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TECHNICAL ARTICLE

Evaporative Mine Water Controls on Natural Revegetation of Placer Gold Mines, Southern New Zealand

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Abstract Surface and ground water runoff is controlled by impermeable substrates exposed by mining at two abandoned historic placer gold mines. The arid climate at these sites ensures that much of the mine water evaporates on these impermeable substrates to leave saline residues that include halite and bloedite encrustations up to 1 cm thick. Mine water compositions were reconstructed by leaching of the substrates. The dissolved load in the mine waters was derived primarily from marine aerosols in rainwater, with a minor component from water–rock interaction in the mines. Salination of the sites from mine water runoff has taken <100 years, and the saline soils have limited the colonisation of tall native and exotic plants. Instead, the mine soils now support a distinctive and rare inland salt-tolerant ecosystem with low-growing plants, and this natural rehabilitation has resulted in enhanced biodiversity for the area. Natural rehabilitation may be an appropriate management strategy for mines located in similar geological settings nearby, and elsewhere in the world.

Keywords Groundwater · Runoff · Evaporation · Salination · Flora

Introduction

Management of mine sites after mining ceases is a major scientific and political issue that is attracting increasing attention around the world (Hilson and Murck 2000; Laurence 2006; McHaina 2001). Historically, most mine sites were abandoned and left to physically stabilise and revegetate naturally, while sediment and mine water discharges were largely ignored (e.g. Grant et al. 2002; McHaina 2001; Pentreath 1994). This approach is now deemed unacceptable in most political jurisdictions, and sites are typically subjected to extensive landscape remodelling and mine water management, followed by addition of topsoil and planting of vegetation cover (Banning et al. 2011; Bell 2001; Li 2006). In this way, mine sites can be rapidly transformed into agricultural land, recreational areas, or amenity and/or production forests (Bell 2001; Hüttl and Weber 2001; Smith and Underwood 2000), although mine water management remains an issue at most sites. Planning of mine projects is now undertaken with the end product, a rehabilitated site, as an important part of the management process during mine development (Lottermoser 2010; McHaina 2001; Tordoff et al. 2000).

Water management is a common issue of most abandoned historic mine sites, and this can dominate rehabilitation strategies (Banks et al. 1997; Younger 1997). However, in this paper we present a particular situation of two historic mine sites which, due to the semi-arid climate in which they are set, are characterised by evaporation of almost all of the mine water throughout most of the year. The loss of mine water through evaporation, coupled with the geological nature of the substrates at these mines, has caused the sites to become anomalously saline compared to immediately surrounding land, to the point that thin salt crusts have developed in some places (Fig. 1). This enhanced salinity facilitated establishment of distinctive and relatively rare flora (Allen and McIntosh 1997; Rogers et al. 2000). Natural saline soils occur in the surrounding area, but these are fragile and are currently threatened by agricultural development. The survival of the endangered

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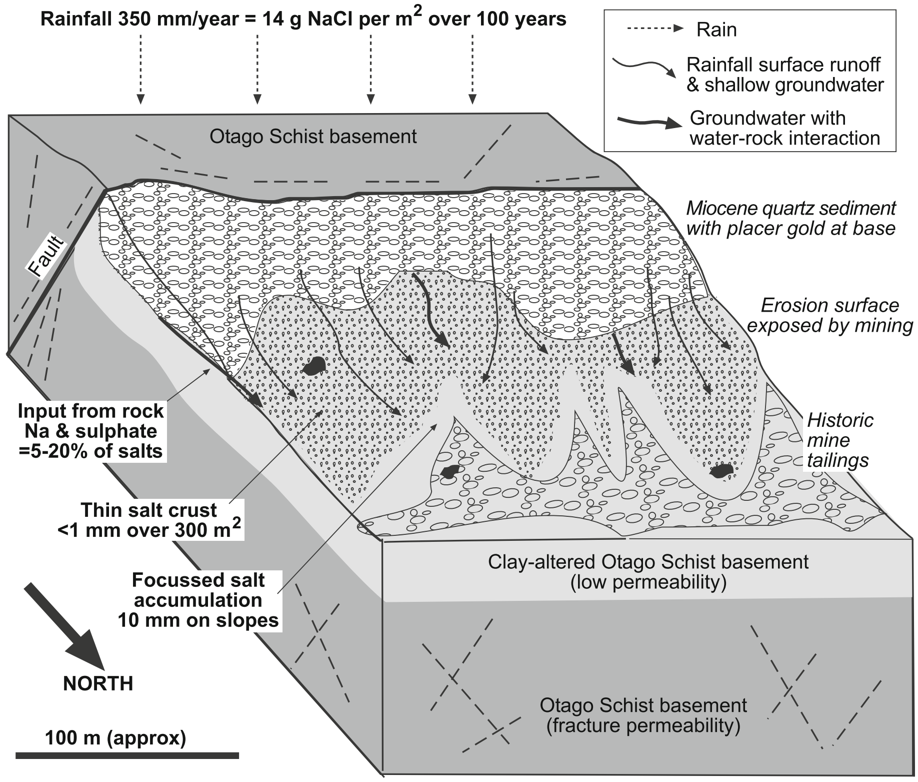


Fig. 1 Schematic block diagram (not strictly to scale) of part of the Chapman Road site, showing the principal physical features, salt budget, and water flow pathways that have led to salination since mining ceased. *Black shapes* are remnant silcrete boulders

species is threatened by habitat loss due to farming and its modern practices (irrigation) as well as due to exotic weed infestation (Allen 2000; Allen and McIntosh 1997; Rogers et al. 2002). The saline sites of Central Otago are considered from the botanical and ecological perspective to be important ecosystems due to their rarity, and the two mine sites have recently been developed and managed as scientific reserves to preserve the saline substrates and their unusual flora.

In this study we define and quantify the physical and chemical controls on evaporation of mine waters and associated salination processes at these two historic mine sites. This includes reconstruction of mine water compositions that are lost due to high evaporation rates. Earlier studies have focused on the ecology, distribution, and abundance of salt-tolerant species while in this paper we relate this information to the geological controls of salination from mine water and natural revegetation at the sites.

Despite the strong modern focus on mine rehabilitation, there is a growing body of scientific evidence that engineered site rehabilitation does not necessarily yield the best long-term environmental outcomes. In this study, we suggest that knowledge and understanding of inter-relationships between geology, climate, and ecology can be used for rehabilitation management of mine sites, to enhance biodiversity and landscape diversity while

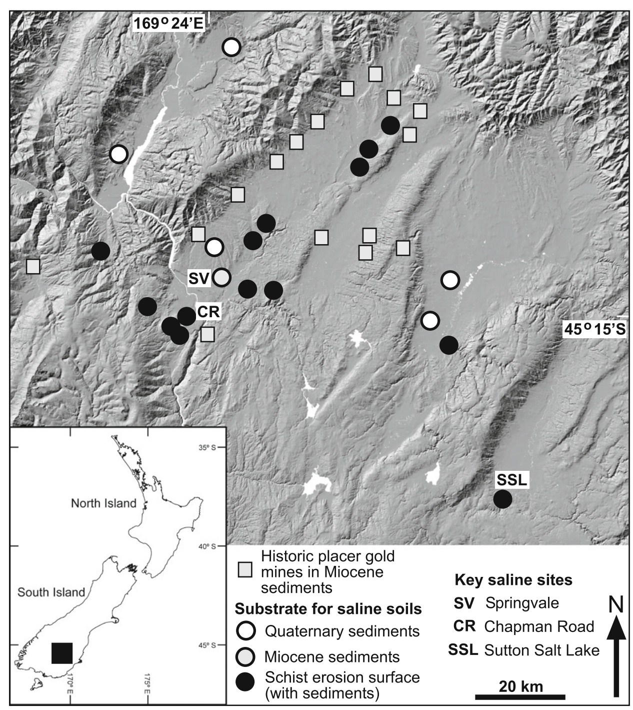


Fig. 2 Hillshade image showing topography of Central Otago in southern New Zealand (see *inset*). Locations of the saline mine sites of this study (Springvale, Chapman Road) and other relict saline sites (after Allen and McIntosh 1997) are indicated, as are some historic placer gold mine sites

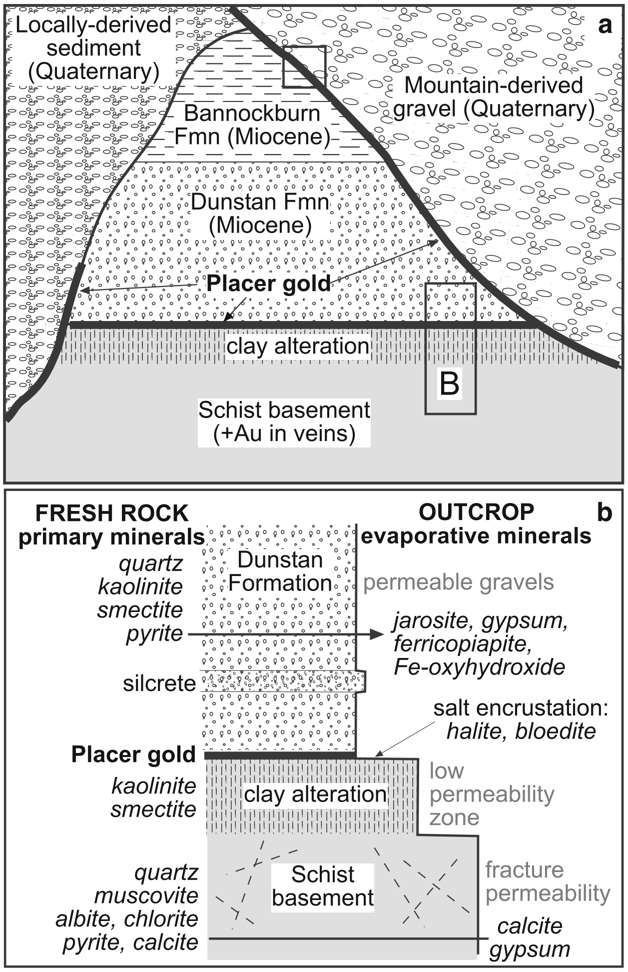


Fig. 3 Schematic depiction of the principal geological units relevant to placer gold accumulation and subsequent salination. **a** Regional stratigraphic relationships. **b** Key features of the base of the Miocene Dunstan Formation resting on schist basement, with principal minerals in rocks (*left*) and in outcrops (*right*)

reducing rehabilitation costs. We do not advocate complete abandonment of mine sites; rather we advocate limited engineering and management targeted at mine water management where necessary, coupled with improving long-term biodiversity rather than short-term site coverage.

General Setting

The Central Otago region, in which the Chapman Road and Springvale sites are situated, is in the rain shadow of the mountains on the western side of the South Island, and consists of broad basins separated by smooth-topped ranges, on a 20 km scale (Fig. 2). Rainfall is typically between 300 and 400 mm/year, mean annual temperature is ≈11 °C, and the region has hot summers (typically 20–30 °C) and cold winters (typically −10 to 5 °C). The area is also subject to frequent warm föhn winds, up to 100 km/h. Hence, evaporation (>700 mm/year) greatly exceeds precipitation (Craw and Beckett 2004; Raeside et al. 1966).

The basement rock is Otago Schist, an extensive Mesozoic (200–100 million years) metamorphic complex that includes gold-bearing quartz veins. The basement is overlain by young terrestrial sediments (Fig. 3) that range from Miocene (20 million years) to late Quaternary (<100,000 years). There are numerous erosional breaks within the sedimentary record, and placer gold, eroded from the underlying basement, has accumulated in fluvial sediments at or near many of these erosional breaks (Fig. 2a, b; Youngson et al. 1998). The most widespread erosional surface occurs beneath the Miocene sediments, on the schist basement, and sediments at and near this surface zone have been extensively mined historically (Fig. 2). The smooth surfaces of the schist mountain ranges (Fig. 2) are weakly dissected remnants of this erosion surface.

The schist immediately beneath the Miocene sediments at this erosion surface has been extensively altered to clay minerals during groundwater percolation from the overlying sediments (Fig. 2b; Craw 1994). The alteration zone is up to 20 m thick, although the most pervasively altered rock is generally only ≈5 m thick immediately below the sedimentary cover. The alteration process resulted in direct replacement of schist minerals and textures by clay minerals, leaving only primary quartz unaffected. Relict muscovite (K–Al mica) and/or albite (Na feldspar) are locally preserved, especially in the less pervasively altered rocks in the transition to fresh rocks >10 m below the sediments. Kaolinite ($Al_2Si_2O_5[OH]_4$) is the dominant clay mineral, with subordinate smectite (Na–Ca–Fe–Mg silicate), a swelling clay that results in formation of desiccation cracks on exposed surfaces.

The Miocene sedimentary sequence consists of basal fluvial sediments (Dunstan Formation) overlain by lacustrine clay-rich mudstones and siltstones of the Bannockburn Formation (Fig. 2a; Douglas 1986). The Dunstan Formation contains gravels made up of quartz pebbles (1–2 cm), and these contain most of the placer gold. The gravels are interlayered with quartz-rich sands and silts, and lignite and associated carbonaceous mudstone. Groundwater passing through the permeable quartz gravels has cemented some layers with quartz to make hard silcrete layers, typically <1 m thick, and some cementation of the sediments by pyrite (FeS_2) has occurred as well (Youngson 1995). Surface oxidation of the pyrite yields several evaporative minerals, including ferricopiapite (Fe sulphate), jarosite (K–Fe sulphate), and gypsum (Ca sulphate) (Fig. 2b; Youngson 1995).

Methods

On-site field observations and aerial photography were used to construct site maps of geology at both sites (Fig. 2). Historic mining activities were interpreted from soil disturbance, excavation morphology, and relict anthropogenic landforms. Sampling, followed by geochemical and mineralogical characterisation, was focused on the Chapman Road site because it has better-developed salt encrustations than Springvale site. Approximately 0.5 kg of variably-saline soil and other substrate materials were collected in clean plastic bags from the depth of 0–15 cm. The sample set included four altered schist samples, of which two were schist substrates supporting salt tolerant vegetation, one quartz sediment, one clay pan sample, three dry soils, and one wetland soil (Table 1).

Mine waters are ephemeral, so mine water compositions were estimated by production and analysis of water leachates from mine substrate samples. The samples were air dried and sieved below 8 mm. Then, 150 g of the substrate material was placed in 2 L containers and 1.5 L of deionised water was added. The mixtures were stirred and left covered for 10 days. The leachates were subsequently drained and collected into plastic bottles.

The leachates were analysed by the Hill Laboratories in Hamilton, an internationally accredited laboratory. The samples were filtered through 0.45 µm membrane filters and their anion/cation profiles were established using ICP-MS, colourimetry, and ion chromatography, following APHA standard methods (APHA 2005). APHA method 3125B was used for the analysis of major cations while methods 4500 Cl^- E and 4110 B were used for chloride and sulphate analyses, respectively. The pH was measured according to APHA method 4500-H^+ B, and electrical conductivity (EC) according to method 2510 B. Total alkalinity was established by titration to pH 4.5 (APHA 2320 B). Bicarbonate content was calculated from pH and alkalinity (APHA 4500-CO_2 D). The detection limit for EC was 0.001 mS/cm and for major ions, it ranged from 0.02 mg/L for Mg and Na, through 0.05 mg/L for Ca and K and 0.5 mg/L for Cl and SO_4, to 1 mg/L for HCO_3.

The mineralogy of nine sample materials was determined using an X-ray diffraction (XRD) method. The analyses were performed by a PANalytical X'Pert PRO X-ray diffractometer in the Department of Geology, University of Otago. Standard sample preparation techniques were used and samples were analysed both in powder disc form as well as on glass slides. In addition to XRD, scanning electron microscope (SEM) images of one salt encrustation sample were also obtained. A JEOL field emission SEM was used at the Department of Anatomy and Structural Biology, University of Otago. The samples were mounted onto sample studs and coated with Au/Pd coating prior to analysis.

The major ion compositions of three leachate samples provided information for the calculation of some idealised mineral contents of the Chapman Road salts. The leachates extracted from three substrate samples were selected (CR12, 14, 16, Table 2), all of which were saline, as indicated by the high EC readings (Table 1). The minerals involved in the theoretical calculations included two salts known to exist at the Chapman Road site, minerals known to occur at other nearby sites, as well as some plausible inferred choices that could, in theory, develop at a site of this nature and setting. A number of assumptions and logical deductions were made to enable the calculations, such as that all K content was due to the presence of sylvite (Table 2). These calculations resulted in molar compositions of major ions, each representative of a particular mineral, and were then converted to per cent compositions. The calculations were made iteratively in order to achieve compositions that would make up ≈100 % of each sample.

Table 1 Representative analyses of leachates from salt substrates at Chapman Road mine site

	CR2 Schist clay	CR3 Schist clay	CR7 Quartz sediment	CR10 Schist substrate	CR12 Soil w/salt crust	CR14 Schist substrate	CR16 Salt clay pan	CR17 Wetland soil	CR18 Mine soil
pH	7.7	7.4	5.6	7	6.8	8	7.7	7	7.5
EC	1.064	0.085	3.05	0.78	15.78	4.04	8.49	0.111	0.994
Ca	23	0.22	56	35	187	15.6	210	3.2	14
Mg	24	0.22	52	9.9	340	129	360	1.73	31
K	1.95	0.23	7.5	30	29	10.4	27	2.2	9
Na	152	17.4	480	91	3,200	640	1,350	14.2	136
HCO_3	41	11.2	3.8	37	36	106	250	7.2	39
Cl	240	14.1	830	87	3,800	990	1,890	18.3	126
SO_4	121	10.2	210	185	3,500	650	2,600	16.2	260

Results are in mg/L, except for electrical conductivity (EC, mS/cm) and pH

Table 2 Idealised mineral contents of salts, calculated iteratively from leachate analyses (Table 1)

Mineral calculation	Mineral formula	CR12 Soil w/salt crust, %	CR14 Schist substrate, %	CR16 Salt clay pan, %
All K as sylvite	KCl	0.5	0.7	0.8
Remaining Cl as **halite**	NaCl	73.8	75.9	62.2
Sufficient thenardite to balance Na and Mg	Na_2SO_4	2.1	0	0
Remaining Na as **bloedite**	$Na_2Mg(SO_4)_2{\cdot}2H_2O$	18.6	0.6	7.3
Remaining Mg as epsomite	$MgSO_4{\cdot}7H_2O$	0.4	14.3	13.9
Excess sulphate as *ferricopiapite*	$Fe_5(SO_4)_6O(OH){\cdot}9H_2O$	0	3.7	10.9
Remaining sulphate as *gypsum*	$CaSO_4$	4.2	0	0
All alkalinity as *calcite*	$CaCO_3$	0.4	4.8	4.9
Ca deficit/excess		−1.4	−3.7	1.3

Minerals in bold have been observed in salts, minerals in italics occur nearby, and other minerals are inferred but plausible

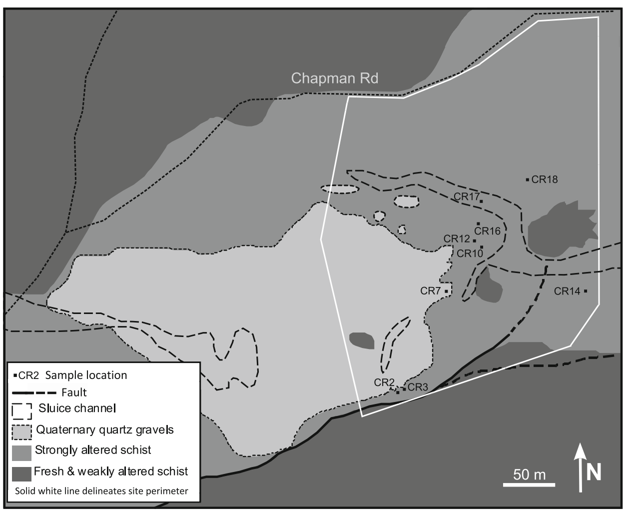


Fig. 4 Geological map of the Gilbert's Gully mine site, with the Chapman Road reserve boundary indicated. Sample sites for this study are shown with *black dots*

Placer Gold Mine Descriptions

Chapman Road

The Chapman Road scientific reserve incorporates part of a placer gold mine called Gilbert's Gully (Fig. 4) that was developed initially in the nineteenth century and may have been reworked in the early twentieth century. Recorded details of the operations are scant, but the mining processes used, and underlying geology, are similar to the many other placer mines of the area (Fig. 2). The site was originally a small remnant of Miocene sediments (Dunstan Formation, Fig. 3) that rested on clay-altered schist basement. Placer gold was concentrated near the base of the Dunstan Formation, in quartz gravels. The quartz gravels were cut by a fault on the southern side of the site, and this fault has uplifted unaltered schist (Fig. 4). Quaternary erosion of unaltered schist, and some of the Dunstan Formation, associated with fault uplift resulted in a thin (<1 m) veneer of locally-derived coarse gravel on top of the Dunstan Formation. There was some placer gold accumulation at this boundary as well (Fig. 3a).

Mining at the site involved sluicing the sediments with strong jets of water, and the resultant slurry flowed through channels in which gold-saving boxes were placed strategically. The tailings from this activity were discharged from the site via drainage channels (Fig. 4). Sluicing mobilised the gold and fine to medium grained sediments (typically up to 5 cm), and left large areas of bare clay-rich altered schist (Fig. 4) with scattered schist and silcrete boulders that were too large to mobilise. When mining ceased, only small remnants of the original sediments remained, and the site was abandoned.

During wet seasons (winter), precipitation and groundwater-derived mine water accumulates temporarily in the central part of the reserve, in one of the historic sluice channels where it forms a wetland (Fig. 4), as well as in ephemeral pools throughout the site. However, surface water is generally absent and most of the site experiences drought-like conditions.

Springvale

The Springvale gold mine was developed in Quaternary river gravels that had been transported into the basin from the adjacent rising mountain ranges. These gravels are dominated by schist basement debris, with tabular clasts up to 20 cm across, and abundant greywacke clasts transported from more distant mountains to the north (Fig. 2). In

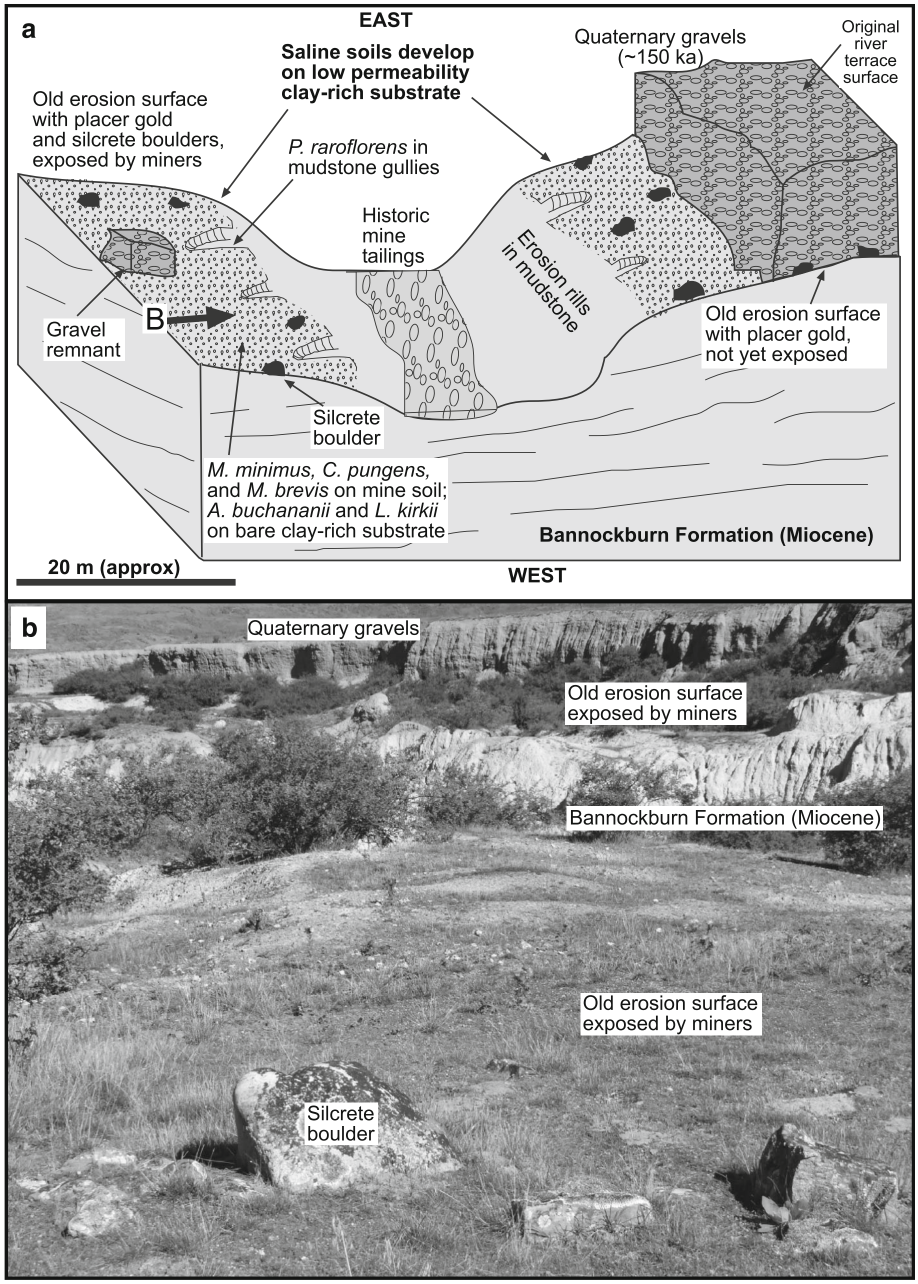


Fig. 5 Principal features related to geology, gold mining, and salination of the Springvale placer gold mine. **a** Sketch block diagram (not strictly to scale) showing the geological structure and the geometry of the impermeable erosion surface exposed by mining. Salt-tolerant plant distributions are also indicated. **b** Photograph (as indicated in '**a**') of the now-saline erosion surface on the Bannockburn Formation mudstone, exposed by mining, with remnants of gravel and silcrete boulders. The Quaternary gravels (*top*) originally covered most of the site

addition, there are abundant quartz pebbles and silcrete boulders derived from erosion of the uplifted Dunstan Formation, and much of the gold was presumably recycled from the Dunstan Formation as well. The gold accumulated primarily near the base of the gravel sequence, where it rested on Bannockburn Formation mudstones (Figs. 3a, 5a).

Mining at this site was focused at and near the erosional base of the Quaternary gravels, where the gold was most abundant (Figs. 3a, 5a). The gravels were sluiced by historic miners in a similar manner to the Chapman Road site, exposing the underlying Bannockburn Formation mudstones (Fig. 5a, b). The exposed erosion surface now has scattered remnants of sluiced Quaternary gravel and some silcrete boulders (Fig. 5a, b). Mine waters run off impermeable clay surfaces, and drain freely through coarse gravel mine tailings. Hence, no surface accumulations develop, other than during rain storms.

Salt Accumulations

Source of Salts

All rain in the southern South Island contains dissolved marine aerosols transported from nearby (<100 km) coasts (Craw and Beckett 2004; Jacobson et al. 2003). The combined NaCl content of rain is typically ≈0.4 mg/L (Jacobson et al. 2003). Exposed clay-rich substrates prevent downward percolation of rain into the underlying rock at both mines, so rainwater either pools temporarily on the impermeable surfaces or runs off the gentle, clay covered slopes into adjacent channels. Hence, incoming rainwater is exposed at the surface to strongly evaporative conditions, and salt is deposited when the rainwater evaporates. The key to the precipitation and accumulation of salts in this process is the surface exposure of large areas of impermeable substrate with gentle relief.

Springvale Salts

The Springvale mine site is dominated by a low relief erosional surface, cut into the clay-rich Bannockburn Formation that has been exposed by mining (Fig. 5b). Sluicing cut rills and gullies into the mudstone, forming localised relief on the 1–3 m scale, exposing more mudstone in channel walls (Fig. 5a). The mudstone is dominated by kaolinite clay, with subordinate smectite. The latter mineral facilitates formation of abundant desiccation cracks in the exposed surface zone. These desiccation cracks are the main sites for deposition of evaporative salts, which coat crack walls and other exposed clay-rich surfaces. Visible salt coatings are typically thin (0.1 mm) and discontinuous, and most are preserved below the exposed surface, in cracks that extend up to 5 cm into the mudstone. There are also bare clay-rich patches in some areas of active water flow in lower, sloping parts of the exposed mudstone walls, and thin (<1 mm) salt deposits also accumulate on these surfaces. A thin veneer of gravel residue from mining is also saline below the exposed surface, especially near the underlying mudstone surface.

Chapman Road Salts

Samples of salt encrustations and salt-impregnated substrates were collected from the Chapman Road site (Fig. 4). These samples all contain some component of silicate rock material as well as salt, and one sample was collected from a wetland located in the middle of the site in one of the historic sluice channels. Saline substrates at the site are all closely associated with the exposed clay-altered schist basement (Fig. 4). This clay-altered schist is almost entirely transformed to kaolinite, with relict quartz fragments up to 5 cm across. No smectite is detectable in this clay by XRD (Druzbicka and Craw 2013), and the strongly-altered surface clays have low Na contents (0–0.3 wt% Na_2O), indicating very low Na-smectite contents. However, abundant desiccation cracks attest to the presence of minor smectite, as at most other such clay occurrences (Craw 1994).

Outcrops of the clay-altered schist are friable at the exposed surface, and have shallow desiccation cracks in the upper 5 cm. This network of cracks hosts thin (<1 mm) salt encrustations, generally below the exposed surface. Clay pans have been formed on flat surfaces and in shallow depressions in the exposed surface by mine-related or subsequent rain-related redeposition of basement clay; these pans are impregnated with salt and commonly have thin encrustations on their exposed surfaces. More permeable surface deposits of remnant gravel and mine tailings (typically 0.1–1 m thick) have salt impregnations at and near their exposed surfaces.

In addition to the dispersed salt described above, there are also localised (1–10 m) accumulations of salt encrustations that can exceed 20 mm in thickness (Fig. 6). These salt accumulations typically occur on steep bare clay slopes (Figs. 4, 6a), and in the lee of remnant blocks of schist and silcrete boulders on sluiced slopes. The salt encrustations are irregular in shape, with crystalline growths and protrusions (10 mm scale), locally overgrowing and partially burying low grass tufts that have become established on the otherwise bare clay surfaces (Fig. 6b). The salt encrustations are dominated by halite with subordinate bloedite (Fig. 7; Table 2). These two minerals are the only ones positively identified by XRD, but others have been inferred from direct observations at this site and elsewhere, and from idealised calculations using leachate analyses (Fig. 3b; Tables 1, 2).

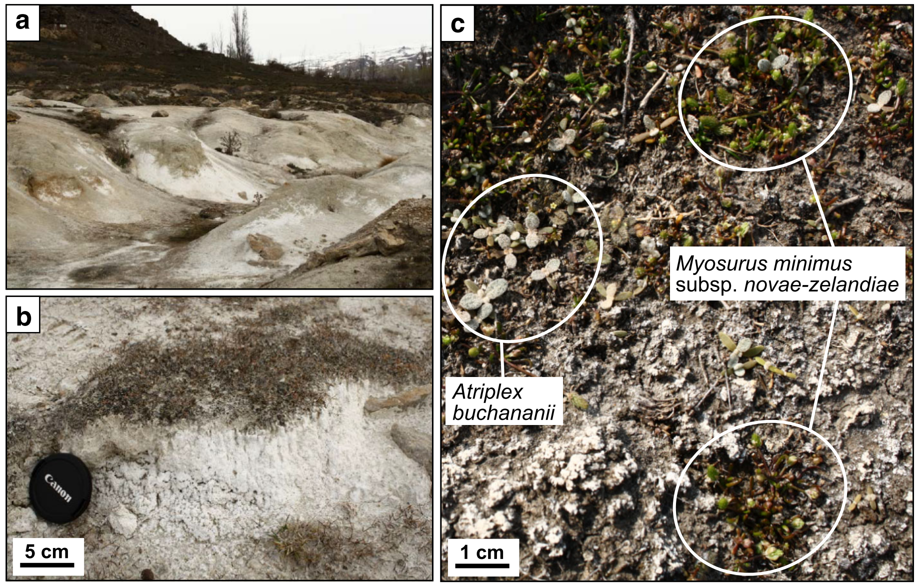
Leachate analyses show that the soluble salts have Na/Cl and Ca/Cl ratios similar to seawater, with minor Na enrichment (Fig. 8a). The leachate compositions are distinctly different from nearby groundwater compositions that have been affected by water–rock interaction and dissolution of albite (Na feldspar) and calcite (Fig. 8a). Sulphate/Cl ratios of leachates imply that most salts are enriched in sulphate compared to seawater, and there is some overlap with groundwater sulphate compositions (Fig. 8b). Likewise, some leachates have minor potassium enrichment relative to seawater, similar to groundwater (Fig. 8b). However, some leachates, from the most salt-rich samples, are depleted in potassium compared to seawater and groundwater (Fig. 8b). This potassium depletion is apparent in the direct comparison to normalised seawater compositions, as are the enrichments in sodium and sulphate, and minor enrichments in calcium and alkalinity (Fig. 8c).

Discussion

Salt Accumulation Budget

Leachate compositions from the Chapman Road site showed close chemical relationships between soluble salt

Fig. 6 Salt encrustations on the clay-altered schist exposed by mining at Chapman Road. **a** Channels in clay-altered schist were eroded by sluicing during mining, and thick salt encrustations (*white*) have built up on bare slopes. **b** Thick and irregular salt encrustations (*white*) have grown over and within exotic grasses (*top centre* and *right*), with some endemic *Puccinella rarofloren*s clusters at *top left* (*arrowed*). **c** *Myosurus minimus* subsp. *novae-zelandiae* and *Atriplex buchananii* growing on mine soil at the Chapman Road reserve



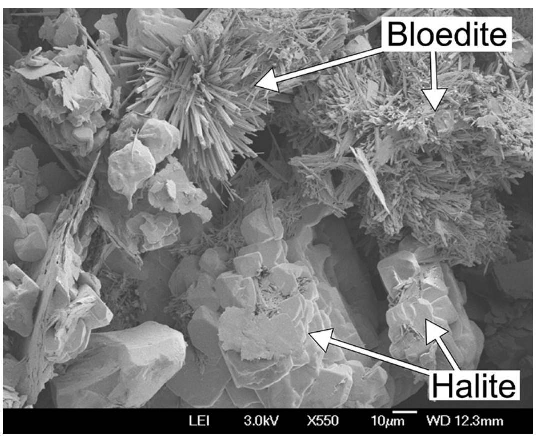


Fig. 7 SEM image of salts present at Chapman Road site

compositions and seawater (Fig. 8a–c). This confirms earlier observations from another Otago saline site, Sutton Salt Lake, which showed rain-transported marine aerosols provide the predominant input for inland salt (Fig. 1; Craw and Beckett 2004). However, we found that there are small but significant deviations from seawater compositions that imply a contribution of components derived from rocks as well (Fig. 8a–c). In particular, relative enrichment in sodium and sulphate have led to formation of the mineral bloedite (Table 2; Fig. 7), which is not present at Sutton Salt Lake (Craw and Beckett 2004). On the contrary, Sutton Salt Lake salt accumulations are relatively depleted in sulphate compared to typical seawater (Craw and Beckett 2004).

Evaporative sulphate minerals derived from pyrite oxidation are common on outcrops of Dunstan Formation quartz gravels (Fig. 2b; Youngson 1995), and their characteristic yellow stains occur sporadically on remnants of Dunstan Formation at Chapman Road. These minerals, and possibly some relict pyrite in the Dunstan Formation and schist basement, are the most likely sources for the additional sulphate in the salt encrustations. Pervasively clay-altered schist has had most Na leached from altered feldspar during clay mineral formation, and the clay-rich rocks typically have <0.5 wt% Na_2O, compared to fresh rocks with >3 wt% Na_2O (Craw 1994). The Chapman Road clays have even lower Na contents (<0.3 wt%, above). Nevertheless, this remnant Na is apparently loosely bound in the clays, so that it has been mobilised by percolating shallow groundwater over the past 100 years. The combination of these rock-derived components has apparently led to significant bloedite deposition (Fig. 7; Table 2). Calcite and gypsum are common evaporative minerals derived from Central Otago rocks by groundwater (Fig. 3b), but their inferred presence in the Chapman Road salt encrustations is minor (Table 2; Fig. 8c).

The total input of marine salt to the Chapman Road site can be estimated from annual rainfall, the inferred time since mining ceased, and the inferred rain salt content (Jacobson et al. 2003), and this estimate is incorporated into Fig. 1. The result, 14 g/m^2, if contributed to a 6 ha area that includes the remnants of the Dunstan Formation and the exposed schist hillside above the site, implies 850 kg of salt addition. This is sufficient to provide a 1 mm salt crust on $\approx$300 m^2 of the apron of exposed clay-altered schist (Fig. 1). Implicit in this calculation is that rain-borne salt has been transported and concentrated by down-slope movement of water gathered from a large area and focused on to the impermeable clay surface exposed by mining,

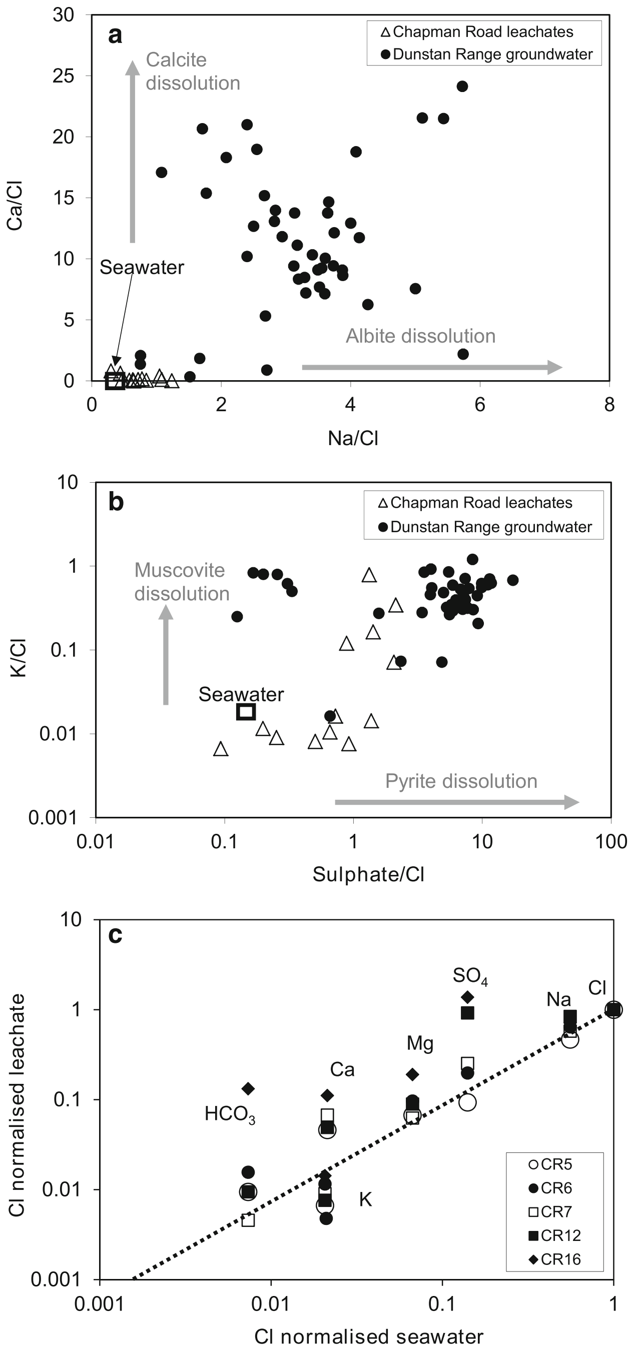


Fig. 8 Comparisons between leachate compositions from Chapman Road salt substrates, seawater composition, and nearby groundwater composition. Data are presented as ratios to chloride contents to allow for variable amounts of dilution or concentration of various waters. **a** Na/Cl versus Ca/Cl ratios. Effects of dissolution of sodium feldspar and calcium carbonate from rocks are indicated with *grey arrows*. **b** Sulphate/Cl versus K/Cl ratios. Effects of dissolution of pyrite and muscovite from rocks are indicated with *grey arrows*. **c** Comparison of the most saline substrate leachates to seawater, for all the major ions normalised to chloride. *Dotted line* indicates 1:1 seawater correlation, and deviations from that *line* indicate additions (*above*) or depletions (*below*) of elements with respect to seawater

where evaporative concentration has occurred. A subordinate component of rock-derived salts has contributed to the salt budget as well (Fig. 1; Table 2). In addition, localised thicker concentrations of salts have developed on steeper slopes, requiring on-going dissolution and re-evaporation down-slope (Fig. 6a, b; Table 1). This latter process may have been responsible for minor depletion of potassium from the thicker salt crusts, as less-soluble potassium salts may lag behind these dissolution/reprecipitation fronts.

Implications for Site Biodiversity

Naturally developed evaporative saline soils and associated salt-tolerant flora used to be present over large areas of Central Otago (>400 km^2) before human settlement in the area (Fig. 2; Allen and McIntosh 1997; Rogers et al. 2000; Walker et al. 2004). Herbs such as *Ceratocephala pungens* and *Myosurus minimus* subsp. *novae-zelandiae,* apparently used to be at least locally abundant (Allen and McIntosh 1997; Rogers et al. 2000; Walker et al. 2004). Agricultural development has substantially depleted the saline soil areas over the past 50 years, and only a few scattered sites remain (Fig. 1; Allen 2000; Allen et al. 1997; Patrick 1989; Rogers et al. 2002). Several of these remaining sites have now been placed in reserves and they include an ephemeral salt lake, Sutton Salt Lake (Fig. 2; Craw and Beckett 2004), and the two historic gold mines that are the topic of this study: Chapman Road and Springvale (Fig. 2).

A direct implication of the development of saline soils at the two historic mine sites is the establishment of rare saline ecosystems that include native salt-tolerant flora. The salt-tolerant flora currently present at the Chapman Road and Springvale sites includes nine low-growing, characteristic species, ranging from non-threatened to nationally critical (Table 3; Fig. 6b, c). The plants are found growing on a variety of substrates, including clay pans, clay-lined floors of mudstone gullies, clay-rich altered bedrock and mine soils. The plants' distribution, including their abundance and affinity for certain substrates, varies between the species at the two sites (Table 3). For example, *Puccinella raroflorens* and *Atriplex buchananii* are relatively widespread at the Chapman Road site (Table 3; Fig. 6b, c), while at Springvale, although still relatively common, they are confined to mudstone exposures and clay-lined floors of the mudstone gullies, respectively (Table 3; Fig. 5a). Other species, such as *Lepidium kirkii* and *Myosotis brevis,* are numerically rare and confined to small, very localised communities at both sites (Table 3; Fig. 5a).

It is an unusual situation for a disused mine site to be recognised as a site worthy of protection due to its

Table 3 List of halophytic and salt-tolerant species present at Chapman Road (CR) and Springvale (SR) sites, including their threat status and typical distribution and habitat information (NZPCN 2012; C. Wilson, J. Barkla, D. Lyttle, pers. comm.)

Species	Threat status	Distribution/habitat	Occurrence	
			CR	SR
Lepidium kirkii	Nationally critical	Endemic to South Island. Found only inland at 12 sites in Central Otago	Rare	Rare
Puccinella raroflorens	Nationally critical	Endemic. South Island (Central Otago salt pans) and Stewart Island	Common	Local
Myosurus minimus subsp. *novae-zelandiae*	Nationally critical	Endemic to NZ. Lowland to upland, commonly in damp depressions	Rare	Common
Ceratocephala pungens	Nationally critical	Endemic. South Island (Mackenzie Basin and Central Otago). Inland, dry open ground	Rare	Common
Myosotis brevis (*Myosotis pygmaea* var. *minutiflora*)	Nationally endangered	Endemic to NZ. Coastal to alpine	Rare	Local
Atriplex buchananii	Naturally uncommon	Endemic to NZ. Coastal and inland	Common	Local
Apium prostratum subsp. *prostratum* var. *filiforme*	Not threatened	Indigenous. Coastal and lowland, saline and freshwater	Local	N/r
Samolus repens	Not threatened	Indigenous. Mainly coastal salt marshes	Rare	N/r
Chenopodium glaucum var. *ambiguum*	Not threatened	Indigenous	Common	N/r

N/r Not recorded

enhanced biodiversity, as is the case for both of the historic gold mines presented here. Documented examples of unreclaimed mining or industrial sites that became valued ecological 'hot spots' are limited. Some examples have been recorded from the UK, Belgium, and the United States, where some of the sites are protected (Sites of Special Scientific Interest, or SSSI, in the UK) on the basis of their botanical significance (Bizoux et al. 2004; Greenwood and Gemmell 1978; Holliday et al. 1979).

The two mine site examples examined in this study show that there are two principal physical requirements for the formation of saline substrates in this climatic setting: an impermeable clay-rich substrate and a gentle slope to allow rainwater to flow over that substrate and concentrate dissolved marine salts. A contribution of shallow groundwater is a useful additional input for dissolved salts. This physical combination of gently sloping clay surfaces is widespread in the region, where it formed naturally during mountain uplift (Fig. 2). These natural surfaces, especially those on the clay-altered schist, were an important component of the original saline soil inventory (Fig. 2). The historic gold mining at the sites in this study created artificially-exposed replicas of the natural clay surfaces.

Hence, the mine sites, when viewed in retrospect, were ideal for enhancement and preservation of the distinctive salt-tolerant flora. Without the mine abandonment, in combination with no engineered rehabilitation, this establishment and preservation of biodiversity would not have occurred. Over time, rare, native species have clearly been able to self-colonise surfaces highly altered by mining processes.

The natural succession of vegetation on unreclaimed mine sites can proceed relatively quickly in some cases. Bradshaw (2000) indicates that colonisation can deliver fully-developed and functional ecosystems within 100 years. However, natural colonisation has been slow at the sites in this study, particularly at the Chapman Road reserve. Factors limiting plant succession are typically edaphic and the usual practice in rehabilitation programmes would be for these physico-chemical problems to be eliminated (Bradshaw 2000; Shu et al. 2005). Here, however, the particular soil and substrate conditions largely exclude exotic weed species and are favoured by certain native and indigenous flora to which the biodiversity enhancement of the sites is attributed today. As a result, in this unusual setting, these specific edaphic conditions are being protected.

Implications for General Mine Site Management

Geologically similar placer gold deposits, with quartzose sediments resting on clay-rich substrates, occur in California and Victoria, Australia, and these were mined extensively by similar methods to those used in Central

Otago, at about the same time (Kelley 1954; Phillips and Hughes 1996). These areas have similar semi-arid climate to Central Otago, and saline substrates could develop, in a similar way to the Central Otago sites, on unrehabilitated clay substrates. However, evaporative salination is more common in those areas than in Central Otago, and is commonly considered undesirable (Rengasamy 2006; Ridley and Pannell 2005). Hence, our Central Otago salt-maximising natural rehabilitation model is unlikely to be applicable in such areas. Nevertheless, suitable and minor engineering of these gold mine sites could facilitate natural rehabilitation of bare ground in a similar manner to coal mines. Sedimentary rock sequences that host coal mines are commonly similar fluvial sediments to those that host placer gold, and therefore coal mine rehabilitation involves similar issues to placer gold mines (e.g. Rufaut and Craw 2010).

When the Chapman Road and Springvale sites were originally abandoned, unstable surfaces probably discharged turbid water during rain storms (Druzbicka and Craw 2013) and dust clouds during the frequent föhn wind events. These environmental effects are undesirable and considered to be unacceptable in the modern regulatory environment. Hence, while long-term environmental effects of site abandonment can be positive, the short-term effects make complete abandonment an unacceptable management option for such sites. However, armed with an understanding of the underlying physical and geological drivers of the positive effects, it is possible to effect a compromise that limits short-term environmental issues but does not preclude long-term biodiversity gains. Engineered surface stabilisation and contouring could limit erosion and therefore minimise both dust and suspended sediment mobilisation (Hancock et al. 2003; Nicolau 2003; Smith and Underwood 2000). Importantly, addition of rock and soil cover should be avoided, to maximise the exposure of the key impermeable surfaces. Likewise, addition of extensive plant cover has to be avoided, to allow natural regeneration of the distinctive and well-adapted local flora and fauna. This avoidance of artificial cover and planting is contrary to widespread mine closure practice (Bradshaw 2000; Mendez and Maier 2008; Tordoff et al. 2000). The additional issue of human abhorrence of the visual aspects of artificial bare sites (Menegaki and Kaliampakos 2006; Sklenička and Kašparová 2008) can be addressed with sight-screens such as engineered berms and perimeter tree planting.

Natural revegetation of bare ground with high endemic biodiversity values, similar to that which has occurred on the Central Otago gold mine sites of this study, could be enhanced by deliberate planting of suitable nursery-grown rare and desirable flora to appropriate substrates. Choice of species for this type of approach requires observations of successes at more-advanced natural rehabilitation at similar sites, as presented in this paper. Prediction of the rates and results of the natural salination and revegetation processes described above, without such direct observations, would have been extremely difficult and risky. Also, transfer of nursery-grown plants into a bare ground setting can have high mortality rates, while natural colonisation by the same species from nearby seed sources can be more effective (Todd et al. 2009). Hence, we advocate minimal site engineering and minimal introduced planting in modern placer gold and coal mine rehabilitation, with that limited engineering and planting being informed by observations of natural rehabilitation successes in nearby abandoned mine sites. We suggest that extensive engineering, covering, and planting of mine sites leads to regionally uniform landscape and biota, whereas rehabilitation of bare ground can lead to locally enhanced biodiversity and preservation of rare species in rare habitats.

Conclusions

The Chapman Road and Springvale sites are two abandoned historic mines situated in a semi-arid climate. The sites are characterised by the cyclical absence of mine waters as a result of high evaporation rates, particularly during the dry summer periods. The development of high salinity is facilitated by mining-induced exposure of impermeable clay-rich substrates, such as clay-altered schist bedrock, and the formation of gentle slopes. These factors allow rainwater to flow, accumulate, and concentrate dissolved marine salts, which at Chapman Road site form a discontinuous layer of salt precipitates up to a few mm think in places. The minerals known to be present include halite and bloedite, but it is probable that others, such as epsomite, ferricopiapite, and gypsum also occur.

As a direct implication of the salts accumulation on impermeable substrates, both sites support rare salt-tolerant flora and they are formally recognised as scientific reserves for their unusual ecological values. The plant species present include *L. kirkii*, *P. raroflorens*, *M. minimus* subsp. *novae-zelandiae*, *C. pungens* and *A. buchananii*. The majority of the species are recognised as nationally endangered or critical in terms of their threat status. It is possible that, apart from having preference for saline soils in some cases, their choice of habitat was also governed by the presence of bare ground and therefore lack of competition from taller species.

Natural succession processes are important in establishing long-term stable and robust ecosystems. The two sites described here demonstrate that natural rehabilitation of disturbed land may give nature a chance to create (or recreate) a unique set of circumstances needed for the establishment of precious ecosystems, which ultimately lead to the enhancement of the region's biodiversity. In these cases, a standard rehabilitation approach in the form of ground recontouring, topsoil placement, and artificial seeding would be damaging to the conservation potential. Here, it is the extreme site conditions that have naturally developed following anthropogenic disturbance that are responsible for the currently-recognised ecological importance of both sites. Observation of such sites gives crucial information that should be considered during post-closure management of modern disturbed sites found in similar settings. This information can guide modern rehabilitation efforts, and hopefully emphasises the important role natural processes should play in them. The limited-interference approach to mine site management is an alternative to typically heavily engineered design methods and one of the significant benefits of such attitude is a reduction of both the cost of rehabilitation and amount of post-mining site disruption. The lessons learned from the two historic mining sites in Central Otago may have implications elsewhere, including the rehabilitation of coal mines found in similar geological settings.

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