PART

EXPLORATION METHODS

10

SURFICIAL GEOCHEMICAL EXPLORATION METHODS

10.1

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ABSTRACT

Surficial geology, till geochemistry, and heavy mineral studies are practical exploration tools in glaciated terrains. Geochemical methods have been widely applied for mineral potential mapping and exploration in Finland and in the Northern Hemisphere for more than 50 years. Till is an effective sampling media in mineral exploration because its composition reflects the nature and composition of fresh bedrock, preglacial weathered bedrock, and older sediments of the up-ice region. From clay-sized particles to boulders, debris in till derived from a mineralized zone have been dispersed some distance from the source(s) in the direction of ice flow, resulting in dispersal trains that are generally larger than the source area exposed to glacial erosion. Several studies have demonstrated that detrital dispersal differs among glacial geomorphological areas. Subglacial processes of active, moving ice differ from passive, ablating ice, resulting in different distance of glacial transport. Furthermore, a number of case studies indicate that the distance of glacial transport varies among glaciomorphological terrains such as transverse ribbed moraines and streamlined moraines, associated to active ice conditions. Till deposits in the ice-divide zone have their own characteristics. Mineral potential studies in Finland have proven that till geochemistry supported by heavy mineral research and new, low-impact sampling methods provide effective ways to do mineral exploration.

Keywords: geochemistry; till; glacial deposits; moraine; weathered bedrock; exploration.

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INTRODUCTION

Geochemistry can be broadly defined as the science concerned with all geological studies involving chemical change (Clarke, 1924). It includes the study of the distribution of elements in minerals, rocks, and soils along with the interaction between these earth materials. In this chapter, geochemical exploration methods refer to the use of chemical properties of naturally occurring substances (including rocks, glacial debris, soils, stream sediments, waters, vegetation, and air) to find economic deposits of metals, minerals, and hydrocarbons.[1] Geochemical exploration methods are mainly based on observations of anomalous concentrations of major or trace elements that are derived from a core part of a mineral deposit itself or a wider halo surrounding the ore body (Rankama and Sahama, 1950; Horsnail, 2001). These halos or zones are useful in detecting or tracing mineral deposits, as they are typically many times larger than the ore deposit itself, and therefore represent a larger mineral exploration target. Halos can be classified as primary or secondary. A primary halo is a zone surrounding the mineralization core and represents the distribution patterns of elements in the bedrock formed during the original ore-forming processes. Primary dispersion halos vary greatly in size and shape as a result of the numerous physical and chemical variables that affect fluid movements in rocks. Secondary dispersion halos form, instead, more widespread anomaly patterns of elements surrounding the mineralization core. Elevated elemental concentrations are the products of erosion or weathering of the mineralization core and primary halo, and are transported by agents such as gravity, groundwater, streams, and glaciers. A common secondary halo in glaciogenic sediments is known as a *dispersal train*, of which shape and extent depend on the main transportation mechanisms involved (Kauranne et al., 1992).

A geochemical survey is based on the sampling of available earth materials in a given survey area. Depending on the size of the area and the sampling density, survey types can be roughly divided into continental, regional, targeting, and local scale. The design of a geochemical survey depends on its purpose: (1) characterizing regional elemental and mineralogical concentrations over a large area, (2) delineating geochemical or mineralogical anomalies related to a potential mineralized zone, or (3) focusing mineral exploration within a known mineralized zone (McMartin and McClenaghan, 2001; McClenaghan et al., 2013). The stage of mineral exploration and costs are usually the dominating factors in decision making for the methods and scales of a geochemical survey. What also must be included in the cost factor is that geochemical techniques cannot be used to pinpoint a mineralization on their own, and generally need to be integrated with geological and geophysical surveys (e.g., Plouffe et al., 2011).

Finland is located in the area of the central part of the last Scandinavian ice sheet of the Weichselian ice age (Fig. 10.1.1). This area has been glaciated several times during cold stages of the Quaternary period (e.g., Svendsen et al., 2004; Johansson et al., 2011). The glaciogenic morphology of Finland varies from subglacial to ice-marginal depositional environments and from an active, warm-based ice-lobe network in the south to cold-based, more passive ice in the ice-divide zone in the north (Johansson et al., 2011). Glacial deposits are related to several glacial phases with separate till sheets, each associated with glacial striations and till fabrics with varying orientations (Hirvas, 1991; Sarala, 2005a). Due to the glaciogenic nature of surficial sediments and their extensive cover (97% of Finland's land area) (Johansson and Kujansuu, 2005), surficial geological, and geochemical methods are essential mineral exploration tools. Till is the most common sediment type and because

[1] http://staging.ecomii.com/science/encyclopedia/geochemical-prospecting

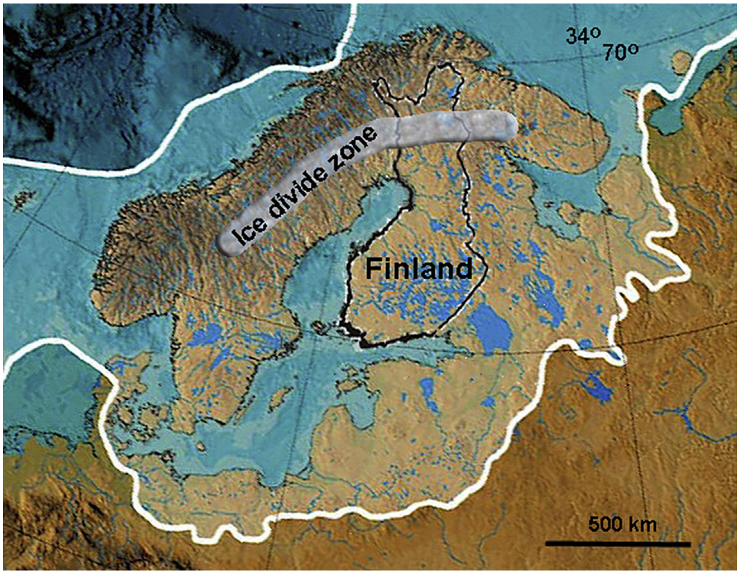

FIGURE 10.1.1 Location of Finland in northern Europe.

The white outline shows the extent of ice at the Last Glacial Maximum (LGM).

its composition reflects the nature and composition of bedrock in the up-ice region, it forms a near-perfect sampling medium for mineral exploration in glaciated terrains.

GEOCHEMICAL EXPLORATION

Geochemical surveys follow the same strategy as other mineral exploration methods: sampling density correlates with the stage of exploration. The primary objective of sparse sampling densities is to identify districts of enhanced mineral potential within which targeted exploration can be conducted. With increasing sampling density, potential mineralized zones or structures in bedrock can be identified. In this context, geochemical methods can rely on the sampling of two mediums: bedrock (lithogeochemistry) and surficial sediments (surficial geochemistry).

LITHOGEOCHEMISTRY

Lithogeochemistry is a geochemical method that involves the sampling of bedrock. It can be considered for the recognition and definition of mineralized and anomalous areas, and to distinguish dispersion halos at different mapping scales (Hawkes, 1957). In a broad sense, lithogeochemistry covers the research of igneous, sedimentary, and metamorphic petrology; hydrothermal alteration; weathering; and diagenesis. Also, it has a close connection to the mining-related fields of applied geochemistry (including exploration and environmental research and monitoring), genesis of mineral deposits, metallurgy, and deep hydrogeochemistry.

Lithogeochemical surveys can be carried out on a grid or on traverses of an area, with samples taken of all available rock outcrops or at some specific interval. After lithological mapping, one or several rock types may be selected for sampling and analyzed for various elements. Using symbols and/or contours, results are compiled in geochemical maps to allow interpretation. Under favorable conditions, mineralized zones or belts may be outlined in which more detailed work can be concentrated. In the case of large territories, geochemical provinces may be outlined.

Isotopic analyses can help build stratigraphical and geochronological models. Applicable isotopic systems include stable isotopes such as $^{16}O/^{18}O$, $^{12}C/^{13}C$, $^{32}S/^{34}S$, and common Pb and radiogenic isotopes such as samarium-neodymium and rhenium-osmium (Faure and Mensing, 2004). For example, the isotopic composition of sulfur can help identify the origin of hydrothermal fluids and the conditions within the depositional environment. Isotopic ratios are also used for age determination of rock types (geochronology) relying on radiogenic isotopes (e.g., U series, U-Pb, K-Ar, Sm-Nd) (Allègre, 2008). Although isotopic geochemistry is an important part of the geochemical research, it is beyond the scope of this chapter and not handled in detail here.

WEATHERED BEDROCK GEOCHEMISTRY

In Finland, and particularly in northern Finland, weathered bedrock has been preserved beneath glacial deposits and needs to be considered in mineral exploration because it can contain elemental enrichment unrelated to mineralization (Hirvas, 1991; Nenonen, 1995). In the ice divide zone of central Lapland, the remnants of weathered regolith up to tens of meters thick are frequently found. The thickest weathering profiles are in topographic depressions under till cover. Typically, only the saprock has been preserved, but in places, also the lower saprolite and parts of the upper saprolite are present. The saprock horizons are strongly fractured and, therefore, are zones of preferential groundwater movement with enrichment of secondary iron minerals such as goethite and some clay minerals. Elements such as Fe, Cu, Ni, Co, Zn, and Mo may have been enriched in the fine fraction of the goethitic weathering crust and their concentrations can be many times higher than in the underlying fresh bedrock (Peuraniemi, 1990a). Several other elements such as Ca, Na, Mg, Au, Br, S, and U are easily mobilized during weathering and can be enriched at the top or bottom of the weathering profile. Consequently, large amounts of secondary enriched weathered material might have been eroded by glaciers causing false geochemical anomalies in till with no relation to mineralization (Peuraniemi, 1982; Sarala and Ojala, 2008).

SURFICIAL GEOCHEMISTRY

Surficial methods are traditionally used in exploration wherever different kinds of soils and unconsolidated sediments cover the bedrock. Surficial geology, and, more specifically, drift prospecting, has been used as a practical exploration tool in glaciated areas (e.g., in North America, Europe, and Russia) since the beginning of the twentieth century (Sauramo, 1924); surficial geochemical methods have been in use since the 1950s (Kauranne, 1958; Wennervirta, 1968; Shilts, 1972; Kujansuu, 1976). Soil, stream sediments, and glacial till surveys have been used effectively in geochemical prospecting and have resulted in the discovery of a number of ore bodies. A benefit of surficial methods is the relative ease and speed of sampling and the possibility of using different sampling strategies, from regular grids to variable sampling lines and scattered models. The principal objective of a surficial geochemical survey is to detect the secondary halo associated with a mineralized zone. In addition to the traditional sampling of fresh mineral soil (C-horizon of soil profile), surficial methods include the sampling of:

- Humus, plants, and peat (i.e., biogeochemistry)
- Weathering profile (i.e., pedogeochemistry)
- Top soil together with selective and weak leach methods
- Groundwater
- Snow

Surficial geochemistry has environmental applications including the field of urban geology (e.g., study of airborne fallout).

Boulder tracing (e.g., Shilts, 1984; Salminen and Hartikainen, 1985; Salonen, 1986) and heavy mineral (i.e., indicator mineral) research (Peuraniemi, 1990c; McClenaghan, 2005) are included in the broad theme of surficial mineral exploration methods. Furthermore, geochemistry applied to hydrocarbon exploration (for coal, gas, and oil deposits) is part of surficial exploration methods (Jahn et al., 2008), but all of these topics are beyond the scope of this section.

In surficial geochemistry, the knowledge of the entire process of erosion, transportation, and sedimentation (or deposition) is a key factor in understanding the geochemical signature in different sedimentary deposits. Secondary dispersion is directly dependent on surficial processes, and, therefore, the methods of sampling, analysis, and interpretation have to take into account the sedimentary environment. For example, fluvial or lacustrine sediments usually represent much larger source areas (i.e., river basins) than glacial till and this fact should be taken into account in geochemical data interpretation. Furthermore, stratigraphical control of samples needs to be considered during sampling and data interpretation. This is particularly important in complex stratigraphic settings with multiple units being sampled. For example, in the case of complex till stratigraphy, sampling at different depths provides necessary information to recognize source areas of different till units (Hirvas and Nenonen, 1990). Till thickness and depth of sampling within a single till unit represents another variable to consider. In the case of till thickness, the general phenomenon is that on high land areas, till cover is thinner than in the valleys or depressions. In thick sequences, a sample from the bottom of a section or from the lowermost till unit will reflect a more proximal bedrock source than a sample collected from the top (Kauranne et al., 1992).

Today, there is an ever-increasing demand to use low-impact exploration methods to decrease the environmental footprint of mineral exploration activities. With this emphasis in mind, the use of humus, peat, and living plants have become more popular methods in conjunction with top soil sampling; that is, the uppermost layers (10–50 cm) of the mineral soil (e.g., Kokkola, 1977; Nuutilainen and Peuraniemi, 1977; Hamilton, 2007). Biogeochemical surveys can be divided into two types (Dunn, 2007). One type uses the trace-element content of plants to follow up secondary dispersion halos of mineralization, similar to the soil geochemical method. The second type is to use specific plants that are sensitive to certain elements in soils and can indicate potential ore mineralization. The latter type is referred to as a "geobotanical survey" and can also be considered one type of surficial geochemical methods.

GLACIOLOGICAL CONTEXT

Prior to implementing a surficial geochemical survey (e.g., soil or till), it is essential to study and understand the Quaternary geological landforms in the target area and the processes by which they formed; that is, the glaciological context of the study area. This can be done by interpreting glacial morphology visible on aerial photographs, satellite imagery, or a digital elevation model (DEM), which in turn allows determination of direction of glacial transport and estimated distance of transport (Salonen, 1988; Aario and Peuraniemi, 1992; Sarala, 2005a).

Morphological interpretation is supported by field work that includes research on the characteristics of different moraines and other glacial landforms and includes geographical distribution of landforms, relation to other landforms, sediment type, internal structure, and till stratigraphy (Hirvas and Nenonen 1990; Aario and Peuraniemi, 1992). Test pit excavations, observations on natural or human-made sections, or drilling-based sampling are part of the field methods for landform research. Till geochemical and heavy mineral sampling are essential in mineral exploration and should be complemented by grain size determinations and pebble count data. Till-fabric analyses and measurements of glacial striations are necessary for the determination of ice-flow direction. Furthermore, till-fabric analyses together with stratigraphic observations can provide useful information as to the subglacial depositional environments and processes (Sarala, 2005b).

In a new study area, a relatively simple field method of excavating test pits can provide valuable information on till stratigraphy and the sediment thickness (Sarala, 2005a). This knowledge is useful later when planning geochemical sampling strategies or conducting other mineral exploration activities such as diamond drilling or mineralized boulder tracing.

TILL GEOCHEMISTRY

Various geochemical analytical methods are available for the analyses of till. The choice of a method will be dictated by the scale and objective of the geochemical survey (e.g., Shilts, 1984; Hirvas and Nenonen, 1990; Kauranne et al., 1992; McMartin and Campbell, 2009; Paulen, 2009). Regular sampling grids are used in regional and local-scale surveys, when the main goal is to map the variation of the elements in the study area. Percussion drilling with a flow-through bit or other low-impact methods (e.g., handmade test pits or hand drilling) are commonly used for till sampling (Fig. 10.1.2A). Linear "fences" are used in regional till sampling when variations have to be minimized, or when the bedrock structure and ice-flow direction are well-known. Test pits and test trenches are effective in detailed studies, when the source (or sources) of anomalies needs to be identified. Vertical variation of the elements can be studied by taking samples at regular intervals from different depth levels. By using test trenches, both horizontal and vertical elemental composition variability in till can be determined using sampling profiles at regular intervals. In the case of thick glacial overburden, soil sampling with different drilling techniques or percussion drilling are the most effective, and many times the only way to take till samples.

The normal procedures for the processing of till samples for geochemical analysis involves drying (room temperature, 40 °C and 90 °C), dry sieving, and leaching. For chemical analysis, the size fraction of <0.063 mm is commonly utilized worldwide because it represents the most homogenous part of the till matrix and includes both local and distal portions of glacially eroded, transported, and deposited materials. Coarser size or high density fractions can be analyzed if the objective is to identify locally derived components of the till.

SELECTIVE AND WEAK-LEACH GEOCHEMICAL METHODS

Selective and weak-leach analytical methods were important developments that occurred in 2000. The best known of these is probably the patented Mobile Metal Ion (MMI™) method, where upper soil

FIGURE 10.1.2 Different till sampling and analysis techniques used in mineral exploration.

(A) Percussion drilling with a flow-through bit in till geochemical sampling; note the vehicle and trailer mounted on wide tracks to reduce impact on vegetation; (B) low environmental impact soil sampling for weak leach geochemistry; note that the moss matt is replaced after sampling, leaving the ground surface undisturbed, (C) portable XRF (pXRF) analyzer for onsite till geochemical analyzes in a dug exposure, (D) heavy mineral separation using a spiral concentrator.

Source: *Photos (A), (B), and (C) by Pertti Sarala; photo (D) by Reijo Lampela.*

samples are leached with very weak acidic solutions to strip only the loosely adsorbed ions from the surface of mineral grains or organic material before analysis by ICP-MS. The method has been studied extensively, especially in North America and Australia, where it has achieved good results in areas of very thick glacial overburden or deeply weathered soils. Some testing has also been done in Finland by exploration companies and GTK (e.g., Sarala et al., 2008). The mobilization, movement, and enrichment of the ions are the sum of many factors including capillary action, diffusion, difference of electrochemical charge, and effect of gases (Smee, 1983; Cameron et al., 2004; Hamilton et al., 2004), as well as biogeochemical processes (Tack, 2010).

The MMI method has advantages including: (1) easy sampling, because the samples are taken from the near-surface top soil (Fig. 10.1.2B), (2) the sample material may be any mixture of mineral-derived soil to purely organic material, (3) it gives a direct indication of the bedrock type through the soil, (4) interpretation of results can be viewed as relative concentrations (to avoid disturbance caused by, for example, seasonal variations or local weather changes), and (5) sample processing and analysis are inexpensive compared to traditional till geochemical methods. Usability of the method has substantially increased due to analytical method development that allows ppt or even ppq detection limits for many elements. Nowadays there are a number of alternative analysis methods besides MMI, using the same theoretical background of ion mobilization from the bedrock through the soil, which broaden the range of elements and ore types that can be explored. Such methods include, for example, various weak acid extraction methods, bio- and enzyme leach, and the soil-gas-hydrogen method. These methods are being tested in GTK's ongoing project, "Ultra low-impact exploration methods for the subarctic," which is a part of the Tekes Green Mining Programme (Sarala and Nykänen, 2014a,b).

PORTABLE XRF METHODS

X-ray fluorescence (XRF) has been a standard method in laboratories for decades and has been used to determine major and minor element concentrations, as well as several precious elements in a variety of sample materials. However, conventional laboratory analyses with sample processing and powder pellet preparation are still time-consuming and increase the costs of the analysis. Significant developments have been made with portable XRF (pXRF) analyzers in the last decade including the reduction of detection limits for many elements to the ppm level. Portable equipment is lightweight and easy to take into the field or use at field camps, and that is why they are also called online XRF scanners (Fig. 10.1.2C). Applications such as ScanMobile®, where the XRF scanner is mobilized using a car-supported system, has facilitated usage of this instrument in field conditions (Sarala, 2009; Sarala and Ojala, 2008; *Mining Journal*, 2012; Sarala and Mäkikyrö, 2012). This application allows till, weathered bedrock, and drill core samples to be analyzed directly in the field or field camp. After collection, the samples are simply placed into drill core boxes for measurement, requiring little or no preprocessing. Although the portable XRF analyzers are widely used in exploration and in mining for bedrock and grab samples, their usage in mineral exploration for the analysis of till or weathered bedrock has so far been relatively limited, but this situation is changing rapidly.

HEAVY MINERAL STUDIES

In addition to geochemical methods, the study of the mineralogy of the heavy mineral fraction of till has been used extensively in mineral exploration (Peuraniemi, 1982, 1990b; Lehtonen, 2005; McClenaghan, 2005). It is based on the separation of the heavy mineral fraction from till or weathered bedrock samples. The size of bulk sediment samples collected for heavy mineral processing varies depending on the purpose of the study, the type of material sampled, and the texture of the sediment. Commonly, sample size varies from 10–12 liters (i.e., 20–25 kg), which is enough to get a representative sample of the heavy mineral composition in the sand size fraction of the material. Separation of the heaviest mineral fraction is based on gravity concentration. Preconcentration can be done with a spiral separator (gold screw panner) (Fig. 10.1.2D), by hand panning, with a shaking table, or a Knelson concentrator (Chernet et al., 1999; McClenaghan and Cabri, 2011).

After removing the magnetic fraction, heavy liquids (density 2.96 g/cm^3 or 3.31 g/cm^3) can be used to separate the heaviest minerals from the preconcentrates. Basic heavy mineral examination is done using a binocular microscope. The elemental composition and, thus, mineral identification of a selected number of grains can be done with a scanning electron microscope with energy-dispersive X-ray spectroscopy (SEM + EDS). Elemental composition of specific minerals is done using an electron microprobe (EMP). FEI's Mineral Liberation Analyzer (MLA) can also be used in mapping the heavy mineral population distribution, by doing automated mineral search and identification. Strict protocols need to be implemented to ensure the quality assurance and quality controls of indicator mineral studies (Plouffe et al., 2013).

Specific indicator minerals within the heavy mineral concentrates are useful for the detection of a variety of mineral deposits, including diamond, precious, and base metal deposits (e.g., Peuraniemi, 1982; Kauranne et al., 1992; Lehtonen, M., 2005; McClenaghan and Kjarsgaard, 2001; McClenaghan and Cabri, 2011; Paulen et al., 2011, 2013; Plouffe et al., 2014). Some lists of indicator minerals usable in mineral exploration have been published by Peuraniemi (1982) and McClenaghan (2005). Indicator minerals may come from the lighter end of the density spectrum normally used in heavy mineral research. For example, some phosphates can be used as indicators for rare earth element (REE) mineralization. A benefit of using heavy or indicator minerals is that transport distances are usually much longer than those of conventional till geochemical anomalies (Peuraniemi, 1990c). This can facilitate the reconnaissance stages of mineral exploration by allowing the use of sparse till sampling grids over a large area, leading to more rapid exploration at lower cost when compared to till geochemistry methods.

TILL GEOCHEMICAL EXPLORATION AT DIFFERENT SCALES

Continental and national geochemical sampling programs are good starting points for mineral exploration and evaluating the potential of different areas for specific elements, metals, and minerals. Sampling grid densities are critical in this view and depend on the extent of the areas under exploration (Theobald et al., 1991). DiLabio (1990) used the classifications continental, regional, local, and property-scale, where the sampling densities vary from over 100 km to under 100 m. Amount of detail usually increases according to survey scale where in the continental or national scale, for instance, the sampling density can be 1 sample/10–100 km^2, giving an indication of the major lithological units or the broad geochemical signature of regional bedrock units.

Regional scale commonly represents the sampling density of 1 sample per ±5 km^2. Regional geochemical mappings with sparse grids can serve to identify targets or anomalies for mineral exploration. A good example of this is the mapping project that was carried out in Finland in the 1980s (Salminen, 1995; Salminen and Tarvainen, 1995). The geochemical atlas for the fine fraction of till (<0.06 mm) was produced based on the same database (Koljonen, 1992). In this national compilation, till geochemistry clearly reflects broad lithological provenances (e.g., green stone and schist belts, granitoid provenances, and granulite belt). Furthermore, this national till geochemical database, with one sample per quarter km^2 is sufficient for directing mineral exploration in some places.

Mineral exploration at a local scale requires a dense sampling grid (<250 m) because geochemical anomalies can be subtle compared to background levels; it seeks mineralized bedrock sources that are small in area, leading to short dispersal trains. Sampling at a local scale (at intervals of tens to hundreds of meters) allows the characterization of small bedrock units and soil composition over a restricted area.

The shape of dispersal trains can be complex in the case of multiple glacial advances with multiple till units. Hirvas and Nenonen (1990) and Klassen (2001) have discussed the shape of dispersal trains along with their relation to glacial morphology. Glacial dynamics can also be inferred from the shape of dispersal trains (Sarala, 2005a; Trommelen et al., 2013). Furthermore, dispersal trains can be defined in three dimensions. DiLabio (1990) showed that dispersal trains rise gently within the till package in the down-ice direction, typically reaching the soil surface after 300–1000 m transportation in shallow till areas. This is the case when the basal glacial conditions are quite stable, warm-based, and the till is deposited by the lodgement process. In the central part of glaciers, under variable subglacial conditions, transport distances can vary greatly. For example, in the drumlin areas in eastern and northern Finland, till anomalies are narrow but long, usually from several kilometers to tens of kilometers, and mineralized boulders can be found far from their source(s) (Hirvas, 1989; Aario and Peuraniemi, 1992). In contrast, till anomalies are distinct and short in the ribbed moraine areas in southern Finnish Lapland, where numerous reported examples reveal very short glacial transport distances, in the order of tens to hundreds of meters down-ice from the distal side of mineralization (Peuraniemi, 1982; Aario, 1990; Sarala et al., 1998; Sarala and Rossi, 2000; Sarala, 2005b; Sarala and Peuraniemi, 2007).

TILLS AND GLACIAL LANDFORMS AS INDICATORS OF TRANSPORTATION

Till genesis can be evaluated and interpreted from (1) till facies analysis or (2) glacial morphological analysis. Identification of different till units is based on the analysis of composition and structure of till deposits. For mineral exploration purposes, a key point is to recognize basal tills such as basal lodgement and melt-out tills from the till types deposited on marginal parts of the glacier, such as flow till and waterlain till. The critical difference is that the latter have been affected by secondary, usually nonglacial processes (e.g., gravity flow) during deposition. Dreimanis (1989, 1990) has listed characteristic features of different till types and produced a classification scheme of till deposition based on the influence of primary and secondary processes. Dreimanis also described a number of till types with specific characteristics that can be related to variable glacial and depositional environments. Subglacial processes are effective at eroding, transporting, and depositing rock fragments and debris in the direction of ice flow. Consequently, lodgement till, deposited at the base of the glacier, is the best sampling media for till geochemical and mineralogical surveys. Other till types, such as deformation till, can be intermixed with a variety of other sediment types and bear evidence of deformation—for example, presence of folds and shears (e.g., Hart, 1997; Piotrowski et al., 2001; Roberts and Hart, 2005). Deformation tills are transitional with melt-out tills and it is difficult to draw a strict division between them.

A close relationship exists between till genesis and the glacial morphology. The glacial morphology provides an indication of depositional conditions and glacial transport distances both at regional and target scales as pointed out in several papers from northern Finland (e.g., Aario, 1977; Aario and Peuraniemi, 1992; Sarala et al., 1998; Sarala, 2005b,c). For mineral exploration purposes, it is important to distinguish active-ice deposits from passive-ice deposits. Active-ice deposits are those that are formed subglacially under a moving ice sheet. Typical landforms and deposits associated with active ice include drumlins, flutings, ribbed moraines, and thin basal till sheets (Fig. 10.1.3). Under passive-ice conditions, hummocky moraines and thick ablation till formations are deposited, usually in the marginal zone during the retreating phase of a glacier. This is also the environment where the end and other marginal moraines occur. Active- and passive-ice deposits have sustained different transport histories. Typically, deformation, lodgement, or basal melt-out tills associated with active-ice deposits are deposited subglacially, grain by grain or fragment by fragment, together with reworking of older deposits under high pressure. In spite of great variation between the transport distances in different formation types, the transport direction is in line with the ice-flow direction. On the other hand, till in passive-ice formations are usually transported englacially or supraglacially, so the transport distance and direction can vary considerably, and, consequently, source areas are not easily traced.

STREAMLINED, ACTIVE-ICE LANDFORMS

Drumlins, flutings, and some other radial moraine types (e.g., the Sevetti moraine in northern Lapland) are clear indicators of ice-flow direction (Aario, 1990). These landforms form typically large streamlined moraine fields consisting of several thousands of unique formations. The dimensions of drumlins are usually 5–50 m in height, 10–200 m in width, and from 100 m to several kilometers in length, and they are mainly formed under warm-based glacial conditions on the marginal zone of an ice sheet. These forms can be both depositional and erosional (Aario, 1990). Deposition happened subglacially when plastic debris was mobilized due to changing stress fields or the influence of active basal meltwater, which carves cavities beneath an ice mass that are later infilled with stratified sediments and till (Menzies and Shilts, 1996). Molding of previously deposited material in subglacial conditions, where the meltwater content is low, is an explanation for erosional forms. For that reason, in this case, the sediment bedding and structures usually represent an earlier glacial or interglacial depositional history of an area.

Flutings are mainly formed in settings similar to drumlins, but their dimensions are much smaller, with heights of 1–2 m, widths of 2–10 m, and lengths of 100–1000 m (Aario, 1990). These forms are usually obvious on aerial photographs as a group of narrow stripes in close connection with drumlins. Identification of these landforms in the field is difficult if there is vegetation cover. Furthermore, in Finland, they are usually surrounded by peat bogs, where surfaces are almost on the same level as the fluting tops.

Transport mechanisms of till in regions of streamlined landforms have been investigated widely (DiLabio and Coker, 1989; Aario and Peuraniemi, 1992; Piotrowski, 1997). In those areas, the transport direction of till is usually parallel to the orientation of the streamlined landforms (e.g., drumlins and flutings), with long transport distances: usually several kilometers, but even tens of kilometers in some places. Aario and Peuraniemi (1992) estimated that sampling till in the regions of streamlined landforms is an effective mineral exploration method. This is certainly the case where only one advance phase occurred during the drumlin formation, (i.e., ice movement was straightforward and older glacial overburden was relatively thin). In contrast, in regions of multiple glacial advances with variable flow directions, glacial dispersion can be very complex and transport distances long. For example, in the Kuusamo drumlin field in northeastern Finland, at least two different flow phases have been observed (Aario and Forsström, 1979). In eastern and southeastern Finland, in several parts of the Pieksämäki drumlin field,

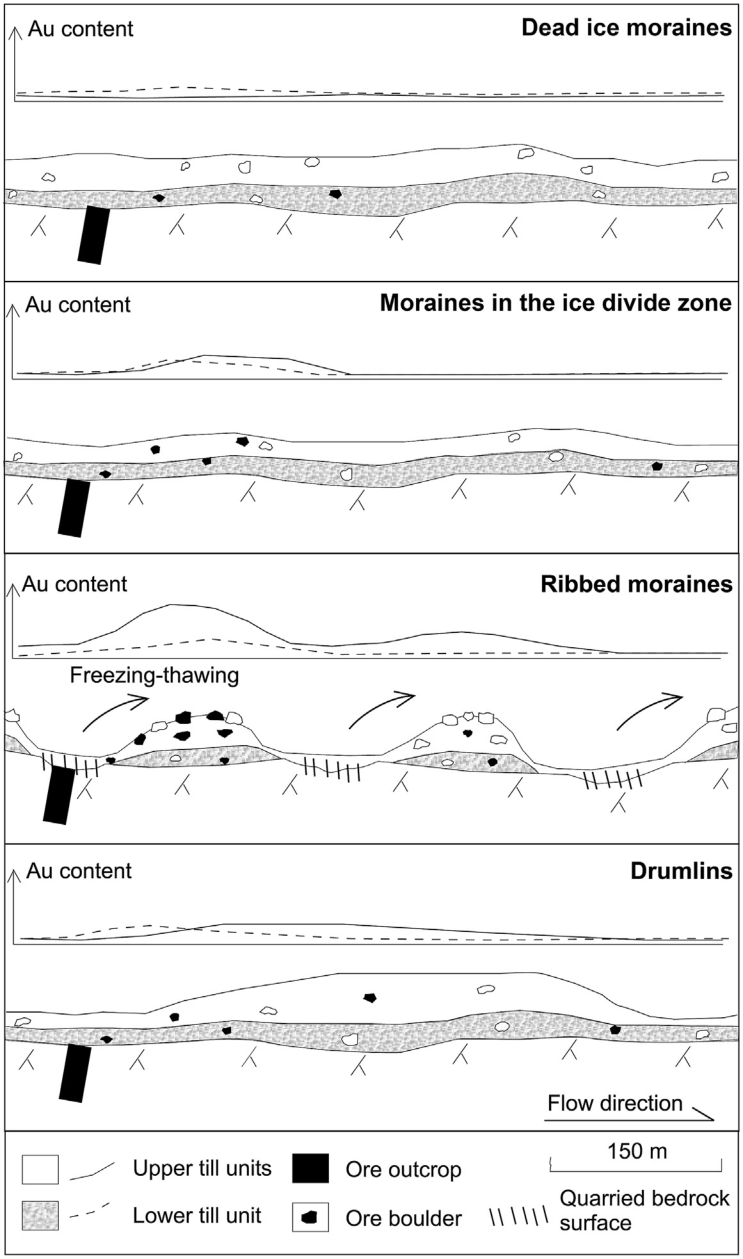

FIGURE 10.1.3 Schematic presentations of gold distribution into two till units representing glacial advance and retreat phases of glaciers in various morphological terrains.

Dead-ice moraines, moraines in the ice divide zone, ribbed moraines, and drumlins.

transport distances vary from 500 m to several km (e.g., Hirvas and Nenonen, 1990; Peuraniemi, 1990b; Hartikainen and Damsten, 1991). Although the secondary halos of the geochemical anomalies are long, they are commonly also very narrow. The same phenomenon is seen in heavy minerals, which form distinct elongated anomaly patterns in the down-ice direction (Peuraniemi, 1990b,c).

TRANSVERSE, ACTIVE-ICE MORAINE FORMATIONS

The transverse, active-ice moraine type in northern Finland is classified as *ribbed moraine* (Sarala, 2003, 2005a) following Hättestrand's (1997) classification. The ribbed moraine morphology consists of till ridges transverse to the ice-flow direction, with dimensions of 100–1000 m in length, 50–200 m in width, and 2–10 m in height. The interval between individual ridges is 100–300 m.

The term *ribbed moraine* is sometimes used as a synonym for *Rogen moraine*, but here it is used as the name for all ridge-type moraines formed by a similar process and with a similar morphology (cf. Sarala, 2003). Hättestrand (1997) has divided ribbed moraines into four subtypes: hummocky ribbed moraine, Rogen moraine, Blattnick moraine, and minor-ribbed moraine. All of these types have been formed as a result of similar conditions and formation processes during deglaciation, under a fast-flowing glacier, at the contact between cold-based and warm-based subglacial conditions. Hättestrand (1997) and Kleman and Hättestrand (1999) suggest that due to tension, subglacial deposits are broken up and transported with the flowing ice resulting in an undulating, puzzle-like ridge morphology.

Sarala (2005a) suggests that the ribbed moraine formation was a two-step process: (1) internal ice movement with tensional pressure caused fracturing of the cold-bed glacier and the subglacial sediments into blocks, which moved under the ice sheet and formed a ridge morphology; and (2) flowing ice transported the material loosened between the blocks by the freeze–thaw process and redeposited it on the surfaces of the new ridges. The deposition occurred in the transitional zone between the cold-bed and the thawed-bed glacier during deglaciation. This two-step mechanism explains the presence of locally derived boulders at the surface and in the uppermost part of the till in ribbed moraines (Fig. 10.1.4). Indeed, several case studies in southern Finnish Lapland show the extremely strong glacial quarrying activity and short transportation of till material and surficial boulders from the underlying bedrock to the top of moraine ridges. Consequently, a short distance of transport should be expected in regions of ribbed moraines common in Fennoscandia and northern America (Aario, 1977; Lundqvist, 1989; Kleman, 1994; Hättestrand, 1997; Sarala, 2005a,b).

Several mineral exploration studies have been completed in regions of ribbed moraines in southern Finnish Lapland (e.g., Sarala et al., 1998; Sarala and Rossi, 2000; Sarala, 2005a; Sarala and Peuraniemi, 2007; Sarala et al., 2007a). Mineral exploration in regions of ribbed moraines is facilitated by the composition of debris and rock fragments in the upper part of the ridges and the surficial boulders on the ridge top, which are derived from the local underlying bedrock. Furthermore, till geochemistry in those regions is characterized by narrow and sharp anomalies also related to local bedrock sources. Due to short and effective glacial erosion and subsequent transportation, fresh heavy minerals, such as sulfides and gold grains, are found to be well preserved in till of ribbed moraine. For example, in southwestern Rovaniemi, within the Paleoproterozoic Peräpohja schist belt, Cu-Au mineralization at Petäjävaara is found in a hydrothermal alteration zone in-between quartzite and mafic volcanic rocks, and is related to 1-m-wide quartz vein with associated pyrite and chalcopyrite dissemination (Sarala and Rossi, 2000). The transport distance of mineralized boulders, pebbles, and other debris is very short (only 5–50 m). Similar mineral exploration case studies with very short glacial transport have been reported in the

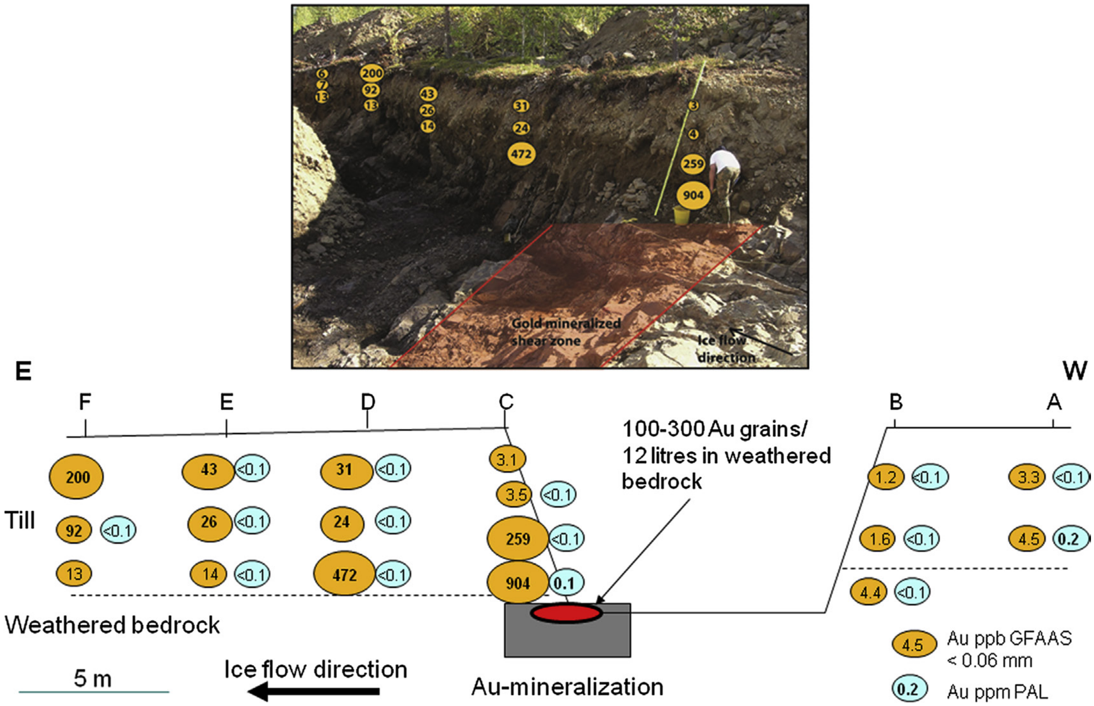

FIGURE 10.1.4 Au contents of the till in the test trench at the Petäjäselkä target, showing very short glacial transport in the central part of the last glaciation.

Yellow ovals show Au contents in the <0.06 mm size fraction after an aqua regia leach followed by graphite furnace atomic absorption spectrometry (GFAAS) analysis. Blue ovals represent Au contents in the <2 mm size fraction after a cyanide leach followed by GFAAS analysis using PAL1000 equipment (simultaneous pulverizing and cyanide leach using 0.5 kg subsample).

Portimojärvi area, north of Ranua village (Aario, 1990; Sarala and Peuraniemi, 2007), and in the Misi area in northeastern Rovaniemi (Sarala and Nenonen, 2005).

CORE AREAS OF GLACIERS

Generally, in regions covered by former ice divides, glacial erosion and transportation is weak. Minimal movement at the base of the glaciers, combined with cold-based conditions, generally resulted in limited glacial erosion, and in places only redeposition of preexisting glaciogenic deposits happens.

One of the studied areas in the ice-divide zone is the Petäjäselkä target in central Lapland, where GTK undertook gold exploration in the 2010s (Sarala et al., 2007b; Nykänen et al., 2007). In the Petäjäselkä target area, gold mineralization follows a heterogeneous and deformed north-northwest trending zone of graphic tuffs, cherts, and intermediate volcanic rocks within a mafic volcanic rock dominated domain (Hulkki et al., 2011). Till stratigraphy is simple: fresh bedrock is overlain by 1–2 m of weathered material composed of fractured bedrock or deeply weathered saprock, in turn overlain by a 1–2 m till that can be divided into two units: a bottom unit deposited during the advance phase and an upper unit deposited as ablation till during the melting phase. Till geochemistry shows very rapid upward dispersion of mineralized material from the bedrock surface into the upper till, 15–20 m down-ice (to the east) from the bedrock mineralization (see Fig. 10.1.4). The anomaly pattern is very sharp and strong, indicating gold mineralization in the underlying bedrock. The observation of a short transport distance is supported by the high number of gold grains in the heavy mineral concentrates close to mineralized bedrock.

Another example of short glacial dispersal comes from the Mäkärä area in the northern part of Sodankylä municipality. Gold and REE exploration have been undertaken here since the 1950s, most recently in 2009. The Mäkärä Au-REE target is located in the Tana belt, south of the 1.9 Ga Lapland granulite belt in northern Finland, where there are prominent lanthanum and yttrium anomalies in regional till and bedrock geochemical data (Sarapää and Sarala, 2013; Sarapää et al., 2013). Test pit and trench excavations, together with deep drilling samples, prove that the elevated gold and REE contents are related to the nearby narrow gold-hematite-quartz veins and the surrounding strongly weathered kaolinitic saprolite derived from arkosic gneiss, implying a short distance of glacial transport of around 100–200 m.

However, even in the ice-divide zone there can be small and local differential movement or reactivation between ice lobes at the end of the deglaciation phase, causing local erosion and even producing active-ice landforms. In places, this is seen particularly in the uppermost till layer, which can include distally transported debris and rounded rock fragments. In those cases, till material has been transported a relatively long distance inside the ice or englacially. After melting of ice, the material is released and deposited, forming a thin till veneer on the underlying sediments and giving no indication of underlying bedrock.In till geochemistry, it is seen as having a low content of elements and dilution of contents to background levels.

TRANSPORT DISTANCES AND DILUTION OF MINERALIZED MATERIAL IN TILL

As noticed in the cases of Petäjäselkä and Mäkärä, till composition can be used to estimate distance of glacial transport. Short and long distances of glacial transport measured from till composition needs to be considered in the interpretation of glacial transport mechanisms (e.g., Larson and Mooers, 2005). The loss of a geochemical or mineralogical signal in till at some distance from a bedrock source is related to a combination of glacial comminution (i.e., crushing of the mineralized debris to small size fraction) and dilution (i.e., unmineralized debris being eroded and incorporated in the glacial load). Therefore, general rules apply to glacial transport. For example, well-indurated intrusive bedrock can be englacially transported over longer distances compared to weathered, sheared, or poorly indurated lithologies. Calculations of glacial transport based on till matrix composition follow the same principles of boulder transport (e.g., Salonen, 1986). This can also be used in a reverse fashion to estimate the maturity of material: The higher the clay content a till has, the more mature it is, meaning the larger the source area of the till material and the longer the till material has been under the influence of glaciogenic processes. In some cases this calculation correlates with the distance from the source areas. Note that when interpreting the results, the high clay content of till can also indicate certain rock types in the bedrock (sensitive to clay-forming processes during erosion and secondary surficial processes) or existence of highly weathered bedrock surface (i.e., saprolite type weathering) as the source for the till.

For example, in the central Lapland area (the area of the last ice-divide zone), transport distances are short, as seen in the case of Petäjäselkä and Mäkärä (described earlier). In the Petäjäselkä area, gold contents dilute to background levels 15–20 m down-ice (east) from the source (see Fig. 10.1.4).

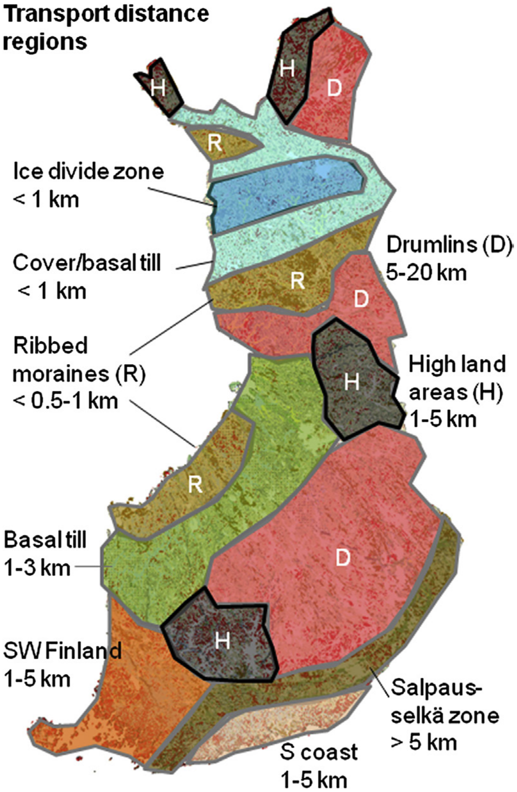

FIGURE 10.1.5 Generalized classification of Finland into eight glaciomorphological terrains and associated distance of glacial transport.

This is based on till geochemistry data and surficial boulder fans in Finland.

In the Mäkärä area, elevated concentrations of gold and REE return to background levels 100 m down-ice (toward the east) from the source (Sarapää and Sarala, 2013). In the ribbed moraine terrains, distance of glacial transport is only some tens of meters to 100 m for gold and a few hundreds of meters for copper and other indicator elements (Sarala et al., 1998; Sarala and Rossi, 2000). Pyrite and chalcopyrite grains preserved in till in those terrains attest to limited glacial comminution at short distances from the bedrock source and to weakly oxidizing conditions in the surface till, which permitted the preservation of sulfide minerals.

Linking glacial morphology and till composition in a variety of settings, it is possible to generate a rough estimation of the distance of glacial transport based on glacial terrain type. Fig. 10.1.5 presents an estimate of glacial transport distances based on glacial geomorphology. The model presented in Fig. 10.1.5 is largely based on till geochemistry and transport distances of mineralized material in till. It can be used as a starting point to interpret till geochemical data and to plan sampling programs in different terrain types. It is worth remembering that when moving into smaller research or exploration scales, the stratigraphical control should be increasingly taken into account.

SUMMARY

Geochemical methods have a long tradition of use in mineral exploration. Till geochemistry and mineralogy are practical methods for mineral exploration. Use of till as a sample material has been the cornerstone in the geochemical exploration of glaciated terrains and has led to the discovery of numerous ore deposits in Finland and abroad. Especially in the 1970s and 1980s, development of chemical analysis and sampling methods was rapid, and till sampling and mapping was very active. Extensive sampling campaigns covered all of Finland and, together with the development of fast and reliable analytical methods, national geochemical mapping was completed. Interpretation of till geochemistry and mineralogy needs to rely on a good knowledge of till stratigraphy and glacial morphology to be effective in mineral exploration. This has been proven in numerous case studies in Finland, as presented in several mineral exploration examples in this chapter from ribbed moraine, drumlin, and ice-divide terrains. Till geochemical methods can now rely on sampling and analytical methods with low environmental impact, which is especially important in exploring sensitive natural areas.

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