre accuracy, are derived from satellite altimetry (both radar and laser altimeter systems), often combined with aircraft or terrestrial data[64-65]. The detailed ice sheet surface topography is an important determinant of ice flow velocity (largely determined by regional surface slope), and hence delineating ice drainage basins, and as a boundary condition for numerical models of ice sheet behaviour; past present and future. The satellite altimeter systems also provide a direct, and increasingly accurate, measurement of ice sheet elevation change and its contribution to sea level rise in response to climate change[66].

Fifty years after the Soviets had first established their temporary base at the Pole of Inaccessibility in December 1958, and more than thirty-five years after the NSF-SPRI-TUD airborne measurements concluded, the Chinese traverse from the coastal Zhongshan Station arrived at Dome A to start building their own summer research station in December 2008. The main thrust of Chinese scientific research, often with international collaboration, is in the fields of glaciology, astronomy, geophysics, medical research, surveying and mapping[67]. Thus, the search for scientific knowledge and resultant increase in national prestige lives on with the ‘brand-new historical era’ in polar development on which China is embarking in the Antarctic[68]. Over the last more than 30 years, Chinese collaboration in Antarctic research has considerably expanded with many nations, including Australia, France, UK and the USA.

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