Geologic controls on natural halophyte revegetation at Placer Gold Mine, Otago

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Abstract

The Springvale alluvial gold mine was developed in Pleistocene gravels of the Manuherikia valley. The gravels were derived from the slopes of the rising Dunstan Range, and were deposited in channels that were incised into Miocene lacustrine mudstones of the Bannockburn Formation. The Pleistocene gravels include quartz clasts recycled from the Miocene Dunstan Formation, greywacke clasts derived from the Pliocene Maniototo Conglomerate, and clasts of schist basement. Eroded gold from the Dunstan Formation settled with sarsen stones at the base of the Pleistocene channels. Historic miners sluiced the Pleistocene gravels to expose the gold-bearing unconformity, exposing the Miocene mudstone over large areas. Evaporative salts derived from marine aerosols in rain crystallise on the impermeable mudstone surfaces, which is enhanced by the arid climate (~300 mm/year rainfall). Salt accumulations are most prominent on erosional/depositional fans (1-10 m^2 scale) that emanate from erosional rills in the Miocene mudstone. These planar fans in particular have been colonised by a salt-tolerant (halophyte) ecosystem that includes rare and endangered plant species. This halophyte ecosystem has prompted Department of Conservation to create a scientific reserve at the site. The high substrate salinities (conductivity >26 mS) prevent incursion of adventive species that would otherwise out-compete the halophytes, which are typically <2 cm tall. The adventives species instead colonise the gravel-rich mine tailings, and partially encroach on remnants of Pleistocene gravels. The lack of mine rehabilitation at this site has directly facilitated the development of the rare ecosystem. This provides a model for modern mine rehabilitation engineering activity, which should aim to create a diverse set of substrates and landforms rather than a homogeneous product in order to enhance biodiversity.

Keywords: mining, rehabilitation, revegetation, salination, runoff.

Introduction

Active remediation of mine sites, which used to be essentially nonexistent, is now seen as an integral part of the mining process (Rufaut and Craw, 2010). Soil and water contamination from Earth excavation is highly concerning to health, and rehabilitation often involves both mitigation of toxic hazards and heavy manipulation of the landscape to promote revegetation (Tordoff et al., 2000). This frequently finalises in mine sites being flattened and having topsoil added to become farmland, forests, parks, etc. (Tordoff et al., 2000). While this method has had success (Holmes, 2001), allowing revegetation to occur naturally has been more successful in some cases (Pensa et al., 2004).

Natural revegetation is largely influenced by the diversity of the topography and by the underlying geology (Craw et al., 2007), and if the right combination of factors come together then it can be an extraordinarily beneficial and efficient option (Druzbicka et al., 2015). In the context of Springvale Scientific Reserve, this paper analyses how diverse landscapes created by mining activities facilitates natural revegetation, enhancing ecological recuperation of the site but necessitating less remedial effort.

In Central Otago, an inactive and unremediated placer gold mine was recently made into Springvale Scientific Reserve under the Department of Conservation (Fig. 1).

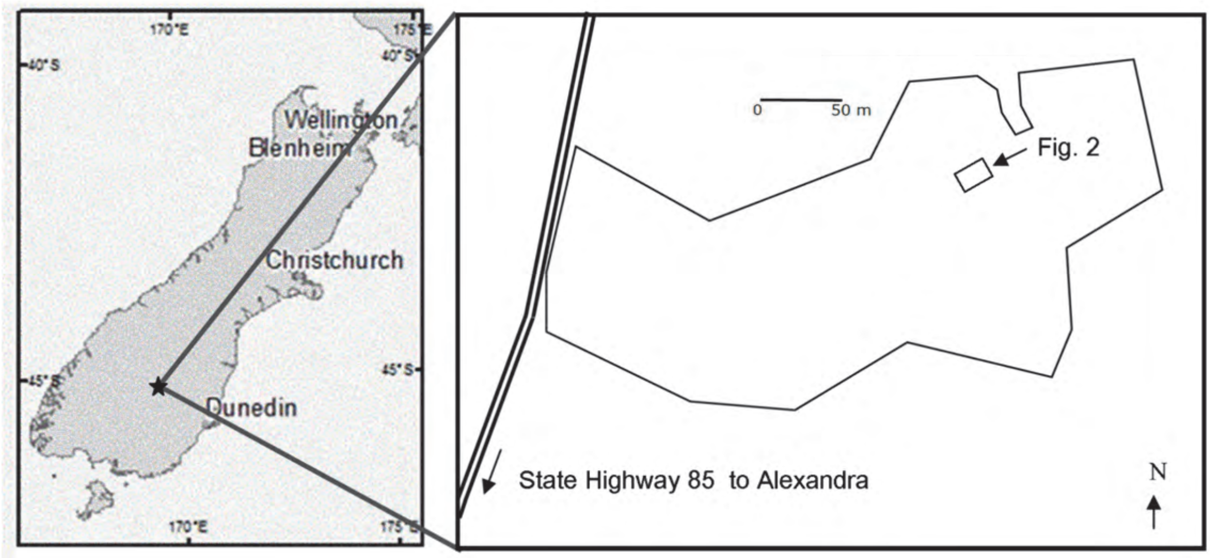

Figure 1. Location map of Springvale Scientific Reserve (irregular black outline) under the Department of Conservation about 9 km north of Alexandra along State Highway 85 in Central Otago, Southern New Zealand. Location of Fig. 2 indicated.

The impetus for the protection of this land is the development of extraordinarily saline soil conditions that allow critically threatened, native salt-tolerant (halophyte) plants to thrive (Druzbicka et al., 2015). Populations of these plants are uncommon because their ecological niche is increasingly transformed to farmland or pasture: only 0.025% of saline habitat remains from the 40,000 ha that was mapped only 50 to 60 years ago (Rodgers et al., 2000).

At Springvale and similar sites like Chapman Road, the geological exposure from unremediated gold mines is the key aspect that enables the development of the disappearing saline environment (Druzbicka et al., 2015). At Springvale, two generations of Pleistocene gravels sit on top of pale Miocene Bannockburn Formation mudstone. Gravels from the Early Pleistocene include deposited clasts and alluvial gold that was eroded from the adjacent Dunstan Range. Both the gold and sarsen stones settled at the angular unconformity that formed between the gravel and mudstone. Nearly identical to the Early Pleistocene gravels are gravels from the Late Pleistocene, which were derived from the earlier gravels and deposited down-slope of them in ancient braided river channels. The two gravels are distinguishable by their bedding and matrixes. The earlier gravel has an orange-tan sandy matrix with strongly graded, horizontal bedding whereas the later gravels have a more tan, finer sand matrix with sloppier bedding that is sometimes graded and still generally horizontal. The majority of both these gravels were sluiced into mine channels to remobilise the alluvial gold and concentrate it at the end of the channels. This left behind large exposures of near impermeable mudstone, trench-like mine channels, and occasional protruding remnants of the gravels, which all contribute to drastic topographic relief within about 20 m of elevation.

Springvale is arid with evaporation rates that exceed the ~300 mm/yr precipitation (Allen and McIntosh, 1997; Druzbicka et al., 2015). All precipitation is saline due to the influence of the oceans surrounding New Zealand, and aerosols are brought to the surface by the limited precipitation (Druzbicka et al., 2015). The rain and the solutes are channelled down the sloped surfaces along rills in the impermeable mudstone, and saline runoff is deposited in near horizontal fans at the base (Druzbicka et al., 2015). The evaporation leaves a residue of salts on the flats, which is very thin (<1 mm) and difficult to see unaided but is essential for the halophytes (Fig. 2).

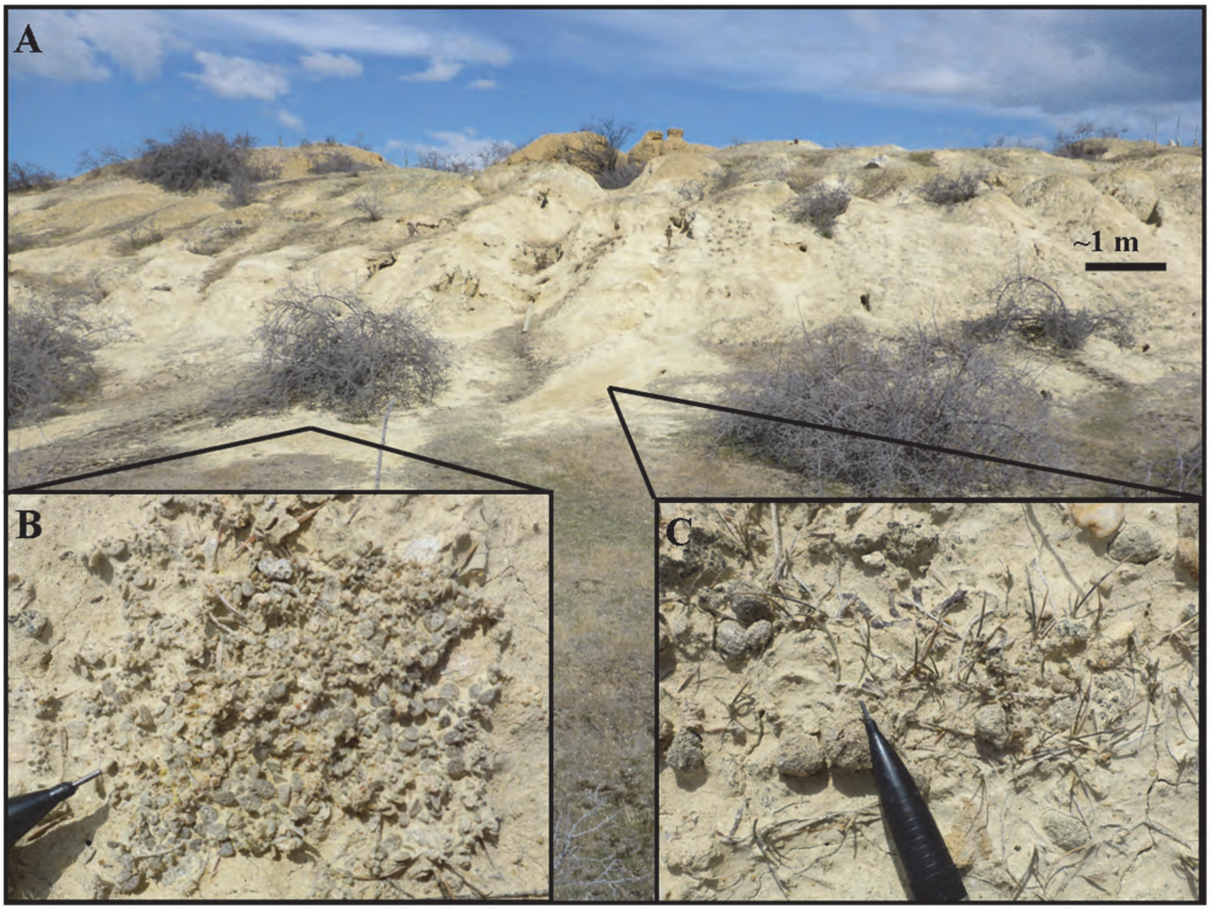

Figure 2. (A) Example of bare, impermeable mudstone exposed at Springvale by historic mining with fans of current runoff along the base of the exposure. Remnants of Early Pleistocene gravels (Orange/tan unit) can be seen along horizon on top of Miocene Bannockburn mudstone. **(B)** Close up of the halophyte *Atriplex buchananii* growing on saline plains created by runoff fans. **(C)** Close up of the halophyte *Puccinellia raroflorens* growing on same saline plains created by runoff fans.

Allen and McIntosh (1997) and Rodgers et al. (2000) published overviews of New Zealand saline ecosystems, which include Springvale. Rodgers identified Springvale as an outlier in terms of exceptionally high conductivity and pH of soils, necessitating further investigation. Druzbicka et al. (2015) did a detailed study of a nearby similar site, Chapman Road, but primarily discussed Springvale in the context of its similar history to Chapman Road. Allen and McIntosh ranked Springvale ninth on a list of important saline sites, making it moderately important, but it was also classified as threatened by intense rains leading to erosion.

However, the data from this study shows quantifiably and in detail that the erosion is actually the reason the salt plains are generated. The study also provides an examination of the conductivity, pH, and salts at this site.

Methods and results

Biogeochemical mapping

Detailed field maps of the geology and vegetation at Springvale were hand drawn on site using observations and aerial photographs over nine days during fall 2015. The vegetation map includes the extent of mudstone runoff, and the geologic map includes the extent of mine tailings. The mine tailings include the layer of pebbles and sarsen stones left at the unconformity when the gravels were washed away and also the protruding remnants of the gravels not sluiced away.

Digital versions of these maps (Figs 3-4) were created in Inkscape, a digital drawing program. It is important to keep in mind that vegetation distribution varies not only annually but also seasonally. Halophyte populations are most abundant and obvious in spring, but this study was done in the fall and so the population estimates might be underestimates.

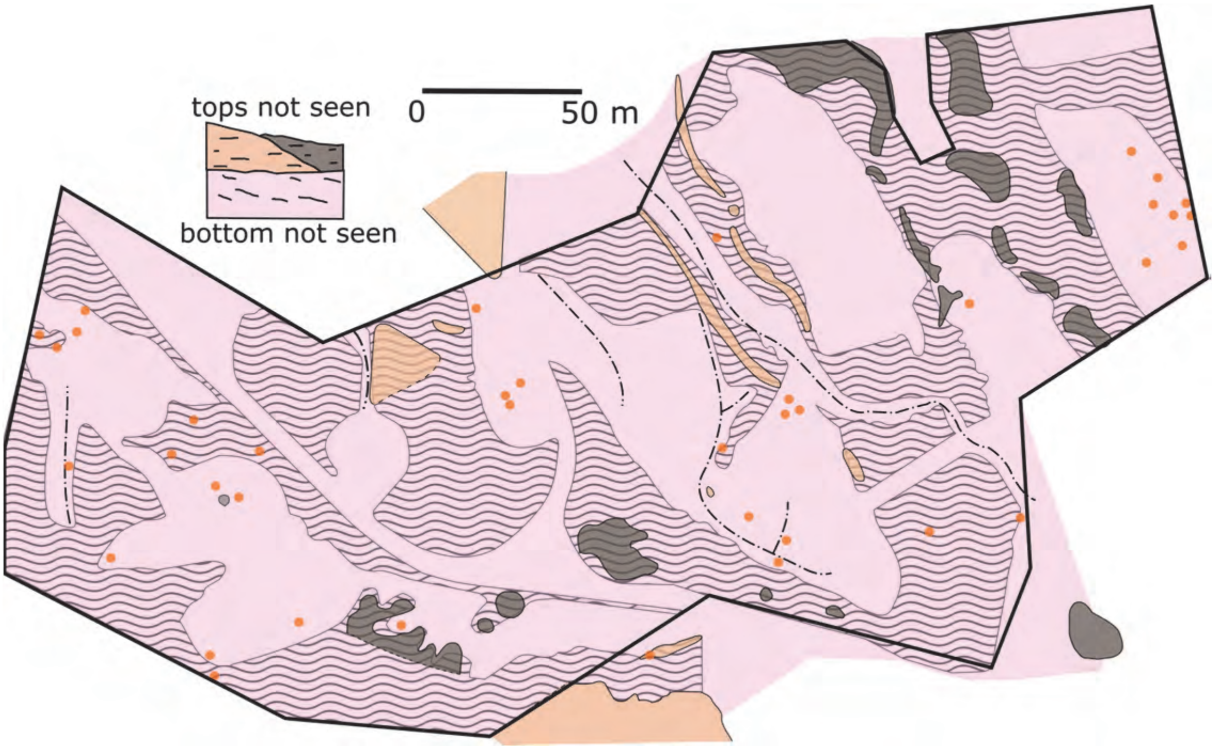

Figure 3. Geologic map of Springvale Scientific Reserve, Central Otago. Orange dots = sarsen stones. Pink = Miocene Bannockburn mudstone. Orange = Early Pleistocene gravels. Brown = Late Pleistocene gravels. Wavy Pattern = mine tailings (gravel layer left on top of underlying geology and unmined gravels). Dot-Dash lines = mine channels. Thick black outline = DoC land boundary.

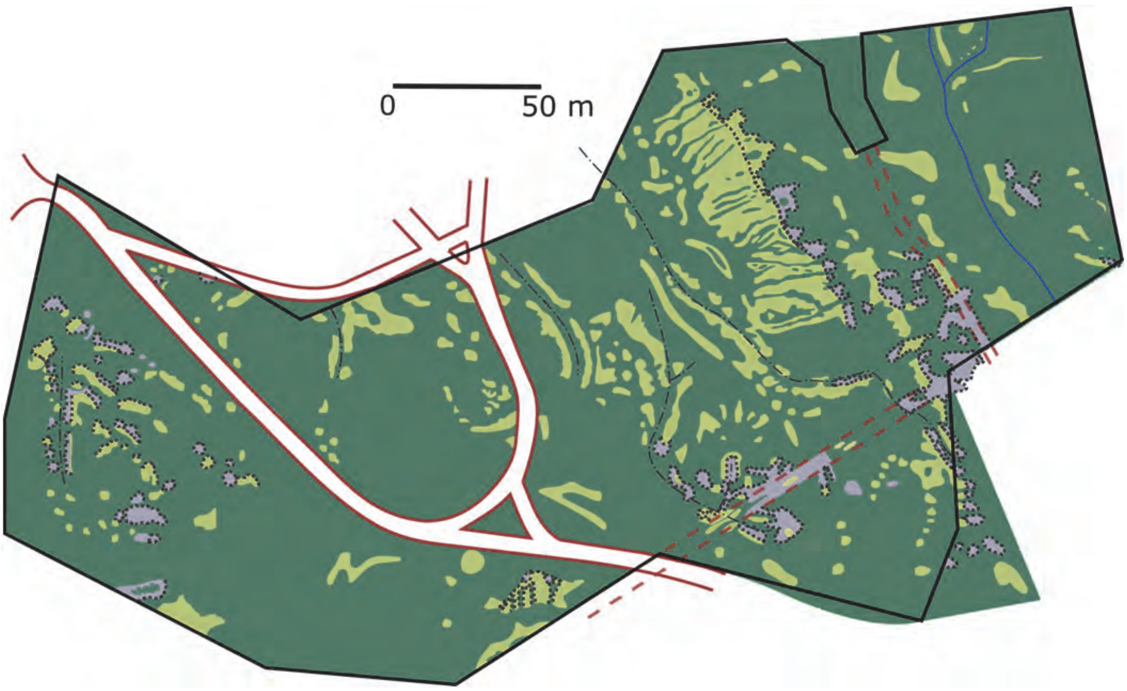

Figure 4. Vegetation map of Springvale Scientific Reserve, Central Otago. Green = heavy weedy vegetation. Yellow = no vegetation. Purple = halophytes. Black dotted lines outline areas of runoff. Dot-Dash lines = mine channels (for reference). Red lines = roads. Dashed red lines = old/not in use roads. Blue = stream. Thick black outline = DoC land boundary.

Additionally, sediment samples were collected at 74 locations across all geologic units and vegetation distinctions. Enough of each sample was collected to later make soil slurries to test for pH and conductivity in a laboratory (Table 1, Fig. 5) using an Oakton Waterproof pH/conductivity/ºC meter.

Table 1. Conductivity (µs) and pH data from soil samples from Springvale.

	Mean	Median	Minimum	Maximum
Conductivity (µs)	2687.50	405.50	8.66	26,800.00
pH	7.52	7.40	6.29	9.59

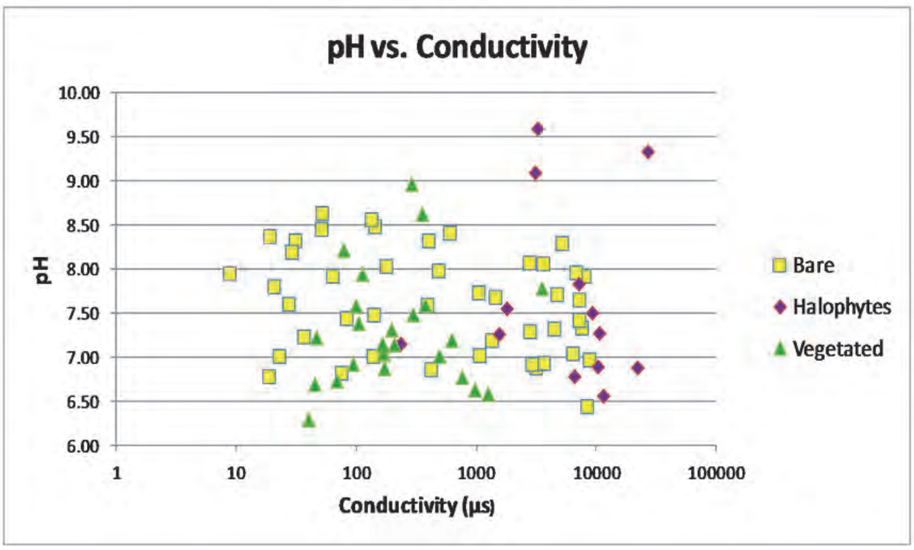

Figure 5. Plot of pH vs. Conductivity (µs) of soil samples from Springvale.

Sample locations were recorded visually on an aerial photograph and also with GPS coordinates, which were later digitally plotted on the aerial photo using arcGIS (Fig. 6). Density of sampling across the site was controlled by the variation in the geology and vegetation – areas with finer scale variation had denser sampling in order to more fully represent the changes in soil chemistry. Locations of high halophyte density as defined by the Department of Conservation were not included due to the importance of the areas.

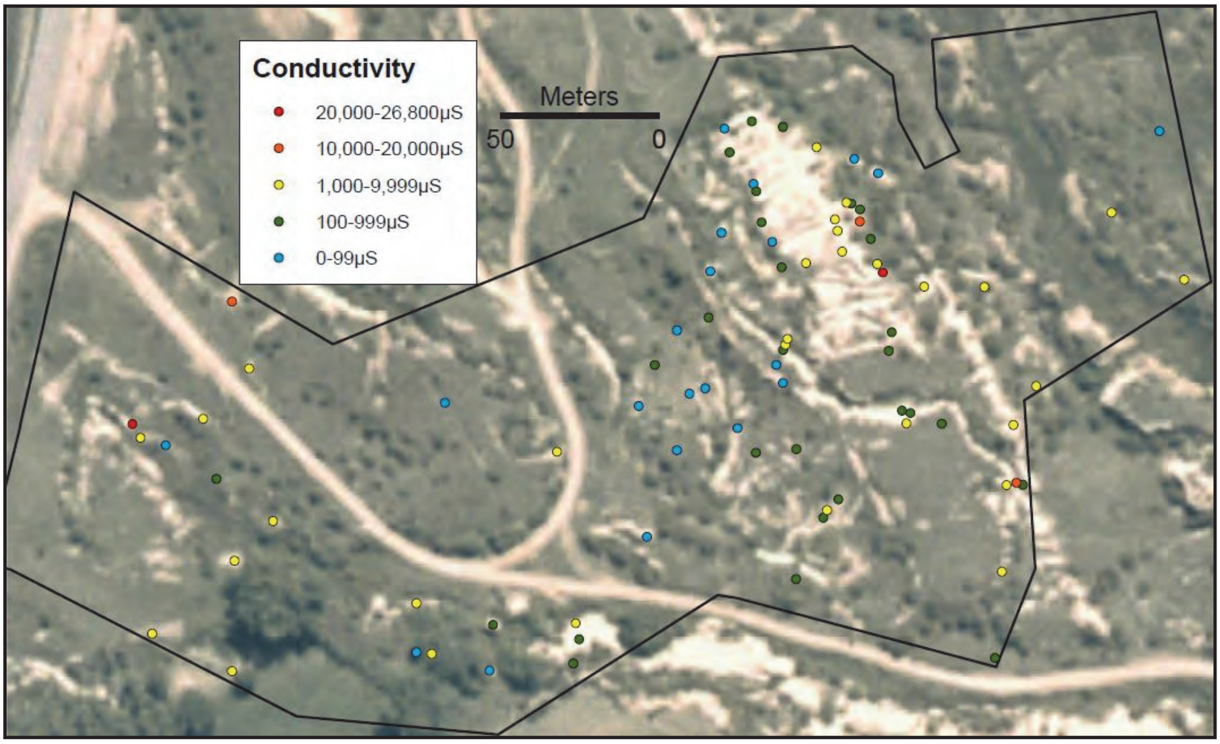

Figure 6. Conductivity map of Springvale Scientific Reserve, Central Otago. Each dot plotted on the aerial photo represents a sediment sample that was tested for conductivity and pH, but only conductivity (μS) is represented here.

Over the nine days of field work, it rained three times during the day and 3-5 times at night. Each day the sun would completely dry out the sediment by sunset, which almost always left the mudstone mud-cracked. Though this causes minor fluctuations in the amount of salts throughout the site, the amount of salts present in different areas of the site retain order of magnitude differences. It is therefore insignificant for this analysis that the samples were collected over a few days time. The samples were analysed within a few weeks of collection.

Analysis of salts

Further chemical analysis was explored using x-ray diffraction (XRD) and scanning electron microscope (SEM) technologies. Standard powdered slide mounts were prepared for 11 samples for XRD analysis in a PANalytical X'Pert PRO X-ray diffractometer. Each sample was run between 3-80 degrees (fixed one degree) for twenty minutes, and the resultant patterns were analysed with X'Pert Data Collector software. There are two samples from each of the following distinctions: mudstone runoff with halophyte population, bare mud-cracked mudstone, younger Pleistocene gravel formation, older Pleistocene gravel formation, and heavily vegetated soil. The eleventh sample is a white mineral picked from a subsurface layer (~2 cm deep) in the mud-cracked Bannockburn mudstone.

A SEM Sigma VP + Oxford EDS coupled with Aztec 24 Oxford Instruments NanoAnalysis software was used to do a detailed comparison between the saline runoff and bare mud-cracked mudstone. Small cohesive blocks of sediment (one from bare mud-cracked mudstone and two from runoff fans) were mounted in cylinders of resin with the surfaces left exposed and unpolished. These were lightly coated with carbon before analysis in the SEM. Chemical mapping was used to analyse the salts and imaging was used to visual the small scale surface texture of the samples (Fig. 7a, b).

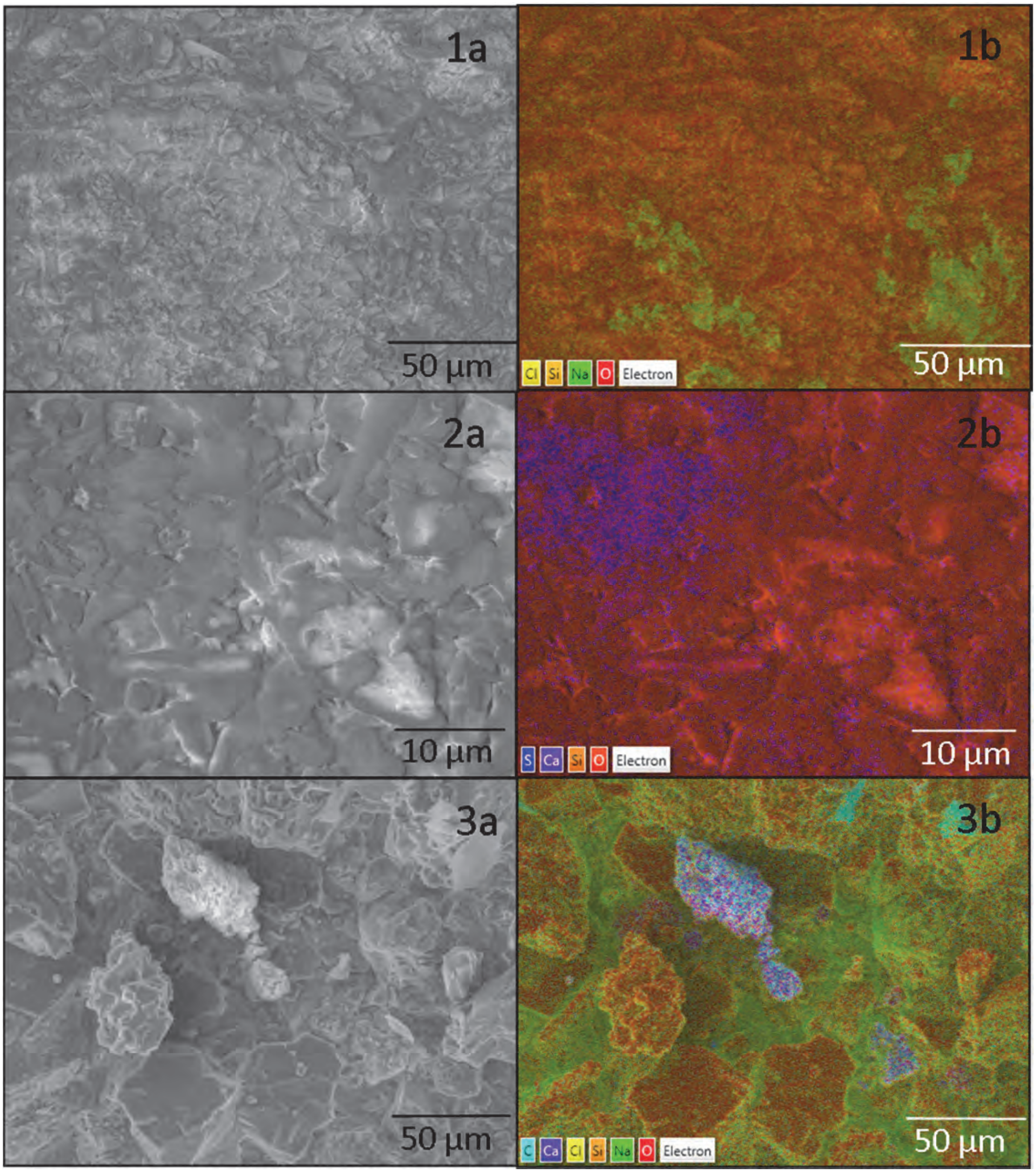

Figure 7a. SEM data. Sample 1 = bare mudstone. Samples 2 and 3 = saline runoff fans. 1a, 2a, and 3a are photographs showing the surface textures of each sample. 1b, 2b, and 3b show chemical maps overlain on the photographs. Red/orange = areas rich in Si and O. Green/yellow = areas rich in Na and Cl. Dark blue/purple = areas rich in Ca and S. Light blue/purple = areas rich in Ca and C.

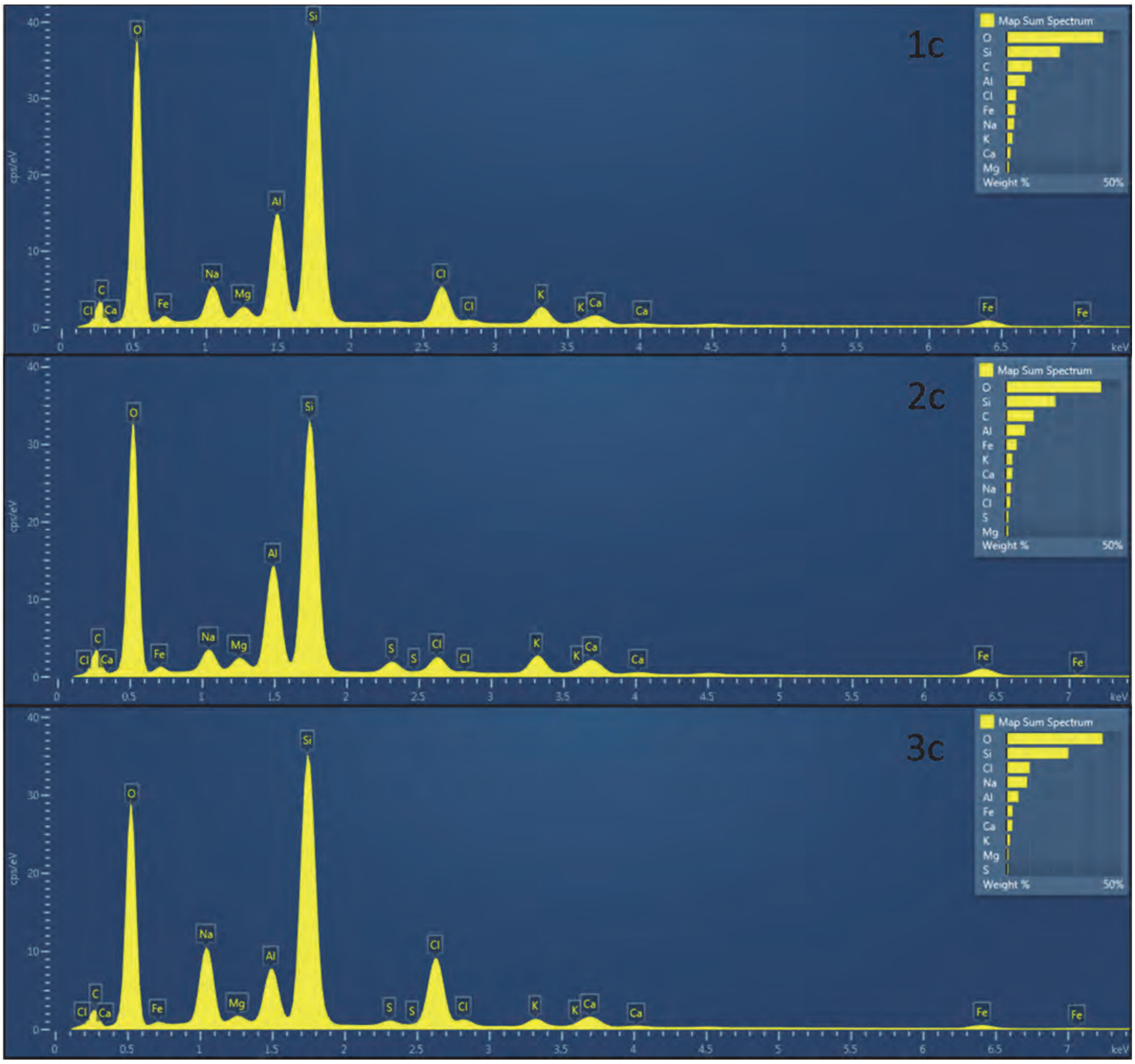

Figure 7b. SEM data. Bulk chemical compositions of samples 1, 2, and 3. Again, sample 1 = bare mudstone and samples 2 and 3 = saline runoff fans.

Discussion

Map correlation

The geologic map (Fig. 3) shows that most of the gravels were completely removed during the mining process, leaving a layer of pebbles (wavy lines) over much of the mudstone at the exposed unconformity. The sections where gravels were left intact are designated by the orange and brown shapes, which extend beyond the edge of the DoC land because the reserve only includes the most saline parts of the old mine. The abundance of *in situ* sarsen stones reinforces the observation that the unconformity is almost entirely exposed.

When this is compared to the vegetation map (Fig. 4), it is clear that the halophytes primarily grow on areas where runoff has settled in planar fans down-slope from exposures of the Bannockburn mudstone. Most intriguing is the conformity of the halophyte populations along the two old, not-in-use roads. The weedy section in the middle of the south-eastern old road lies at the apex of a hill, and the two areas of halophytes within that road are downhill of the apex. This supports that the salts accumulate from runoff travelling down gradients, especially considering that the largest single fan emanates from the eastern end of the old road.

This again displays that anthropogenic landscape manipulation actually creates opportunities for the restoration of the dwindling ecosystem. Also apparent from comparing the two maps is that most of the heavy, weedy vegetation is growing on the layer of pebbly mine tailings (not including the remnant gravel outcrops).

The conductivity map (Fig. 6) shows that the samples with lower conductivity (green and blue) primarily correlate with vegetated areas or spots with intact gravels (Figs 3-4). It also shows that the samples with the highest conductivity (orange and red) correlate with the halophyte populations in the runoff. The bare mudstone tends to have intermediate conductivity (yellow). This is to be expected based on previous accounts (Druzbicka et al., 2015), but quantifies the current situation at Springvale. It also provides current quantitative data of the extremely high conductivity (>26 mS) and basic pH (>9.5) (Table 1) that Rodgers et al. (2000) observed of Springvale sediments. It is interesting to note the seeming randomness of the pH (Fig. 5). There are some particularly basic areas, but no correlation between pH and geology, vegetation, conductivity, or location was observed. This may be a topic worthy of further investigation.

Salts

XRD

The XRD patterns are fundamentally the same for all the samples tested, although naturally there are minor variations and differences in intensities of the peaks. This implies that the bulk compositions of all the sediments of the geologic and vegetated categories are the same but they occur in different proportions in different settings. The differences in the units then become a function of both ancient and current weathering, erosional, and depositional processes.

The main minerals in all of the samples (except the calcite sample) include albite, quartz, and muscovite. The peaks of these minerals dominated the XRD patterns, but if the clay minerals from the samples had been separated out and analysed as their own samples it would have been found that the small peaks at low degrees (<8 degrees) represent clay minerals like kaolinite and smectite (Druzbicka et al., 2015). These are most abundant in the Bannockburn mudstone samples, and the smectite is particularly relevant because it swells with water and contracts with dehydration, creating the mud-cracking characteristic of mudstone at sites like Springvale and Chapman Road (Druzbicka et al., 2015).

The main outlier of the XRD samples is the fine-grained, white mineral that was picked from a subsurface layer (~2 cm deep) underneath bare, mud-cracked mudstone. It was found to be calcite. Such layers occur when rain washes some of the salts down between the cracks in the otherwise impermeable mud-cracked formation and the minerals precipitate out of solution (Rodgers et al., 2000). Such layers are too deep to be of relevant availability to the halophytes (Rodgers et al., 2000), and it seems plausible that these deeper layers would aid in preventing larger competitor plants from establishing in the saline runoff.

SEM

The main salts that are bioaccessible to the halophytes are on the surface of the runoff, and these primarily include halite, gypsum, and calcite.

In Fig. 7a, the green/yellow areas represent halite ($NaCl$), the dark blue/purple areas represent gypsum ($CaSO_4 \bullet 2H_2O$), and the light blue/purple areas represent calcite ($CaCO_3$). The red/orange areas represent minerals rich in silica and oxygen (Fig. 7a), including mostly muscovite, albite, and clays. The bulk chemical composition of each of sample (Fig. 7b) shows the relative proportions of the other elements that constitute these minerals. The oxygen (red) layer does not show up well for the sulphate in gypsum and carbonate in calcite because it is not as prominent as the oxygen in the silicates. The halite was by far the most abundant salt, with gypsum and calcite present but sparse. All three salts were vastly more abundant in samples 2 and 3, which were from the saline fans, than sample 1, which was the bare mud-cracked mudstone (Fig. 7a). The surface texture of the saline fans as shown by 2a and 3a in Fig. 7a also demonstrate more relief than the bare mud-cracked mudstone (1a in Fig. 7a), which is due to the salts forming by evaporative processes. Even so, there is not clear crystal form for the salts, even at the most saline spot found on site (sample 3).

Conclusions

It is clear that a lenient natural rehabilitation strategy is an ideal revegetation method at mine sites like Springvale and Chapman Road. It takes little to no extra remediation effort and actually enhances biodiversity in a way that is needed. The combination of drastic topographic relief, an exposed impermeable geologic unit, and being in the appropriate climate leads to the reestablishment of a rare ecosystem. But, the case is not so simple for most sites. Every mine will have a different context and goal for rehabilitation, and thus will face different obstacles once extraction is completed. While it is important to know that natural rehabilitation methods can happily be relied upon, it is also crucial to assess how appropriate that method is for each mine site and if it needs to be coupled with more active strategies.

Acknowledgements

This research was funded by Ministry for Business, Innovation and Employment, through a mine environment contract to CRL Energy and University of Otago. Department of Conservation kindly provided a sampling permit for the Springvale Scientific Reserve. Able technical assistance was provided by Damian Walls (XRD instruction and analysis), Brent Pooley (SEM sample preparation), and Kat Lilly (SEM images and analyses). Enthusiastic field assistance by Sherri A. Law contributed greatly to the success of the field work.

References

Allen, R.B. and McIntosh, P.D. 1997. Guidelines for conservation of salt pans in Central Otago. Science for Conservation 49, Department of Conservation, Wellington.

Craw, D., Rufaut, C.G., Hammit, S., Clearwater, S.G. and Smith, C.M. 2007. Geological controls on Natural Ecosystem Recovery on Mine Waste in Southern New Zealand. Environmental Geology 51(8): 1389-1400.

Druzbicka, J., Rufaut, C. and Craw, D. 2015. Evaporative Mine Water Controls on Natural Revegetation of Placer Gold Mines, Southern New Zealand. Mine Water and the Environment 1-13.

Holmes, P.M. 2001. Shrubland restoration following woody invasion and mining: effects of topsoil depth, seed source, and fertilizer addition. Restoration Ecology 9: 71–84.

Pensa, M., Sellin, A., Luud, A. and Valgma, I. 2004. An analysis of vegetation restoration on opencast soil shale mines in Estonia. Restoration Ecology 12: 200–206.

Rogers, G.M., Hewitt, A. and Wilson, J.B. 2000. Ecosystem-based conservation strategy for Central Otago's saline patches. Science for Conservation 166, Department of Conservation, Wellington.

Rufaut, C.G. and Craw, D. 2010. Geoecology of ecosystem recovery at an inactive coal mine site, New Zealand. Environmental Earth Science 60(7): 1425–1437.

Tordoff, G., Baker, A. and Willis, A. 2000. Current approaches to the revegetation and reclamation of metalliferous mine wastes. Chemosphere 41(1): 219–228.