Relationships and significance of contaminants in soils of the Transantarctic Mountains

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ABSTRACT. The behaviour of Antarctic soils towards contaminant materials depends on the nature of the contaminant and the properties of the soil. Relevant properties are: depth to permafrost, whether the permafrost is ice-cemented or dry frozen; the active layer depth, active layer moisture content, and frequency of liquid water; soil salinity characteristics; and the geological composition of the soil materials.

Soil contaminations in the McMurdo region have been investigated through several years in a number of studies, including site surveys, field investigations, and experiments. Results of these studies are summarized in this paper and the significance of the contaminations is discussed. The behaviour of contaminants at the sites investigated conforms to existing knowledge of the soil properties. In the presence of some summer water or occasional moisture influxes from snowmelt, soluble contaminants may be transported variable distances through soils, both downwards and laterally, depending on the amount of water available. Ice-cemented permafrost restricts the downward movement of most contaminants but may aid distribution via lateral flow, especially low-freezing-point contaminants such as hydrocarbons. In dry-frozen soils, low-freezing-point contaminants may penetrate deeply into the soil.

With respect to the sites investigated, the heavy metal contaminations were typically above the values from undisturbed sites, but there may at times be appreciable natural variation. The presence of solid materials in soils — such as particles of plastics, wood, fibre, etc — represents a widespread and pernicious form of contamination, because they are foreign to the environment and are non-degradable.

Contents

Introduction

The Transantarctic Mountains region of Antarctica comprises around half of the ice-free ground of the continent and has a most severe climate. Because of its unique features and ready access from the Ross Sea, the area has been the focus of continuing scientific attention since the early 1950s, and, during recent years, of increasing tourist activity. The Dry Valley region comprises about a quarter of the total bare ground of the Transantarctic Mountains and this locality has been the centre of most of the activity owing to its unique features and ready access from the substantial United States and New Zealand bases on southern Ross Island. These bases also service other more remote stations, such as South Pole, the former Vanda Station, and numerous research sites. Because of the concentrated activity at these stations and the accompanying significant logistical activity, there have been some marked and notable environmental disturbances at these sites, with associated varying degrees of soil contamination.

With the advent of the Antarctic Treaty and its Environmental Protocol, the comprehensive protection of the Antarctic environment and its associated ecosystems has become a major principle in Antarctic environmental management through the application of specific technical annexes. Matters relating to waste management and waste disposal, the prevention and management of contamination from all types of activities, and clean-up procedures have now assumed considerable importance. While preventing or minimising soil contamination from current activity is a prime objective, the assessment of the significance and extent of contaminations from past activities, coupled with decisions regarding any remedial clean-up are also important, not only for environmental considerations but because of the potential costs.

Because of the natural environmental variability within the Transantarctic Mountains, an understanding of the behaviour of contaminants in soils and their significance in respect to ecosystems is essential not only for sound day-to-day management of activity within Antarctica but also for decisions regarding the management of contaminated soils.

The authors have investigated Transantarctic Mountains soils since the 1960s, and during the past decade have undertaken specific soil-contamination studies at

Scott Base, Vanda Station, and Marble Point. Results of these observations are summarized in this paper and allow a broad overview of the nature and significance of soil contaminations in this region of Antarctica.

The soil environment

Soils of the Transantarctic Mountains region have been extensively studied and their general properties are now well known (Campbell and Claridge 1987; Campbell and others 1998b). The main features are: a stony surface pavement, predominantly sandy to bouldery gravel textures with loose consistence, a soil profile that ranges from non-weathered to distinctly and deeply oxidised, the presence of soluble salts either at the surface or as discrete deposits within the soil, permafrost at depths varying from near the surface to around 70 cm depth, and the virtual absence of soil organic matter. Transantarctic Mountain soils have developed under a range of climatic conditions, and differences in the local or regional climate are expressed largely through soil thermal and hydrologic properties, including the length of the thaw period, depth of thaw or active layer thickness, active layer moisture content and permafrost characteristics, including whether dry frozen or ice-cemented, and soil-salinity characteristics.

General physical properties

Transantarctic Mountains soils are predominantly formed on tills and fragmented bedrocks and to a minor extent on fluvial deposits and windblown sands. The surface desert pavement horizon is typically stony and very loose with a relatively low sand content, and it usually passes abruptly into loose, structureless, sandy to bouldery gravel with the ratio of fine (<2 mm% fraction) to coarse (>2 mm% fraction) material being highly variable. Occurrences of plant materials and accumulations of organic matter are rare. Older soils are clearly distinguished from younger soils in having browner or reddish colours with an increased depth of oxidation. Young soils are typically lithochromic. The increased weathering found in older soils has little influence on the permeability of the soil, as increased weathering typically results in only a very small increase in the fine fraction. Silty or clayey layers with potentially lower infiltration and increased chemical adsorption capacities are rarely found; hence most soils have a high capacity for the rapid infiltration of liquid contaminants. Salts are present as distinct horizons in inland older soils and sometimes as surface efflorescences in the younger soils near the coast.

Soil climatic relationships

Soil temperature, moisture, and salinity are important climate-related attributes that influence the behaviour of contaminants within the soils. They affect the rate of movement of contaminants and the contaminant reactivity within the soil. The principal factors influencing soil temperatures are surface albedo and surface cooling. Surface albedo determines the amount of incoming solar radiation that is available to heat the soil and drive the soil processes (Campbell and others 1997b), whereas cooling, or the rate of heat loss from the soil, is governed primarily by air temperatures, which are appreciably lower at higher altitudes. Albedo varies due to differences in the colour of the surface soil, to surface roughness, and to the length of time that the surface is covered by snow. Most sites, apart from those shaded by mountains or seasonal snow cover, receive similar amounts of solar radiation, but soil temperatures inland at higher elevation are markedly cooler than those in coastal areas, due to greater convective and radiative heat loss. The thermal properties of the soils that can influence the movement of contaminant solutions through the soils are the length of the thaw period and number of freeze–thaw cycles, the depth of thaw or thickness of the active layer, and the amount of water within the soil, both in the active layer and in the underlying permafrost (Campbell and Claridge 2000). All of the above are a function of the total amount of energy available for soil heating.

The most vulnerable sites in respect of the transmission of contaminants (excluding contaminants with low freezing points, such as hydrocarbons) through the soils are in the coastal regions of the Transantarctic Mountains, where air temperatures, soil temperatures, and depth to permafrost are greatest (Campbell and Claridge 2000) and there are fewer freeze–thaw cycles. The least vulnerable sites are in inland and high elevation areas where the number of freeze–thaw cycles and diurnal temperature range are greatly increased and the permafrost depth is least. This vulnerability is determined on the basis of the depth of the active layer, the presence of liquid-water content that promotes the mobility of contaminants, and the presence of biological life forms likely to be affected by contaminants.

Soils of the Transantarctic Mountains region have wide variations in the moisture content of both the active layer and the permafrost. Results of extensive soil-moisture investigations have been reported by Balks and others (1995), Campbell and others (1994, 1997a, 1998a, 1998b), Campbell and Claridge (2000), and Campbell (in press), and there is now a considerable understanding of the significance of spatial and temporal soil-moisture differences. Soils of the warmer coastal regions have the highest active layer and permafrost water contents because precipitation in coastal regions is greatest and temperatures are warmer. The soil-water content near the soil surface is typically around 0.5% and rises to around 12% near the permafrost boundary. In the ice-cemented permafrost of coastal soils, the gravimetric water content may exceed 150%.

The inland and Dry Valley regions have markedly lower water contents, primarily as a result of lower temperatures, precipitation, and humidity. In these locations, the active layer water content is very low, sometimes averaging less than 1% through the entire soil profile. In the permafrost, similar low values may be found with insufficient water present to form

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ice-cemented permafrost, which is then termed dry-frozen. Where ice-cemented permafrost is present, the water content is usually much lower than in that of the coastal regions. Because of the low water content of these inland soils, transportation of contaminant solutions through the active layer will be more restricted than in the warmer and moister soils of the coastal regions. However, where dry-frozen permafrost is present, deep penetration by contaminants with low freezing points, such as fuels, can occur.

The availability of soil water after snowfalls, from snow-thaw sites, from soil adjacent to water bodies such as lakes, and from an irrigation trial has been investigated to provide information on the movement and rates of loss of water from soils and hence on the potential movement of contaminants within soils (Campbell and Claridge 2000; Campbell, in press). Water from thawing snow after a summer snowfall is typically lost by sublimation or evaporation from the soil surface horizons within 24–36 hours, although a small amount may penetrate deeper, depending on the climatic conditions. At the thaw sites of transient snowdrifts, water, moved through the soil by capillary flow, is soon lost by evaporation, and the soil typically returns to ambient moisture conditions after around 14 days. In areas adjacent to water bodies such as streams and lakes, the moistened fringe zone seldom extends more than 5–10 metres, the water transport in this zone being primarily by capillary flow. These data suggest, therefore, that in the absence of excess water, the movement of contaminants in soils of the Transantarctic Mountains region is likely to be slow. The length of the thaw period and the amount of water available will determine the extent of contaminant transport in low-salinity contaminant solutions.

Soils of the Transantarctic Mountains contain soluble salts, often in considerable quantities, and these can influence the behaviour of soil contaminants because they extend the temperature range over which a liquid aqueous phase will be present and thus influence the mobility of contaminants. The general nature and distribution of salts in Transantarctic Mountain soils was described by Claridge and Campbell (1968, 1977). On inland old land surfaces, the soluble salts often form horizons up to 10 cm thick and are dominantly nitrate and sulphate, but chloride anions are absent. The cations are mainly sodium, calcium, and magnesium. In coastal regions, the salts in the soils are of direct marine origin, with the same ratio as those of sea water. They seldom occur in thick horizons, but are more usually found as surface efflorescences.

Study sites

The authors have investigated contamination of soils in several localities in the McMurdo Sound region of Antarctica, in particular Marble Point, on the shores of McMurdo Sound; the site of Vanda Station, beside Lake Vanda in the Wright Valley; and in the vicinity of Scott Base, on Ross Island. These localities are shown in Fig. 1. The investigations provide a basis for a broad understanding of the behaviour and significance of contaminations in the McMurdo region and are discussed below. In particular, the authors studied heavy-metal pollution arising from human activities and the effects of oil spills. Foreign debris — such as metal fragments, wood scraps, broken plastic, and paper — arising from human activities are present at all sites, but were not investigated in detail and are only briefly described. In addition, the mobility of artificially added contaminants (lithium chloride) in soils was studied.

Scott Base

Scott Base was established in 1957 at Pram Point adjacent to the sea on Ross Island. The base was subsequently rebuilt with accompanying considerable site land surface modification, and, as a result, both strongly modified and little modified soils are present around the base. The soils are from thin late-glacial drift, overlying fractured scoria bedrock from the McMurdo volcanics (Kyle 1977). Mean annual temperature is $-18°C$, and precipitation 188 mm a^{-1}, distributed evenly throughout the year. Summer snowfalls are common, while summer soil moisture contents are around 1% near surface to 10% at the active layer base, with ice-cemented permafrost below the active layer at 35 cm. At the Scott Base site, the authors investigated heavy-metal contamination around the base and also mobility of lithium chloride in soils.

Vanda Station

Vanda Station was constructed by the New Zealand Antarctic Programme near the edge of Lake Vanda in Wright Valley in 1968 and was occupied for four winters and all summers until 1994. As part of the environmental impact evaluation for its decommissioning, precipitated by rising adjacent lake waters, an assessment study of soil contamination was undertaken in 1992/93 (Sheppard and others 1994). During its earlier years of occupation, greywaters, urine, battery acids, etc, were discarded locally onto the soils and there were frequent spillages of hydrocarbon fuels. The soils around Vanda Station comprise mainly thin drift material from granite (including some lamprophyre dyke rock material that is common in the area) over fractured bedrock. Some later reworking of surface materials from fluctuating lake levels has occurred. Mean temperatures are a little lower than at Marble Point or Scott Base, but precipitation is approximately 13 mm a^{-1}, and soil moisture levels are very low. The active layer depth is about 35 cm, and the permafrost in the area is dry-frozen. At Vanda Station, the authors studied the contamination of soils arising from the activities around the base, and the effects of oil spills. The mobility of lithium chloride in soils was studied on an uncontaminated site remote from the base itself, on the north side of Lake Vanda.

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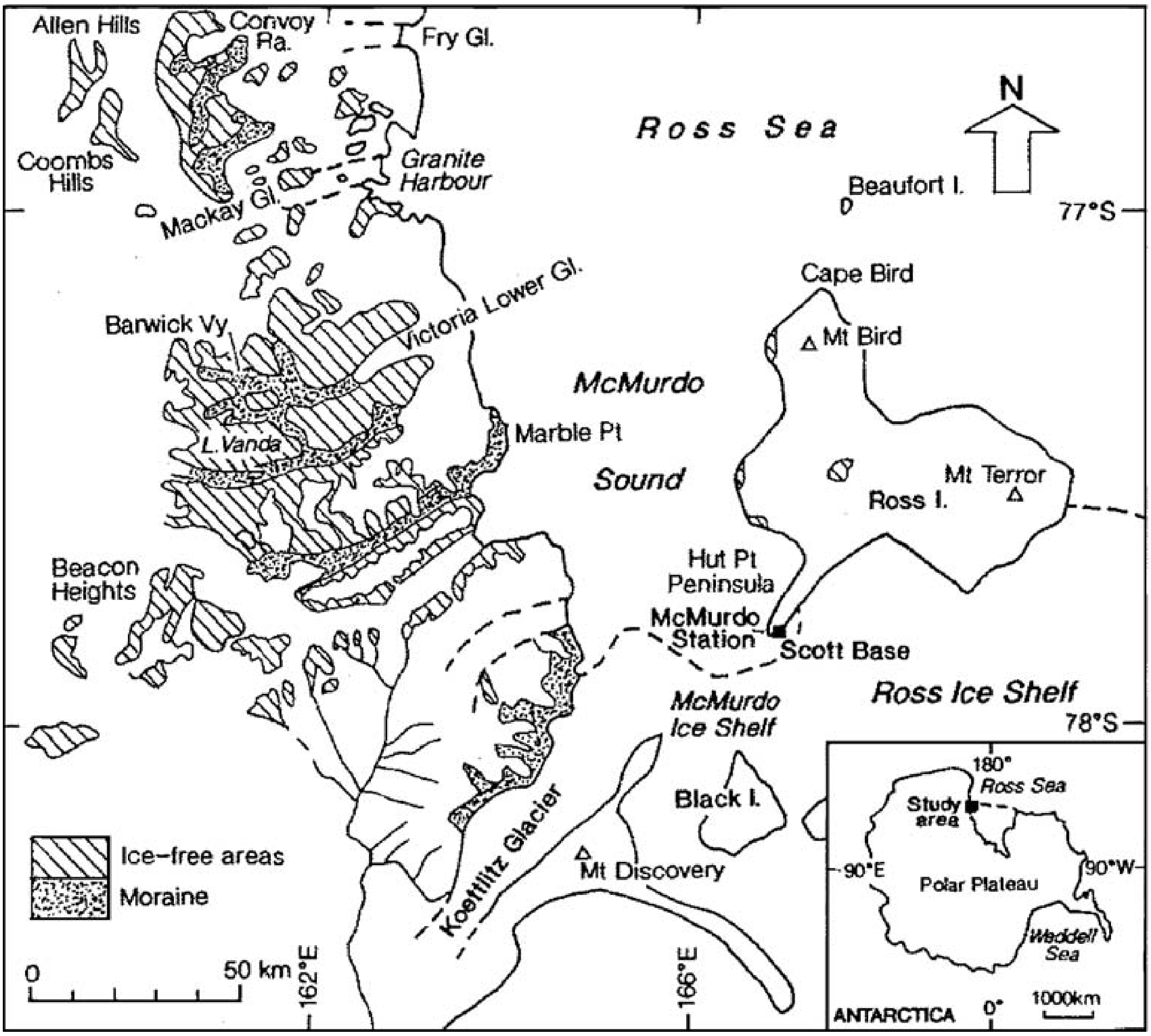

Fig. 1. Locality map, showing locations discussed. Vanda Station is situated on the south side of Lake Vanda in the Wright Valley.

Marble Point

Marble Point, situated near the coast on the western side of McMurdo Sound, was occupied in the late 1950s for the purposes of constructing an all-weather ground runway for fixed-wing aircraft. After the project was discontinued, the site was abandoned, but some years later, a site 'cleanup' was undertaken, which largely involved flattening the site with some burial and burning of materials (Broadbent 1994). Considerable amounts of rubbish remained at the soil surface, including crushed lead batteries, copper artefacts, used food cans, and building materials. In addition, residue from discarded heavy lubricating oils covered the ground surface at several sites. The soils at Marble Point are formed from till, the parent materials are dominantly from granodiorite with some marble and gneiss, and the active layer is around 70 cm thick and overlies ice-cemented permafrost. The climate is coastal (mean temperature around –18°C), and active layer soil moisture values range from about 0.5% at the soil surface to 12% (gravimetric) at the base of the active layer. Precipitation figures are not available but are not likely to differ markedly from those at Scott Base.

Contaminant investigations

Heavy metals

Scott Base

In 1993 an evaluation of metal-contaminated soils at Scott Base was carried out by sampling soils on traverses across the base site (Sheppard and others 2000). Seventy-two samples were collected from 15 pits and analysed for a range of metals. Results showed that soil carbon values were significantly greater at some sites than those normally found for Transantarctic Mountain soils, while conductivity values were appreciably higher at sites of greatest soil disturbance. Of the metals analysed for in extracts — Ag, As, Cd, Cu, Pb, and Zn — when compared with the relatively undisturbed reference sites,

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were markedly greater at sites adjacent to present or past buildings or where dumping or storage of materials had occurred. Dispersal by wind or water and mechanical movement of soil were thought to be contributing to the contaminant dispersal. It is likely that the presence of silver in marine sediments off the shoreline at Scott Base was the result of drainage from the base site (Anderson and Chague-Goff 1996). The results also indicated that metals such as Fe, Al, Ni, Cr, and Mn, which may have been associated with weathering, appeared to have been mobilised by water. Surface water flow from freeze–thaw cycles commonly occurs in this highly disturbed environment. Metal values in the reference sites were also appreciably greater than in the undisturbed sites at Vanda Station.

Vanda Station

At Vanda Station the authors identified the main disposal sites and other potentially contaminated sites, such as helicopter-landing areas, and an extensive sampling programme of these sites, which included a number of undisturbed remote sites, was undertaken. At several places, the soils were sampled at increasing distances from the disposal site to determine the extent of lateral down-slope movement of contaminants through the soils. Soils from 35 sites were analysed for 28 properties, including particle size, moisture content, pH, major salt components and nutrients, and a range of heavy metals.

The results of analyses (Sheppard and others 1994) showed that pH was lower at most of the disposal or spill sites compared with the reference sites; salts were mostly higher than in the reference sites; metals including Zn, Pb, Cu, Hg, and Cd were appreciably higher at various disposal sites (up to 400 times greater) than at reference sites; and other metals (As, Co, Ni, and Cr) were high but were derived from the local rock. The soil carbon contents were variable due to presence of cyanobacterial accumulations from past lake-level fluctuations, however, distinct soil darkening was observed at the regular greywater disposal sites. There was clear evidence for down-slope transport of contaminants at sites where greywater had been discarded, but at sites where there was no or minimal liquid discharges, down-slope movement appeared slight. At the sites of ongoing fluid disposal, icy permafrost had formed at around 35 cm depth and appeared to have facilitated the down-slope movement of contaminants. One reference site, which was remote from Vanda Station and on an appreciably older glacial surface, had values for the salts and for a number of the metals that were greatly in excess of those at some of the contaminated sites and the other reference sites and is presumed to be accumulating weathering products and atmospherically deposited salts from snowfalls (Claridge and Campbell 1977).

Marble Point

At the site of the old camp at Marble Point, the authors sampled soils from beneath a crushed lead battery, copper wire, rusted cans, and a rubbish fire site to assess what contamination may have resulted from these surface artefacts during the estimated 30-year period since their emplacement. Soil from an undisturbed site nearby was sampled for comparison. Results of the soil analyses were reported by Claridge and others (1995). Concentrations of soluble Zn, Pb, and Cu were barely detectable in extracts from the reference site (<0.09–0.04 $\mu g\,g^{-1}$) but were present in varying levels (up to 28.5 $\mu g\,g^{-1}$) at all of the contaminated sites. Beneath the battery and at the battery edges, a relatively large concentration of lead and smaller concentrations of zinc were detected while smaller concentrations were found 30 cm laterally. The concentrations reduced in the horizons beneath the surface, but increased slightly at the permafrost surface. Beneath the other artefacts, there was a similar distribution of lead, zinc, and copper, with highest concentrations in the surface horizon and lesser concentrations with increasing depth.

Oil spills

Studies of the effects of oil spills on the properties of soils at Scott Base, Vanda Station and Marble Point were made by Balks and others (1998, in press). The authors also observed traces of oil in sample sites at Scott Base but did not investigate them further. Around Vanda Station, where oil spills were identified, it was found that the fuel contaminant had penetrated more than 50 cm into the dry-frozen permafrost, whereas aqueous pollutants at this site moved horizontally over the anthropic icy permafrost, rather than vertically. The icy permafrost was not so firmly cemented as at the moister Marble Point site.

Two hydrocarbon spills were investigated at Marble Point. The first was heavy lubricating oil discharge on sites that were probably used for vehicle maintenance, or a generating plant dating from 1958–59 when the old base was occupied. The spill sites were very obvious, with dark coloured and caked surface soil overlying darkened and somewhat sticky subsurface soil. Small globules of oil were present at the surface of the permafrost, but there was little indication of hydrocarbon accumulation within the ice-cemented permafrost. The second hydrocarbon spill was examined in 1990 adjacent to a building where approximately 200l of fuel oil had been spilt eight days previously. At the spill site, the soil was soaked to the permafrost surface, where fuel oil had ponded. Five metres away, at a site that had not received any of the surface spillage, fuel oil was present on the surface of the icy permafrost, presumably having flowed laterally across the permafrost surface.

Debris

The environs of Scott Base are generally well-policed, and most rubbish is cleaned up. However, small fragments mix with and are incorporated with the surface soil, and may be buried more deeply by earthmoving activity. During the course of sampling for heavy-metal contamination (Sheppard and others 2000), debris — mainly fragments of wood and plastic, nails, bits of rubber, and traces of fabric — was found. Remote from the base, larger pieces

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of wood and paper, blown from the base area by strong winds, are frequently found trapped behind rocks.

At Vanda Station, the surface horizons of the sample sites contained abundant foreign material, fibres, human hair, dried food scraps, paint flakes, cigarette butts, etc (Sheppard and others 1994). Away from the base site, larger debris was found in places, old rubbish dumps with burnt food cans and bottles and windblown pieces of wood and cardboard. Some of these may be found several kilometres from the base.

Debris is widespread around the site of the old camp at Marble Point, because the remains of the camp were crushed and partly buried during the original site cleanup. Debris is widespread: metal fragments, wire, nails, pieces of canvas, broken wood, clothing, etc. The debris has not decomposed during its 40 years of exposure, some of the clothing, especially gloves, still being usable. As at other sites, strong winds have dispersed larger fragments of wood and paper over a wide area.

Contaminant mobility experiments

The capacity for soluble contaminants to move through soils is an important consideration in respect of the assessment of Antarctic environmental risk and management and was examined in an experimental study by Claridge and others (1999). In this study, two experimental plots were established near Scott Base, where the climate is moist coastal, one site being on a dry ridge and the other on a periodically moist gully floor. For comparison, two plots were established on slopes on the north side of Lake Vanda, where the climate is inland and very dry. For all four plots, lithium chloride solution was irrigated onto the soil surface at the same rate, and the soils subsequently sampled over several years at various depths and distances down-slope from the application plots.

The results showed that at the dry Scott Base and Vanda sites, most of the applied Li remained near the soil surface, with only a small amount penetrating into the soil over several years. Some Li was detected 2 m down-slope, but the amounts were very small and the movement of Li at the Vanda site after 48 months compared with the Scott Base dry site was even less. At the moist Scott Base site, the initial distribution was similar to the dry sites, but after 23 months, Li was detected 3 m down-slope and at a depth of 55 cm and in the ice-cemented permafrost.

Discussion

Transantarctic Mountains soils are inherently susceptible to the rapid transit of contaminant solutions because their coarse textures and loose consistencies offer little restriction to the passage of fluids through them. Significant limitations for the movement of contaminant solutions are, however, provided by soil environmental conditions that include the length of thaw period, the depth of thaw, the frequency of freeze–thaw cycles, the amount of water available in the soil, the nature of the permafrost, and the soil salinity. These attributes are a function of climate, and, although they vary from place to place, there are distinct regional differences in soil properties. Soil contaminant behaviour and reactivity can therefore be expected to vary in correspondence with regional and local site and soil conditions.

Soils of the warmer coastal regions, where moisture contents are highest, where there are longer thaw periods, and where permafrost is at greater depth, have the greatest capacity for transport of low-salinity contaminant solutions, with freezing points close to 0°C. Ice-cemented permafrost restricts the downward movement of contaminant solutions, but transfer by ionic diffusion may take place. Soils with least capacity for transport of contaminant solutions are those in the colder regions, where the thaw period is least, dry-frozen permafrost is at a shallow depth, and the soils are extremely arid. However, solutions with low freezing points, such as hydrocarbon fuels, are able to penetrate deeply into the soils in the cold arid regions, where there is no ice-cemented permafrost.

The studies at Scott Base, Vanda Station, and Marble Point have illustrated the significance of the soil differences in respect of contaminant activity. The soils around Scott Base are measurably contaminated with heavy metals, concentrated at dump and storage sites, but also widely distributed over the whole area of the base. Considerable movement of contaminant ions appears to have occurred, associated with surface and sub-surface flows occurring during the short summer thaw season. The lithium chloride leaching experiment clearly showed that in the absence of significance amounts of liquid water, the transport of contaminants through the soil is very slow but that contaminants may penetrate the ice-cemented permafrost if sufficient water is present.

At Vanda Station, a cooler and drier inland site, contamination was associated with the discharge of waste waters, which had moved contaminants some distance down-slope, largely because of the presence of an anthropic ice-cemented permafrost horizon, along which the discarded solutions had flowed. At other sites where little solution had been applied, the lateral movement of contaminants was limited. Without significant amounts of water, contaminant movement is extremely limited in this dry inland environment. However, spilt fuel at Vanda Station had permeated through the frozen soil, which was uncemented because of the low moisture content, and into the fractured bedrock beneath.

At Marble Point, in a warm coastal environment with moderate soil moisture levels and no site water flows, contaminations from the oxidation of metallic artefacts had penetrated the soil and moved only a small distance laterally during some 30 years. Spilt fuel oil, however, had quickly migrated laterally across the permafrost surface, which in this case was firmly ice-cemented.

The very high levels of salts and metals in one of the Vanda reference sites and the higher metal values in the Scott Base volcanic soils illustrates that the interpretation and significance of metal contaminations need to be kept in perspective with the natural variability that occurs within the soil environment. However, the bioavailability

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and speciation of contaminants, and the probable presence of synthetic organic compounds such as chlorinated solvents — as yet untested for — need to be investigated if effects on ecosystems are to be assessed.

Spilt fuels behave differently because of their low freezing point. Their movement through these soils is primarily influenced by the permafrost properties. In the absence of ice-cemented permafrost, fuel or any other low-freezing-point solution can easily penetrate deeply into the permafrost. Light-fraction hydrocarbons quickly evaporate under prevailing environmental conditions, while heavy-fraction hydrocarbons persist for a long time.

The most visible and widespread form of soil contaminating material is the wide variety of accumulated organic and inorganic foreign materials that are commonly found. These are typically smaller and less noticeable particles that escape general surface cleanups or that become incorporated into the soils from mechanical activity. They will persist within the soil because of the absence of biological or chemical decomposition.

Conclusions

Human activity has resulted in the contamination of Antarctic soils with fragmented debris, heavy metals, and hydrocarbon fuels, especially around sites of habitation. Fragmented debris does not decompose to any extent in the cold, arid environment, but is redistributed by wind. Heavy metals from corrosion products, such as paints, are relatively immobile under arid conditions, but their mobility is increased wherever moisture is present. Hydrocarbon fuels, with low freezing points, can penetrate deeply into soils and migrate along ice-cemented permafrost surfaces. Where the ice-cemented material is absent, discontinuous, or fragmented, hydrocarbons can penetrate deeper into the soil. These investigations have provided much useful information regarding the rates of accumulation, the movement through soils, and the likely downstream influence of contaminants. The movement of contaminants through soils is extremely limited unless significant amounts of water are available. When considering possible responses to contaminations, it will be necessary to consider the widely differing soil and environmental conditions that exist in the Transantarctic Mountains region.

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