Data mining of petrophysical and lithogeochemical borehole data to elucidate the origin of seismic reflectivity within the Kevitsa Ni–Cu–PGE bearing intrusion, northern Finland

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ABSTRACT

The Kevitsa mafic-ultramafic intrusion, located within the Central Lapland Greenstone Belt in northern Finland, hosts a large, disseminated Ni–Cu–PGE sulphide deposit. A three-dimensional seismic reflection survey was conducted over the Kevitsa intrusion in 2010 primarily for open-pit mine planning and for deep mineral exploration purposes. In the Kevitsa three-dimensional seismic data, laterally continuous reflections are observed within a constrained region within the intrusion. In earlier studies, it has been suggested that this internal reflectivity mainly originates from contacts between the tops and more sulphide-rich bottoms of smaller scale, internally differentiated magma layers that represent a spectrum of olivine pyroxenites. However, this interpretation is not unequivocally supported by the borehole data. In this study, data mining, namely the Self-Organizing Map analysis, of extensive Kevitsa borehole data is used to investigate the possible causes for the observed internal reflectivity within the Kevitsa intrusion. Modelling of the effect of mineralization and alteration on the reflectivity properties of Kevitsa rock types, based on average modal compositions of the rock types, is presented to support the results of the Self-Organizing Map analysis. Based on the results, we suggest that the seismic reflectivity observed within the Kevitsa intrusion can possibly be attributed to alteration, and may also be linked to the presence of sulphide minerals.

Key words: Borehole geophysics, Petrophysics, Seismics, Interpretation.

1 INTRODUCTION

In the past decades, seismic reflection methods have increasingly been used for mining and mineral exploration applications in hard rock environments (Milkereit et al. 1996; Eaton, Milkereit and Salisbury 2003; Heinonen et al. 2012; review by Malehmir et al. 2012a; Buske, Bellefleur and Malehmir 2015 and references therein). In addition to their depth penetration, seismic reflection methods are of particular interest because of their significantly higher resolution when compared to other geophysical methods, and because petrophysical properties of sulphide minerals imply that sulphide deposits should generate strong seismic signals in typical hard rock environments (e.g. Salisbury, Harvey and Matthews 2003). The sulphide deposits could even directly be observed if they meet the size, thickness and geometrical constraints required for reflection or diffraction.

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However, interpretation of seismic reflection data from hard rock mining and exploration environments is often challenging because of the geological complexity emanating from multiple phases of deformation and alteration that the rocks have experienced during their history (e.g. L’Heureux, Milkeriet and Vasudevan 2009). Available borehole data sets provide only localized characterizations of the subsurface and are typically multiplex from the point of view of interpreting the causes of seismic anomalies on a larger scale. In recent years, data mining approaches have been used in growing numbers for data-driven analyses of the complex geophysical and geological data sets typical for mining and exploration camps (e.g. Klose 2006; Bierlein et al. 2008; Steel 2011; Cracknell, Reading and McNeill 2014; Kieu, Kepic and Kitzig 2018; Horrocks 2019), but examples on the use of data mining techniques for the interpretation of seismic data in hard rock settings are still lacking.

We use Self-Organizing Map (SOM; Kohonen 1981, 2001; Fraser and Dickson 2007) analysis to examine borehole data for the causes of seismic reflections within the Kevitsa intrusion. An SOM is a type of an artificial neural network and works on a vector quantization methodology that allows unsupervised analysis to identify the underlying linear and non-linear relationships between different data variables. Unsupervised analysis is preferable when there are no clear, previously established relationships between the data variables, for example between alteration and reflectivity properties, as is the case with the Kevitsa borehole data.

The Kevitsa mafic-ultramafic intrusion in northern Finland hosts a large, disseminated Ni–Cu–PGE sulphide deposit.
Figure 2 3D seismic reflection cube within the Kevitsa intrusion, viewed from the northeast: inline 1187 and crossline 1088 (migrated; Malehmir et al. 2012b) with reflections indicated by black arrows. The base of the Kevitsa intrusion from Koivisto et al. (2015) is shown in light grey as a reference.

(Fig. 1). Four intersecting two-dimensional seismic reflection profiles were acquired at Kevitsa in 2007 as part of the HIRE project (High-Resolution Reflection Seisimcs for Ore Exploration 2007–2010) to test the applicability of seismic surveying for exploration (Kukkonen, Lahti and Heikkinen 2009; Koivisto et al. 2012). In addition to the two-dimensional survey, a three-dimensional seismic reflection survey (see details from Malehmir et al. 2012b) was conducted in 2010, primarily for mine planning (Malehmir et al. 2012b; Koivisto et al. 2015; Lindqvist et al. 2017; Malehmir et al. 2017), but also for deep mineral exploration purposes (Malehmir et al. 2012b; Malehmir et al. 2014; Koivisto et al. 2015; Malehmir et al. 2017). In the seismic data, laterally continuous reflections were observed within a constrained region around the Kevitsa disseminated sulphide mineralization, from about 300 m to about 1 km depth (Fig. 2). These reflections were initially interpreted to originate from contacts between the tops and bottoms of smaller scale, internally differentiated olivine pyroxenite magma layers (Koivisto et al. 2012; Malehmir et al. 2012b; Malehmir et al. 2014; Koivisto et al. 2015). The magmatic layers were inferred to control the extent of the economic mineralization, with sulphides concentrated at the bottoms of the layers (Standing et al. 2009; Gregory et al. 2011). However, Koivisto et al. (2015) noted that while the acoustic impedance contrast between the suggested tops and bottoms of the magmatic layers seemed to be enough to produce detectable reflections, this explanation for the internal seismic reflectivity was not unequivocally supported by the borehole data as only little plagioclase-bearing olivine websterite, constituting the tops of the previously described magma layers, had been logged within the Kevitsa resource area (Gregory et al. 2011). Plagioclase-bearing olivine websterite has been logged only for 38 boreholes out of 871 boreholes available in the database provided by the mining company. The lack of plagioclase-bearing olivine websterite was tentatively attributed to varying historical logging practices that might not have correctly identified all the variants of olivine pyroxenites prior to a re-logging campaign that recognized the possible role of the magmatic layering in 2009 (Gregory et al. 2011). However, more recent geological works by Le Vaillant et al. (2016) and Luolavirta et al. (2018a,b) do not support such continuous layering but interpret the resource area to be associated with a local development of cyclic units, generally lacking obvious internal layering. Thus, the question arises as to what factors, other than mineralogical variations related to continuous smaller-scale magma layers, may explain the internal seismic reflectivity. In particular, the effect of alteration on the reflectivity properties has remained an open question (e.g. Koivisto et al. 2015).

The Kevitsa intrusion has gone through multiple alteration cycles resulting in widespread but varying alteration zones within the intrusion (Le Vaillant et al. 2016). However, in the borehole data, alteration is inadequately logged by varying practices over the years. For example, alteration is partly, but not consistently, indicated by a ‘metaperidotite’ label in the lithology rather than the alteration field. Metaperidotite refers to various degrees of amphibole alteration of olivine pyroxenites. The primary lithology, which has not been logged, may be olivine pyroxenite, olivine websterite, websterite or plagioclase-bearing olivine websterite, and the alteration may range from non-pervasive to pervasive. This masks the identification of the specific rock type as well as the degree of alteration. Separate alteration logs are available for some boreholes, but not consistently for all the data.

We use SOM analysis of Kevitsa borehole data to better understand the origin of the reflectivity within the Kevitsa intrusion, and its relationship with the lithological variation, alteration, and disseminated sulphide mineralization. First, theoretical calculations (Abers and Hacker 2016) are presented to provide insights into the effect of sulphide mineralization and alteration on the reflectivity properties of the Kevitsa rock types in order to support the interpretation of the SOM results. Then, we present SOM analysis of the borehole...
data using different geophysical, geotechnical and geochemical data. Based on the results, we conclude that the seismic reflectivity observed within the Kevitsa intrusion can possibly be attributed to alteration, and may also be linked to the presence of sulphide minerals, rather than to primary lithological contacts between the tops and bottoms of smaller scale magma layers within the intrusion. Additionally, fracture and fault zones, rock fragments (dunite, host rocks, etc.), as well as dykes and veins internal to the Kevitsa intrusion could be potential reflectors if they meet the geometrical requirements for observable reflections.

2 GEOLOGICAL BACKGROUND

The Kevitsa intrusion and deposit are described in detail by Mutanen (1997) and Mutanen and Huhma (2001). The intrusion is located within the Central Lapland Greenstone Belt (CLGB) in northern Finland (Fig. 1). The CLGB rocks are mainly layered volcanic and sedimentary rocks of Palaeoproterozoic age. These volcano-sedimentary rocks and the Kevitsa intrusion were metamorphosed and hydrothermally altered during a regional greenschist facies metamorphic event (Mutanen 1997). The southwest dipping intrusion, dated at about 2.06 Ga (Mutanen 1997; Mutanen and Huhma 2001), consists of gabbroic rocks in the southwest and mafic-ultramafic olivine pyroxenite and its variations in the northeast. Several (probably) older dunite units, which may have played a role in the larger scale emplacement of the Kevitsa intrusion and possibly also in the formation of the disseminated mineralization (e.g. Luolavirta et al. 2018c), are found within and around the intrusion (e.g. Central Dunite in Fig. 1). The intrusion covers an area of about 16 km² on the surface (Mutanen 1997), and it reaches a depth of about 1.5 km at its deepest parts (Koivisto et al. 2012; 2015). The economic mineralization occurs in compositionally heterogeneous olivine pyroxenites (more about this below), whereas more homogeneous olivine pyroxenites occur outside the Kevitsa resource area.

Open-pit mining, with a planned final pit depth of about 550 m, commenced in 2012 by First Quantum Minerals Ltd. As of June 2016, Boliden operates the mine. The total mineral resource of Kevitsa is about 160 million tons with a cutoff of 0.16% Ni (Kokko 2018). At the current mining rate of about 8 million tons of ore per year, the expected life of mine is until 2032 (Kokko 2018).

Several different ore types have been identified (Mutanen 1997; Gregory et al. 2011; Santaguida et al. 2015; Luolavirta et al. 2018a,b). A southwest-dipping ore zone averaging 0.30% Ni and 0.41% Cu – the so-called regular ore – occurs as a layered series of a couple of tens of meters thick bodies, extending up to hundreds of meters, consisting of 2–6% disseminated sulphide minerals; mostly pyrrhotite, pentlandite and chalcopyrite, and several platinum group minerals with lesser economic contribution (Gregory et al. 2011). The average PGE grades of the regular ore are 0.21 ppm Pt, 0.15 ppm Pd and 0.11 ppm Au (Gregory et al. 2011). In addition to the regular ore, north plunging high-grade Ni–PGE mineralization has been identified. These high-grade Ni–PGE ore zones are discordant to the regular ore. They are generally considered to have formed separately, but the origin continues to be debated (Mutanen 1997; Yang et al. 2014; Santaguida et al. 2015). The high Ni–PGE mineralization occurs as small, discontinuous, lens-like bodies that have thicknesses of a few to tens of meters. The overall sulphide content is similar to the regular ore, but the main sulphide minerals present are pentlandite, pyrite, millerite and heazlewoodite (Yang et al. 2014; Le Vaillant et al. 2016). This mineralization has higher and more variable nickel content, with Ni tenor greater than 10% (Santaguida et al. 2015), and lower copper content than the regular ore, and it contains more PGEs. The regular ore comprises the most important economic resource in Kevitsa, whereas the high Ni–PGE mineralization is volumetrically less significant (Gregory et al. 2011; Luolavirta et al. 2018a). In addition, a transitional ore type between the regular and high Ni–PGE ores has been identified (Mutanen 1997). Contact-type sulphide mineralization, possibly representing remobilization (Gregory et al. 2011), is intersected by a few boreholes that reveal Cu- and Ni-poor semi-massive to massive sulphides, which occur at or below the basal contact of the intrusion. Finally, the so-called ‘false ore’ (Mutanen 1997) refers to uneconomic iron sulphide minerals, almost entirely pyrrhotite, with very low Ni (Ni tenor of only 2–3%) and Cu concentrations (e.g. Santaguida et al. 2015; Le Vaillant et al. 2016). It occurs mainly at the margins of the intrusion.

After re-logging of selected boreholes in 2009, Standing et al. (2009) and Gregory et al. (2011) suggested that the extent of the main economic high-Cu mineralization (i.e. the regular ore) is controlled by the extent of smaller scale, laterally discontinuous, and internally differentiated olivine pyroxenite layers (Fig. 3a). The thicknesses of these individual magma layers were interpreted to be tens to hundreds of meters, within a restricted area inside the Kevitsa intrusive complex (Standing et al. 2009). The magma layers were suggested to represent a spectrum of olivine pyroxenites (Fig. 3b) ranging from plagioclase and orthopyroxene-rich tops (plagioclase-bearing olivine websterite) to increasing percentages of olivine and clinopyroxene (olivine pyroxenite) towards the bottoms of the layers.

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Figure 3  (a) Schematic drawing showing the mineralogical trends in the differentiated olivine pyroxenite magma layers, as suggested by Standing et al. (2009) (modified from Standing et al. 2009 and Gregory et al. 2011). Plagioclase (PLAG) and orthopyroxene (OPX) are more abundant at the top whereas olivine (OL) and clinopyroxene (CPX) are present throughout the layer, but dominate at the bottom. The mineralogical changes are gradational, that is, no hard boundaries exist within an individual magma layer. The sulphide mineralization grade gets higher towards the bottoms of the magma layers. (b) IUGS classification for ultramafic intrusive rocks (modified from Gregory et al. 2011): transparent grey area covers the general olivine pyroxenite variants in the Kevitsa resource area, whereas the transparent yellow area shows the approximate location of the north-plunging dunite intrusive. (c) Schematic drawing of the contamination of dunitic material (e.g. Standing et al. 2009) where plagioclase and orthopyroxene are replaced with olivine and clinopyroxene, hence resulting in magmas richer in olivine pyroxenite.

In the Kevitsa area, olivine clinopyroxenites are also called olivine pyroxenites (Standing et al. 2009). In addition, the orthopyroxene threshold for classification as olivine websterite was lifted from 10% orthopyroxene to 20%, in order to separate out the most distinctive rocks from the background, which generally contains 5–15% orthopyroxene. Olivine websterite is called ‘plagioclase-bearing olivine websterite’ where there is more than 5% plagioclase. The mineralogical change was interpreted to be gradational within an individual layer, with olivine websterite in the middle of the layers, and no internal contacts within the layers. However, the base of one layer (olivine pyroxenite) was described to grade relatively sharply to the top of another layer (plagioclase-bearing olivine websterite). The mineralization was suggested to be more strongly associated with the bases of these individual magma layers. However, this interpretation was not unambiguously supported by the borehole data, with only a handful of samples logged as plagioclase-bearing olivine websterite (Gregory et al. 2011; Koivisto et al. 2015). Recently, Le Vail- lant et al. (2016) interpreted the ultramafic unit as composed of interlayered olivine pyroxenite and websterite with a local development of cyclic units, but for the most part lacking obvious internal layering. Luolavirta et al. (2018a) state that the overall internal architecture of the ultramafic unit is complex and dominated by relatively uniform olivine pyroxenites ranging in modal mineralogy from olivine clinopyroxenite to olivine websterite with local (i.e. only within the ore domain) discontinuous zones of plagioclase-bearing olivine websterite, but lacking obvious internal layering.

It has also been suggested that the dunite units within and around the Kevitsa intrusion have played a role in the genesis of the economic mineralization (e.g. Standing et al. 2009; Gregory et al. 2011; Luolavirta et al. 2018c). The Kevitsa intrusion is associated with a large dunitic body, called the Central Dunite (Fig. 1), with an overall discordant relationship to the Kevitsa intrusion (Koivisto et al. 2015; Luolavirta et al. 2018c). The Footwall Dunite forms a lens like body at the basal contact of the intrusion. Recent studies by Koivisto et al. (2015) and Luolavirta et al. (2018c) suggest a link between the Footwall Dunite and the Central Dunite that could indicate a shared origin of these two units. Additionally, dunitic and related ultramafic rocks occur as numerous
inclusions within the Kevitsa intrusion, being most common within the resource area. The dunite occasionally contains disseminated sulphides. Standing et al. (2009) proposed that contamination by dunitic material took place when the main Kevitsa magma intruded, and that this contamination may also mask magmatic layering. Mixing of dunitic material with the plagioclase and orthopyroxene-rich tops of the magma layers would result in more olivine and clinopyroxene-rich magmas, similar to the previously described bottoms of the magma layers (Fig. 3c).

Three main alteration styles have been identified within the Kevitsa intrusion: (1) a widespread amphibole alteration, consisting of replacement of clinopyroxene and orthopyroxene by tremolite-actinolite and cummingtonite-grunerite, respectively; (2) a pervasive, partial serpentinite alteration of olivine in peridotitic rocks; and (3) a structurally controlled epidote alteration associated with NE-trending faults cutting across the deposit (Le Vaillant et al. 2016). The serpentine alteration appears to be the first alteration event in Kevitsa, followed by amphibole alteration, and lastly epidote alteration (e.g. Standing et al. 2009). The epidote alteration style is concentrated within the NE-trending fault zones towards the south end of the ore body, whereas the amphibole and serpentinite alteration styles are spread throughout the intrusion, and enclose decimetre-scale patches of essentially fresh igneous rock. Alteration of pyroxenes and olivine is intense in places, making primary rock types difficult to identify. In the borehole data, the detailed distribution of the alteration is difficult to assess, and has been recorded with varying practices over the years, but the most intense zones appear to be directly associated with relatively late mafic dikes and veins (Santaguida et al. 2015; Le Vaillant et al. 2016). Large amphibole alteration zones containing closely spaced carbonate and carbonate-quartz veins are common throughout the intrusion; the veins are intimately associated with the alteration (Le Vaillant et al. 2016). It is thought that the alteration processes did not affect the Ni and PGE grades (Santaguida et al. 2015; Le Vaillant et al. 2016). Nevertheless, Le Vaillant et al. (2016) suggest that Cu and Au grades may have been affected by remobilization from centimetre to kilometre scale.

3 PHYSICAL ROCK PROPERTIES

Kevitsa has been the target of extensive geological and geophysical investigations since its discovery in 1987. A vast number of geophysical and geological data sets, including extensive borehole data and two-dimensional and three-dimensional (3D) seismic reflection data, are available. We have access to about 900 boreholes drilled within the Kevitsa resource area and its surroundings. However, about 70% of the boreholes are less than 300 m deep, and only 134 boreholes contain geophysical logs. Furthermore, sonic logs are only available from 16 boreholes.

In Fig. 4, the average P-wave velocities are plotted against average densities for the main lithologies observed in the Kevitsa borehole data (values listed in Table 1). The highest velocities and densities are associated with olivine websterite and olivine pyroxenite. The corresponding rock types with lesser amounts of olivine – websterite and pyroxenite – have lower seismic velocities and densities. The presence of plagioclase also decreases the seismic velocity and density. The peridotitic rocks in Kevitsa have undergone pervasive serpentinization of the olivine minerals (e.g. the Central Dunite). Serpentine has lower seismic velocity and density than olivine (e.g. Table 2; Bass 1995; Abers and Hacker 2016) and thus serpentinization lowers seismic velocity and density of the rocks (e.g. the difference between dunite and Central Dunite, in Fig. 4a, the latter of which is thoroughly serpentinized). Widespread amphibole alteration has taken place within the whole intrusion. Amphibole has lower seismic velocity and density than pyroxene (e.g. Table 2; Bass 1995; Abers and Hacker 2016) and, therefore, this replacement of pyroxenes with amphiboles also reduces seismic velocity and density of the Kevitsa rock types (e.g. change from olivine pyroxenite to meta-peridotite, which is partly, but not consistently, used to describe amphibole-altered olivine pyroxenites in the Kevitsa borehole data; Fig. 4a). Overall, the hosting Central Lapland Greenstone Belt rocks are associated with lower velocities and densities than the intrusive rocks. The lowest seismic velocities and densities are associated with fractured and sheared rocks.

Referring to the earlier studies associating reflectors with magmatic layering (e.g. Koivisto et al. 2012, Koivisto et al. 2015), Fig. 4(a) indicates that the contrast between the physical properties of plagioclase-bearing olivine websterite, the tops of the magma layers, and olivine pyroxenite, the bottoms, would be enough to produce detectable reflections. However, for interpreting 3D seismic reflection data, there is a challenge in comparing pointwise borehole data with continuous 3D seismic reflection data. In the case of Kevitsa, tying the borehole data to the seismic reflection data is further complicated by poor reflectivity at shallow depths due to the high background velocity of the Kevitsa intrusion (greater than 6500 m/s) and issues with the sampling of the seismic wavefield at shallow depths (and low seismic fold). Due to these issues the observed reflectivity starts from approximately 300 m depth (i.e. shallower reflectors are simply not imaged), and the
Figure 4 (a) Average P-wave velocity versus density plotted for the main lithologies observed in the Kevitsa borehole data (Table 1). Standard deviation is used for the error bars. The solid black curves correspond to constant acoustic impedance, and the difference between two curves represents a detectable reflection (reflection coefficient equals to 6%; Salisbury et al. 1996; Salisbury et al. 2003). There is sufficient contrast between the physical properties of plagioclase-bearing olivine websterite (blue dot) and olivine pyroxenite (grey dot), constituting the said tops and bottoms of suggested magma layers, to produce detectable reflections. (b) Overall distribution of density and P-wave velocity among different rock types in Kevitsa based on 15 boreholes. The figure has been modified from Koivisto et al. (2012) and does not include all the later boreholes included in this work.

Laterally most continuous reflections start at depth of about 500 m (Fig. 2). Thus, the lack of borehole data at the depths of the reflections (only 61 boreholes out of 134 selected for the analysis are deeper than 500 m) limits the interpretation efforts.

3.1 Theoretical modelling of the effect of sulphide mineralization and alteration on the reflectivity properties of the Kevitsa rock types

In order to support the interpretation of the borehole data with regard to the reflectivity properties, we constructed forward models of the effect of sulphide mineralization and alteration on the densities and seismic P-wave velocities, that is on the seismic impedances of the Kevitsa rock types and ore. This helps overcome the inadequate and incomplete log data on the distribution of alteration within the intrusion. Alteration has been logged for only 41.5% of the samples chosen for the analysis, but an empty logging field for alteration indicates missing information and not necessarily lack of alteration. Exact quantitative modal compositions of Kevitsa lithologies are not available. Therefore, we calculated theoretical rock densities and velocities of the main rock types in Kevitsa using plausible modal compositions of the rock and ore types guided by the petrographic data provided by Mutanen (1997). Bulk rock properties were estimated using the
Table 1  Average P-wave velocities ($V_p$) and densities for the main lithologies and their standard deviations. The average acoustic impedance for each lithology group is also calculated. Originally, there were more than 70 different lithology labels used for the borehole data, but these were re-organized and simplified into 18 different classes listed here.

| Lithology Group Name                  | Average $V_p$ (m/s) | Standard Deviation (m/s) | Average Density (kg/m$^3$) | Standard Deviation (kg/m$^3$) | Acoustic Impedance ($10 \times 10^6$ kg/m$^2$/s) | No. of Samples |
|--------------------------------------|---------------------|--------------------------|-----------------------------|-----------------------------|-----------------------------------------------|----------------|
| Olivine pyroxenite                   | 7066                | 526                      | 3121                        | 99                          | 22                                           | 3640            |
| Olivine websterite                   | 7161                | 508                      | 3211                        | 111                         | 23                                           | 2917            |
| Plagioclase-bearing olivine websterite| 6441                | 373                      | 2993                        | 24                          | 19                                           | 24              |
| Metaperidotite                       | 6652                | 627                      | 3052                        | 108                         | 20                                           | 1696            |
| Pyroxenite                           | 6616                | 487                      | 2940                        | 117                         | 19                                           | 243             |
| Websterite                           | 6324                | 613                      | 3000                        | 92                          | 19                                           | 267             |
| Central Dunite                       | 5085                | 658                      | 2695                        | 276                         | 14                                           | 363             |
| Footwall Dunite                      | 7222                | 731                      | 3196                        | 81                          | 23                                           | 82              |
| Dunite                               | 6525                | 329                      | 3031                        | 117                         | 20                                           | 183             |
| Gabbro                               | 5426                | 1335                     | 2931                        | 195                         | 16                                           | 93              |
| Olivine gabbro                       | 6457                | 389                      | 3012                        | 85                          | 19                                           | 44              |
| Dyke                                 | 6256                | 948                      | 3011                        | 168                         | 19                                           | 36              |
| Vein                                 | 6493                | 496                      | 2997                        | 151                         | 19                                           | 66              |
| Metavolcanics                        | 5938                | 416                      | 2905                        | 105                         | 17                                           | 671             |
| Metasediments                        | 6151                | 678                      | 2891                        | 135                         | 18                                           | 129             |
| Xenolith                             | 6336                | 352                      | 3090                        | 81                          | 20                                           | 14              |
| Fracture zone                        | 7179                | 0                        | 2626                        | 0                           | 19                                           | 1               |
| Sulphide vein                        | 6826                | 0                        | 3209                        | 0                           | 22                                           | 1               |

Table 2  Theoretical densities and P-wave velocities for the most important rock and ore-forming minerals in Kevitsa (Bass 1995; Abers and Hacker 2016).

| Mineral                | Density (kg/m$^3$) | P-wave Velocity (m/s) | Notes                  |
|------------------------|--------------------|-----------------------|------------------------|
| Pyrite                 | 4910               | 7990                  |                        |
| Chalcopyrite           | 4280               | 5120                  |                        |
| Pyrrhotite             | 4710               | 4600                  |                        |
| Pentlandite            | 4680               | 4560                  |                        |
| Graphite               | 2226               | 11,650                |                        |
| Magnetite              | 5202               | 7271                  |                        |
| Mg-Olivine (Forsterite)| 3223               | 8385                  |                        |
| Fe-Olivine (Fayalite)  | 4401               | 6838                  |                        |
| Talc                   | 2785               | 6533                  |                        |
| Chlorite               | 2636               | 6837 (Mg-chlorite)    |                        |
| Orthopyroxene          | 3197               | 8155 (Enstatite)      |                        |
| Clinopyroxene          | 3269               | 8104                  |                        |
| Hornblende             | 3183               | 6849                  |                        |
| Tremolite              | 2980               | 7164                  |                        |
| Serpentine             | 2586               | 6660 (Antigorite)     |                        |
| Ca-Plagioclase (Anorthite) | 2761         | 6869                  |                        |
| Na-Plagioclase (Albite) | 2621               | 6435                  |                        |
| Epidote                | 3348               | 8128 (Zoisite)        |                        |
| Carbonate              | 2861               | 7100 (Dolomite)       |                        |
| Sericite               | 2829               | 6203 (Muscovite)      |                        |
| Quartz                 | 2650               | 6030                  |                        |

geometric means of the mineral properties (shown in Table 2) weighted by the volume percentages of the minerals. The densities and seismic velocities were calculated for 0.03 GPa and 25°C (approximately corresponding to conditions in Kevitsa at 1 km depth) using the software and data by Abers and Hacker (2016) and Bass (1995). Porosity was assumed to be small and negligible.

The results of our theoretical modelling are shown in Fig. 5 and Table 3. Compositional trends related to alteration are shown as well as the effect of increasing sulphide mineral content. Alteration of olivine into serpentine, magnetite and carbonate was calculated assuming that in a thorough alteration of the mineral, the forsterite component has produced serpentine and the fayalite component has produced magnetite and carbonate. For the forsterite content, we applied a value of 85% (the range of values reported by Mutanen (1997) is about 77–90%). Amphibole alteration of pyroxenes was modelled assuming that the secondary amphibole consists of 50% hornblende and 50% tremolite (seismic velocity and density values are available for these; the properties should be close to tremolite-actinolite and cummingtonite-grunerite which are the alteration products of clinopyroxene and orthopyroxene, respectively). Properties of unaltered and altered plagioclase were calculated using an anorthite content of 80% (Mutanen 1997). Table 3 presents results for model
compositions assuming fresh, altered (50%) and thoroughly altered (100%) compositions. The model compositions (Table 3) are not meant to be exact numerical representations of the results of complicated mineral reactions, but only to demonstrate the trends due to compositional variation and alteration.

Based on these results, it is obvious that unaltered rocks are not able to produce strong reflection contrasts. There is practically no impedance contrast between fresh variants of olivine pyroxenites (Fig. 5 and Table 3). Even adding 17% plagioclase to olivine websterite (in Kevitsa the plagioclase-bearing olivine websterite typically contains only 5–10% of plagioclase; Standing et al. 2009) is not enough to cause a reflection when in contact with olivine pyroxenite (i.e. this would be the contact between unaltered tops and bottoms of the magma layers as suggested by Standing et al. 2009). Furthermore, adding up to 10% sulphides (pyrrhotite, pentlandite and chalcocypire) to olivine pyroxenite does not markedly change the impedance, although it will increase density. Such a volume of sulphides already exceeds the typical values in the Kevitsa ores (2-6%; Mutanen 1997). The same insensitivity to sulphide content applies to altered or thoroughly altered olivine pyroxenite. On the other hand, alteration is able to create a considerable shift in impedance against unaltered rock, which easily exceeds the detection threshold of a reflector (approximately 6% in reflection coefficient; Salisbury, Milkereit and Bleeker 1996; Salisbury et al. 2003).

Another immediate conclusion from the modelling is that the low sulphide mineral content cannot alone produce reflectivity of the Kevitsa ore. Although magnetite would have a strong (pyrite-like) effect on impedance, it is not present in sufficient amounts to make much of a difference, as can be seen, for instance, in the case of our modelled composition of a thoroughly altered dunite (containing 10% magnetite). On the other hand, alteration easily produces impedance contrasts creating reflection coefficients in the range of 10–15%.

4 METHOD AND DATA

4.1 Self-Organizing Map analysis

A Self-Organizing Map (SOM; Kohonen 1981, 2001) is a type of an unsupervised artificial neural network that is trained to produce a low-dimensional, discretized representation, typically a two-dimensional 'map', of complex high-dimensional input data. It differs from other artificial neural networks in that it applies competitive learning (vector quantization) as opposed to error-correction learning, and it uses a neighbourhood function to preserve topological relationships of the input data space. CSIRO’s (Commonwealth Scientific and Industrial Research Organization) Self-Organizing Map software (Fraser and Dickson 2007), based on a Matlab SOM Toolbox (Kohonen et al. 1996; Vesanto et al. 2000), is used in this study.

SOM analysis has widely been used for applications ranging from engineering and oil industry to life sciences and finance (Kaski, Kangas and Kohonen 1998; Oja, Kaski and Kohonen 2003; Poll̈ä, Honkela and Kohonen 2009). Now, the SOM approach is making its way into hard rock mineral exploration (e.g. Klose 2006; Bierlein et al. 2008; Steel 2011; Cracknell et al. 2014; Leväniemi, Hulkki and Tiainen 2016). Major strengths of the technique comprise robust handling of multivariate, disparate and incomplete input data, including also categorical variables (e.g. Fessant and Midnet 2002;
Table 3 Modal mineral compositions, calculated densities and velocities of modelled rock types

| Mineral | Unit | Unaltered | Unaltered | Unaltered | Unaltered | Unaltered | Unaltered | Unaltered | Thoroughly | Thoroughly | Thoroughly | Thoroughly | Thoroughly | Thoroughly |
|---------|------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
|         |      | Olivine-  | Pyroxenite| Olivine-  | Pyroxenite| Olivine-  | Pyroxenite| Olivine-  | Pyroxenite| Olivine-  | Pyroxenite| Olivine-  | Pyroxenite| Olivine-  | Pyroxenite|
|         |      | Websterite|           | Webserite |           | Websterite|           | Webserite |           | Websterite|           | Webserite |           | Webserite |           |
| Chalcopyrite | v% | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 4 | 0 | 8 | 0 | 0 | 0 | 0 | 0 | 2.0 | 2.0 | 2.0 | 4.0 | 4.0 | 0 |
| Pyrrhotite | v% | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 4 | 8 | 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2.0 | 2.0 | 4.0 | 4.0 | 0 |
| Pentlandite | v% | 0 | 0 | 0 | 0 | 0 | 0 | 1.0 | 2.0 | 4.0 | 8.0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.0 | 1.0 | 2.0 | 2.0 | 2.0 | 0 |
| Quartz | v% | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Fwomite | v% | 72.0 | 36.0 | 7.0 | 3.5 | 0 | 0 | 6.6 | 6.5 | 3.8 | 5.3 | 8.0 | 0 | 6.4 | 3.9 | 5.9 | 0 | 0 | 3.5 | 0 | 0 | 0 | 0 | 0 |
| Enstatite | v% | 18.0 | 9.0 | 2.0 | 1.0 | 0 | 0 | 2.0 | 1.7 | 3.5 | 1.3 | 2.0 | 1.6 | 1.5 | 1.5 | 0 | 0 | 0.9 | 0 | 0 | 0 | 0 | 0 |
| Talc | v% | 0 | 5.0 | 10.0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Chlore | v% | 0 | 1.3 | 2.5 | 0 | 3.14 | 22.8 | 0 | 0 | 0 | 0 | 0 | 0 | 3.2 | 10.8 | 21.6 | 20.5 | 20.0 | 18.3 | 18.3 | 0 | 0 |
| Orthopyroxene | v% | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Grosspyroxene | v% | 10.0 | 5.0 | 0 | 91.0 | 45.5 | 0 | 86.4 | 81.8 | 72.7 | 65.4 | 80.0 | 74.0 | 68.0 | 68.0 | 0 | 41.2 | 0 | 0 | 0 | 0 | 0 |
| Hornblende | v% | 0 | 2.35 | 5.0 | 0 | 22.8 | 45.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 37.7 | 31.6 | 41.6 | 41.0 | 36.5 | 36.5 |
| Tremolite | v% | 0 | 1.3 | 2.5 | 0 | 11.4 | 22.8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Serpenite | v% | 0 | 30.0 | 60.0 | 0 | 4.0 | 8.0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3.2 | 3.3 | 6.6 | 6.2 | 6.0 | 5.0 | 3.0 |
| Anorthite | v% | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Albite | v% | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Biople | v% | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Carbonate | v% | 0 | 5.0 | 10.0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 5.7 | 4.7 | 0 | 0 | 0 | 0 | 0 |
| Sericit | v% | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Graphite | v% | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2.0 | 10.0 | 20.0 |
| Snt | v% | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Bulk rock density | kg/m³ | 3414 | 3126 | 2863 | 3285 | 3123 | 2969 | 3341 | 3392 | 3902 | 396 | 3277 | 3215 | 3173 | 3214 | 30.36 | 31.94 | 30.36 | 31.20 | 31.03 | 30.12 | 28.27 |
| Bulk rock density | m/s | 8193 | 7410 | 6775 | 8109 | 7481 | 6905 | 7804 | 7698 | 7328 | 6991 | 8119 | 7845 | 7633 | 7852 | 6938 | 7232 | 6782 | 6603 | 6734 | 7023 | 7675 |
| Impedance | m/s² | 27.55 | 23.12 | 19.40 | 26.60 | 23.35 | 20.50 | 26.36 | 26.06 | 25.54 | 25.11 | 26.56 | 25.68 | 25.05 | 25.30 | 21.19 | 23.39 | 20.75 | 20.79 | 20.90 | 21.32 | 21.70 |

**Notes:**
- The values are calculated based on the modal mineral compositions provided.
- The bulk rock density is calculated using the densities of individual minerals present in each rock type.
- The bulk rock velocity is calculated using the velocities of individual minerals present in each rock type.
- The impedance is calculated as the square root of the product of density and velocity.
The SOM is robust in performing several operations, such as prediction, clustering, pattern recognition, and classification, on large volumes of data. Because SOM is unsupervised, no prior knowledge is needed of the nature or number of groupings within the data. Here, the principles of the SOM are briefly introduced. For further information, the reader is referred to Kohonen (1981, 2001), Vesanto et al. (2000) and Fraser and Dickson (2007).

An SOM consists of a predefined number of nodes that are organized on a typically two-dimensional, regularly spaced hexagonal or rectangular grid. The size of the SOM is equal to the number of nodes. These nodes are associated with the input data vectors, that is the number of variables associated with the input data. Each node vector is connected to its neighbouring node vectors with a neighbourhood function that dictates the structure of the map. Often, a sheet map shape is used, but cylinder and toroid shapes can also be used.

In the SOM, each input data sample is treated as an n-dimensional (nD) vector, where n is equal to the dimension of the input data vectors, that is the number of variables associated with the input data. The node vector is connected to its neighbouring node vectors with a neighbourhood function which dictates the distance between the node vectors. Often, a sheet map shape is used, but cylinder and toroid shapes can also be used.

First, a random starting input data vector is selected and the similarity between it and all the node vectors of the SOM is measured using, typically, Euclidean distance. The node, which vector is the most similar, that is the closest, to the starting input data vector is called the Best Matching Unit (BMU). After finding the BMU, the node vectors are updated so that the BMU moves closer to the input data vector in the data space. Next, the nodes of the BMU are also updated, but with lesser magnitude depending on the learning rate and distance from the BMU. The training process is repeated several times for each input data vector while reducing learning rate and neighbourhood radius. The training is performed in two phases. At first, the learning rate and neighbourhood radius are initially set large (the neighbourhood radius should at the beginning cover the whole SOM map), and in the second phase they are set smaller. After training, the node vectors are situated within the original input data vectors. Each node vector represents a group or cluster of the data vectors closest to it, and if several node vectors are close together they can be subsets of a larger group or cluster. In the SOM, k-means clustering is used. Davies–Bouldin (DB) analysis (Davies and Bouldin 1979) can be used to determine an appropriate number of clusters. Regression, a process that preserves the topology of the node vectors, is used to map the node vectors from nD space onto a two-dimensional (2D) map (each node on this 2D map represents a node vector in the nD space). The underlying statistical relationships between different data are visualized with the help of these 2D maps that facilitate the interpretation of the complex multidimensional data (e.g. Penn 2005; Fraser and Dickson 2007; Bierlein et al. 2008).

The quality of SOM is measured with two types of error calculations: quantization and topological error. The quantization error describes the map resolution; it measures the average distance between each input data vector and its BMU. The topological error measures the proportion of all data vectors for which first and second BMUs are not adjacent units (Vesanto et al. 2000).

The outputs of the SOM are shown in Fig. 6. The component plot (Fig. 6c) represents each node’s contribution to a particular variable, with red colours indicating higher values of the variable and blue colours indicating smaller values of the variable. The unified distance matrix, or the U-matrix (Fig. 6d), represents the 2D topology of the SOM nodes, where the distance between neighbouring nodes is represented with different colours, blue representing shorter Euclidean distances (i.e. similarity) and red larger distances (i.e. difference). To aid the visualization of the distance between nodes, ‘empty’ nodes are added in between the actual nodes. White hexagons (Fig. 6d) represent the actual nodes. The number of original input data vectors that ultimately reside within each node is represented by the size of the white hexagon (e.g. Fraser and Dickson 2007).

4.2 The Kevitsa borehole data used in the SOM analysis

In total, 134 boreholes were selected for the Self-Organizing Map (SOM) analysis (Fig. 1). The selected boreholes contain data for at least one geophysical variable, are at least 300 m deep (the quality of the three-dimensional seismic data is very poor at shallower depths than 300 m) and are primarily located within the planned Kevitsa open pit area (indicated with a white dashed circle in Fig. 1). Exceptions were made for boreholes containing geophysical data, especially sonic logs.

Before the actual SOM analysis, the borehole data were re-sampled to uniform 1-m downhole intervals using a simple nearest neighbour interpolation method (data samples within 0.5 m from the depth location in question were considered), and anomalous data values (e.g. seismic velocities greater than 10,000 m/s) were removed.

Several tests were run to select representative geophysical, geotechnical and geochemical variables, and to perform preliminary data analyses on the selected variables. Junno et al. (2019) discuss how different sets of variables affect the ability...
of SOM to predict seismic velocities from other available borehole data. The set of variables used in this study was selected based on the SOM analyses presented by Junno et al. (2019). In total, seven geophysical and geotechnical variables and nine geochemical variables were chosen for the final SOM analysis (Table 4). P-wave velocity ($V_p$), S-wave velocity ($V_s$), specific gravity (SG) and rock quality designation were included as direct indicators of properties controlling the reflectivity, and magnetic susceptibility, electrical resistivity and induced polarization effect as indicators of mineralization. Gamma–gamma density logs would have been available for 16 of the boreholes, but SG was chosen over gamma–gamma density as it reflects the same property but is more extensively measured, and based on the preliminary analyses it was found that SG actually correlates better with the seismic velocities. Geochemical variables selected were nickel (Ni), copper (Cu), gold (Au), palladium (Pd), platinum (Pt), iron (Fe), sulphur (S), cobalt (Co) and chromium (Cr) (Table 4). These are the primary constituents of the main sulphide minerals at Kevitsa (pyrrhotite, pentlandite, chalcopyrite and several platinum group minerals) and were included to differentiate mineralization from host rock signatures. Aluminium (Al), calcium (Ca), magnesium (Mg) and sodium (Na) could have been used as indicators of the magmatic layering and alteration; high Ca and Na concentrations are proxies for alteration, whereas high Mg concentrations relate to olivine pyroxenite and high Al to plagioclase-bearing olivine websterite. However, since Al, Ca, Mg and Na have been measured only very sporadically.

\[ \text{Figure 6} \] Principles and outputs of SOM: (a) nD view of the original data (black dots; three variables, i.e., three dimensions), and (b) SOM nodes representing that original data in yellow, green and blue dots (three clusters defined within the data). The outputs of SOM are presented in (c) component plots for each variable, and (d) the unified distance matrix (U-matrix) of the data. The component plot represents each node’s contribution to a particular variable with smaller values of the variable in blue and larger in red. The U-matrix represents the distance between neighbouring nodes with blue colours indicating shorter distances, or similarity, and red colours larger distances, or difference. The white hexagons correspond to the number of original data samples within the node – the bigger the hexagon the more input samples fall within it. ‘Empty’ nodes are added in between the actual nodes to aid the visualization.
Table 4 List of the SOM variables originally selected for the analysis. Also listed is the number of samples containing that particular variable and in how many different boreholes these samples exist. In total, there were 64,999 samples from 134 different boreholes. Only samples that contain at least one geophysical variable are included in the analysis.

| Variables             | Unit          | No. of Samples Containing that Variable | No. of Boreholes | Missing Percentage |
|-----------------------|---------------|-----------------------------------------|------------------|--------------------|
| **Geophysical and geotechnical** |               |                                         |                  |                    |
| Vp                    | m/s           | 12,004                                  | 16               | 81.50              |
| Vs                    | m/s           | 9878                                    | 14               | 84.80              |
| Specific gravity (SG) | kg/m³         | 46,611                                  | 105              | 28.30              |
| Electrical resistivity| Ohm·m         | 31,627                                  | 60               | 51.30              |
| IP                    | pct           | 31,021                                  | 59               | 52.30              |
| RQD                   | pct           | 8113                                    | 13               | 87.50              |
| Magnetic susceptibility| 10 × 10⁻³ SI | 7890                                    | 13               | 87.90              |
| **Geochemical**       |               |                                         |                  |                    |
| Ni                    | pct           | 57,924                                  | 132              | 10.90              |
| Cu                    | pct           | 57,921                                  | 132              | 10.90              |
| Au                    | ppb           | 43,969                                  | 132              | 32.40              |
| Pd                    | ppb           | 42,853                                  | 131              | 34.10              |
| Pt                    | ppb           | 34,465                                  | 124              | 47.00              |
| Fe                    | pct           | 57,924                                  | 132              | 10.90              |
| S                     | pct           | 57,907                                  | 132              | 10.90              |
| Co                    | ppm           | 57,924                                  | 132              | 10.90              |
| Cr                    | ppm           | 57,924                                  | 132              | 10.90              |
| Al                    | pct           | 17,142                                  | 45               | 73.60              |
| Ca                    | pct           | 17,142                                  | 45               | 73.60              |
| Mg                    | pct           | 17,142                                  | 45               | 73.60              |
| Na                    | pct           | 17,142                                  | 45               | 73.60              |
| **Lithological labels** |             |                                         |                  |                    |
|                       |               | 64,541                                  | 134              | 0.70               |
| **Alteration labels** |               | 26,982                                  | 134              | 58.50              |
| **Total**             |               |                                         | 64,999           | 134                |

(Table 4) and from different holes than most of the geophysical variables, they were, after initial testing, left out from the final SOM analysis.

After the SOM analysis, the lithology and alteration labels were checked for each cluster, the results of which are shown in the confusion matrices of Tables 6 and 7, respectively. For this purpose, the lithological classification was simplified (Table 1). The main focus of this work is on the intrusive rocks (olivine pyroxenite variants including also metaperidotite, and gabbro and olivine gabbro) and their relationship to the reflectivity properties, so the original classes for these rock types were respected (about 90% of all lithology labels fell into these groups). The dunite occurrences, about 4% of the lithology labels, were subdivided into three different groups: the Central Dunite, consisting of dunite and peridotite situated within the Central Dunite (Fig. 1); the Footwall Dunite consisting of dunite described at the basal contact of the intrusion; and the remaining dunite situated within the main Kevitsa intrusion (e.g. Standing et al. 2009; Gregory et al. 2011). Host rocks were subdivided into metavolcanics and metasediments that have similar petrophysical properties; this simplified 56 host rock classes into just two classes (in total only about 2.5% of all lithology labels were host rocks). Other rock groups, 1.5% of all lithology labels, include dykes, veins and xenoliths. Sulphide veins and fracture zones (1.3% of all lithology labels) were left as their own groups. About 0.7% of the selected samples had no lithology label logged for them. For the alteration labels, the original classification was respected (there were 11 different classes of alteration logged for the selected samples; Table 7). Alteration had been logged for 41.5% of the samples chosen for the analyses. Amphibole and serpentine were the most common alteration types (about 82% of all the alteration labels were amphibole and 4% serpentine). However, it should again be noted that amphibole alteration has been partly, but not consistently, also logged as metaperidotite in the lithology field rather than in the alteration field. Metaperidotite refers to amphibole-altered (in various degrees) olivine pyroxenite variants.
Figure 7 Selected component plots for different geophysical, geotechnical and geochemical variables. Thirteen clusters were defined within the data, including five clusters defining the barren olivine pyroxenites (clusters 1a, 1b, 1c, 1d and 1e), two clusters defining the transitional ore (clusters 4a and 4b), two clusters for regular ore (clusters 5a and 5b), and one cluster for the high Ni–PGE ore (cluster 6).
Lithological and alteration labels, which refer to descriptive drill hole loggings of lithology and alteration, were not included into the actual SOM analysis since based on extensive preliminary analyses and also according to paper by Junno et al. (2019), labels added uncertainty to the interpretation, and therefore, geophysical, geotechnical and geochemical, that is continuous physical variables, were considered to give more reliable results.

5 RESULTS

We present results for a Self-Organizing Map (SOM) run consisting of above-mentioned geophysical, geotechnical and geochemical variables. After initial testing, a toroid SOM map and an SOM size of 48 × 40 were chosen. The SOM model presented here has an average quantization error of 0.70 and topological error of 0.12. A Davies–Bouldin analysis suggested a local minimum at 13 clusters, which was chosen for further interpretation. The SOM results are interpreted based on the theoretical modelling presented in Section 3.1. The lithology and alteration labels for each cluster were checked after the SOM run and are presented in the confusion matrices shown in Tables 6 and 7, respectively.

5.1 The cause of reflectivity within the Kevitsa intrusion

The component plots for the Self-Organizing Map (SOM) run are shown in Fig. 7. Altogether 13 clusters were defined within the data, including five clusters interpreted as barren olivine pyroxenites (clusters 1a, 1b, 1c, 1d and 1e; Table 5), and four clusters for mineralization (clusters 4a, 4b, 5a and 5b; Table 5). The lithology and alteration were checked for these clusters after the analysis (Tables 6 and 7, respectively). Clusters 1a, 1b, 1c, 1d and 1e correspond to different olivine pyroxenite variants, whereas clusters 4a, 4b, 5a and 5b correspond mainly to olivine pyroxenite (Table 6). Clusters 5a and 5b are associated with the highest Ni and Cu concentrations, as well as low electrical resistivity and high induced polarization (IP) effect (Table 5 and Fig. 7). Cluster 5b is associated with low rock quality designation and, thus, the lowest seismic velocity and density values (Fig. 7 and Table 5). Clusters 4a and 4b are associated with medium Ni and Cu concentrations. Cluster 4a relates to low electrical resistivity and high IP effect, whereas cluster 4b relates to high electrical resistivity and low IP effect. Clusters 4a and 4b relate to higher seismic velocity than that of clusters 5a and 5b (Fig. 8). Cluster 4a and 4b are interpreted to represent transitional ore, and clusters 5a and 5b are interpreted to represent regular ore. These ore

| Cluster | Vp (m/s) | SG (kg/m²) | Impedance (106 kg/m²/s) | RQD (pct) | N | Ni (pct) | Cu (pct) | Au (ppb) | Pt (ppb) | Pd (ppb) | Interpretation |
|---------|---------|-----------|------------------------|----------|----|---------|---------|---------|---------|---------|----------------|
| 1a      | 7396    | 3229      | 24                     | 96       | 16 | 0.06    | 0.05    | 13      | 31      | 16      | 21,852 Olivine pyroxenites (barren; unaltered) |
| 1b      | 7014    | 3160      | 22                     | 94       | 18 | 0.07    | 0.06    | 11      | 29      | 14      | 7367 Olivine pyroxenites (barren; altered) |
| 1c      | 6819    | 3098      | 21                     | 90       | 22 | 0.05    | 0.03    | 11      | 29      | 14      | 6717 Olivine pyroxenites (barren; altered) |
| 1d      | 6643    | 3096      | 20                     | 86       | 28 | 0.11    | 0.07    | 13      | 44      | 28      | 6748 Olivine pyroxenites (barren; altered) |
| 1e      | 6192    | 2993      | 19                     | 94       | 49 | 0.18    | 0.28    | 54      | 91      | 49      | 162464 Olivine pyroxenites (barren; altered) |
| 4a      | 6847    | 3188      | 22                     | 92       | 98 | 0.18    | 0.28    | 54      | 91      | 49      | 6416 Transitional ore |
| 4b      | 6776    | 3184      | 22                     | 92       | 98 | 0.26    | 0.30    | 92      | 152     | 92      | 4288 Transitional ore |
| 5a      | 6479    | 3220      | 21                     | 95       | 95 | 0.36    | 0.44    | 92      | 152     | 92      | 4755 Regular ore |
| 5b      | 5022    | 3110      | 16                     | 92       | 92 | 0.44    | 0.44    | 92      | 152     | 92      | 4288 Regular ore |
| 6       | 5462    | 3156      | 17                     | 84       | 84 | 0.33    | 0.38    | 48      | 95      | 92      | 241738 Veins, dikes and olivine pyroxenites (False ore) |
| 7       | 6275    | 3174      | 15                     | 84       | 84 | 0.33    | 0.38    | 48      | 95      | 92      | 1538 Central Dunite and low RQD |
| 8       | 5400    | 3240      | 15                     | 84       | 84 | 0.33    | 0.38    | 48      | 95      | 92      | 241738 Central Dunite and low RQD |
| 9       | 7041    | 3031      | 21                     | 92       | 92 | 0.13    | 0.08    | 39      | 92      | 92      | 1783 Host and olivine pyroxenites (barren; altered) |

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| Lithological Group | Cluster 1a | Cluster 1b | Cluster 1c | Cluster 1d | Cluster 1e | Cluster 4a | Cluster 4b | Cluster 5a | Cluster 5b | Cluster 6 | Cluster 7 | Cluster 8 | Cluster 9 |
|-------------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| Olivine pyroxenite variants (OLPXs) | 59.59 | 49.25 | 35.09 | 45.45 | 25.13 | 56.87 | 68.33 | 71.69 | 67.09 | 48.44 | 17.84 | 13.33 | 30.85 |
| Olivine websterite | 21.74 | 22.00 | 15.35 | 9.04 | 14.19 | 6.98 | 2.96 | 0.84 | 0.36 | 2.08 | 9.96 | 4.29 | 7.63 |
| Plag.-bearing olivine websterite | 7.75 | 7.90 | 9.16 | 7.90 | 2.87 | 9.16 | 7.90 | 9.16 | 7.90 | 2.87 | 9.16 | 7.90 | 9.16 |
| Pyroxenite | 21.74 | 22.00 | 15.35 | 9.04 | 14.19 | 6.98 | 2.96 | 0.84 | 0.36 | 2.08 | 9.96 | 4.29 | 7.63 |
| Websterite | 7.75 | 7.90 | 9.16 | 7.90 | 2.87 | 9.16 | 7.90 | 9.16 | 7.90 | 2.87 | 9.16 | 7.90 | 9.16 |
| Total OLPXs | 93.08 | 93.02 | 95.30 | 95.27 | 75.96 | 91.44 | 97.32 | 92.13 | 88.24 | 73.01 | 83.40 | 37.91 | 76.56 |
| Other lithological groups | 2.21 | 2.05 | 1.16 | 0.46 | 1.17 | 0.42 | 0.76 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Central Dunite | 2.21 | 2.05 | 1.16 | 0.46 | 1.17 | 0.42 | 0.76 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Footwall Dunite | 0.22 | 1.44 | 0.28 | 1.19 | 2.05 | 2.77 | 0.98 | 2.73 | 0.36 | 0.35 | 0.00 | 1.76 | 1.51 |
| Gabbros | 0.73 | 0.46 | 0.89 | 0.73 | 1.36 | 0.51 | 0.44 | 0.35 | 0.15 | 2.10 | 7.27 | 0.00 | 0.34 |
| Veins, dykes | 0.87 | 0.90 | 0.15 | 0.96 | 3.89 | 0.55 | 0.12 | 0.48 | 0.27 | 5.54 | 8.30 | 2.41 | 1.29 |
| Host | 2.10 | 0.53 | 0.61 | 1.10 | 8.69 | 2.54 | 0.30 | 0.11 | 0.27 | 10.38 | 5.81 | 9.88 | 12.68 |
| Other | 0.43 | 1.10 | 0.57 | 0.28 | 1.61 | 1.93 | 0.82 | 3.64 | 5.38 | 3.46 | 2.49 | 4.75 | 1.40 |
| 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |

Table 7 Confusion matrix showing the percentage of different alteration labels within each cluster identified from the data

| Alteration | Cluster 1a | Cluster 1b | Cluster 1c | Cluster 1d | Cluster 1e | Cluster 4a | Cluster 4b | Cluster 5a | Cluster 5b | Cluster 6 | Cluster 7 | Cluster 8 | Cluster 9 |
|------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| Amphibolitic | 38.52 | 44.25 | 48.58 | 34.80 | 44.58 | 26.90 | 22.29 | 18.68 | 16.59 | 13.49 | 29.46 | 23.67 | 48.35 |
| No alteration label | 57.37 | 53.36 | 48.47 | 62.21 | 47.02 | 69.89 | 76.73 | 80.44 | 79.03 | 82.70 | 61.83 | 32.38 | 30.34 |
| Carbonate | 0.12 | 0.24 | 1.58 | 1.38 | 1.76 | 0.87 | 0.35 | 0.38 | 0.46 | 0.00 | 6.64 | 1.24 | 2.69 |
| Chloritic | 0.04 | 0.03 | 0.15 | 0.23 | 0.56 | 0.31 | 0.02 | 0.27 | 0.18 | 0.00 | 0.41 | 2.15 | 0.56 |
| Serpentinitic | 1.82 | 1.66 | 0.54 | 0.32 | 0.68 | 1.37 | 0.14 | 0.11 | 3.37 | 0.00 | 0.00 | 35.50 | 5.78 |
| Actinolitic | 0.38 | 0.04 | 0.33 | 0.60 | 1.36 | 0.02 | 0.05 | 0.00 | 0.00 | 0.35 | 0.00 | 1.37 | 1.40 |
| Albitic | 0.14 | 0.03 | 0.01 | 0.05 | 0.97 | 0.41 | 0.00 | 0.06 | 0.00 | 0.00 | 0.00 | 1.89 | 2.36 |
| Silicous | 1.24 | 0.00 | 0.04 | 0.00 | 0.42 | 0.11 | 0.00 | 0.06 | 0.00 | 0.00 | 1.24 | 0.39 | 1.79 |
| Biotite | 0.24 | 0.00 | 0.03 | 0.18 | 1.81 | 0.12 | 0.00 | 0.00 | 0.00 | 2.08 | 0.41 | 0.59 | 0.22 |
| Tad-carbonate | 0.01 | 0.37 | 0.27 | 0.00 | 0.40 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.06 |
| Epidote | 0.08 | 0.03 | 0.00 | 0.14 | 0.40 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Talc | 0.02 | 0.00 | 0.00 | 0.09 | 0.05 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.85 | 6.45 |
| 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |
Figure 8  P-wave velocity versus density (SG) for the different clusters defined in Fig. 7. The solid black curves correspond to constant acoustic impedance, and the difference between two curves represents a detectable reflection (reflection coefficient equal to 6%; Salisbury et al. 1996; Salisbury et al. 2003). The black solid and dashed arrows show the effect of alteration and the combined effect of alteration and sulphide mineralization, respectively, based on modelling of reflectivity properties discussed in Section 3.1.

classes are similar to the division suggested by Mutanen (1997) and Gregory et al. (2011). The barren olivine pyroxenites divide into five clusters (clusters 1a, 1b, 1c, 1d and 1e; Fig. 7). The seismic velocity and density decreases from cluster 1a to clusters 1b, 1c, 1d and 1e with highest seismic velocity and density values associated with cluster 1a (Fig. 8). The percentage of metaperidotite, that is amphibole-altered olivine pyroxenites, increases from cluster 1a and 1b to clusters 1c, 1d and 1e (Table 6), that is lower seismic velocities seem to be associated with alteration (see Section 3.1). This is also evident in Table 7, where the percentage of logged amphibole alteration is higher for clusters 1b, 1c and 1e than for cluster 1a. However, it should be noted that the percentage for the ‘no alteration label’ is also high for these clusters. The lack of alteration label does not mean that the samples within these clusters are unaltered but simply indicates missing information on the alteration field. In addition, higher magnetic susceptibility, lower electrical resistivity and higher IP effect associated with clusters 1b, 1c and 1d are indicators of alteration. As evident in Fig. 8, unmineralized olivine pyroxenite (especially cluster 1a) is associated with higher seismic velocities than mineralized rock, but the density does not seem to differ much for the mineralized (clusters 4a, 4b and 5a) and barren (cluster 1a) clusters (Fig. 8). High Ni–PGE ore (cluster 6; Fig. 7) is also identified in the SOM run.

Figure 9 illustrates the three-dimensional (3D) spatial distribution of cluster 1a, representing unaltered, barren olivine pyroxenites, and cluster 1e, representing altered, barren olivine pyroxenites. These two clusters could produce an impedance contrast creating a reflection coefficient of about 13%. Most of the borehole data sit above 500 m depth, beneath which the observed continuous strong reflectivity in the 3D seismic data in Fig. 2 starts (Fig. 9). The two clusters with different average acoustic impedances alternate in the boreholes at these depths, and could cause the observed reflectivity. However, with the sparse borehole sampling, it is not possible to make definite conclusions about the continuity of the borehole layers with regard to the seismic data.

5.2 Other possible causes of reflectivity within and around the Kevitsa intrusion

In addition to alteration and mineralization, the other possible causes of reflectivity within the Kevitsa intrusion are the
fracture and fault zones, dunite fragments and country rock occurrences internal to the intrusion, as well as dykes and veins. The fracture and fault zones and their expressions in the 3D seismic data have previously been extensively discussed by Malehmir et al. (2012b), Koivisto et al. (2015) and Lindqvist et al. (2017). Additionally, recently traveltime tomography using the first break picks of the Kevitsa threedimensional (3D) seismic reflection data (Malehmir et al. 2018) provided an improved coverage at shallow depths, allowing a link between a major brittle structure observed in the 3D seismic data (Koivisto et al. 2015; Lindqvist et al. 2017) and surface observations. This structure is critical for mine planning and extends down to approximately 600 m with a lateral extent of more than 1000 m. However, fault and fracture zones, dunite fragments, country rock slabs or dykes and veins are not expected, at least based on the currently available data sets, to be the causes for the continuous, nearly horizontal reflections observed in the 3D seismic reflection data.

The Footwall Dunite unit is associated with high seismic velocity and density (Table 1). It is clearly visible in the 3D seismic reflection data and forms a lens like body at the basal contact of the intrusion (Koivisto et al. 2015). Low velocities and densities are associated with the thoroughly serpentinized Central Dunite (cluster 8; Table 5), which is clearly identifiable in the 3D seismic reflection data (Koivisto et al. 2015). The host rocks of the intrusion (metavolcanics and metasediments) are associated with the lowest seismic velocity and density values (clusters 6 and 9; Table 5) resulting in reflection coefficients of about 6–18% in contrast with barren olivine pyroxenites, and the basal contact of the intrusion to the host rocks is in fact the most prominent reflector in the area (Koivisto et al. 2012; Koivisto et al. 2015).

6 DISCUSSION AND CONCLUSIONS

The Self-Organizing Map (SOM) analysis of the Kevitsa borehole data, combined with theoretical modelling of the petrophysical properties of the Kevitsa rock types and ore, provides new insights into the origin of the observed reflectivity within the Kevitsa intrusion, and into its relationship to the Kevitsa disseminated sulphide mineralization. Koivisto et al. (2012), Koivisto et al. (2015) and Malehmir et al. (2012b, 2014) have previously suggested that contacts between the plagioclase-bearing olivine websterite tops and olivine pyroxenite bottoms (with increased sulphide mineralization) of smaller scale, internally differentiated magma layers might be the cause of reflections within the Kevitsa resource area. However, this interpretation is not unequivocally supported by the borehole data (Koivisto et al. 2015), since only little plagioclase-bearing olivine websterite is logged from the borehole data to trace such continuous lithological contacts (Gregory et al. 2011; Le Vaillant et al. 2016; Luolavirta et al. 2018a). Our current study similarly does not support that earlier interpretation.

The theoretical modelling of the effect of sulphide mineralization and alteration on the reflectivity properties of the Kevitsa rock types and ore (Fig. 5) suggests that the disseminated sulphide mineralization alone is not enough to produce reflections, but combining mineralization with the effect of alteration (amphibole and serpentinite) could produce observable reflections when in contact with unaltered and unmineralized zones. However, alteration products play the main role in determining the reflectivity characteristics of the olivine pyroxenite variants of the Kevitsa intrusion, and hence, altered, but unmineralized olivine pyroxenites in contact with unaltered, unmineralized olivine pyroxenites may also produce prominent reflections in the area.

The SOM results indicate that the regular ore zones are associated with lower seismic velocities and can be reflective when in contact with unmineralized and unaltered olivine pyroxenites (Fig. 8). Furthermore, the SOM results indicate that the mineralized zones are associated with alteration, which is, according to the theoretical calculations, needed in order to
produce detectable reflections. Since, the main mineralization (i.e. the regular ore) in Kevitsa occurs as continuous bodies extending up to hundreds of meters in diameter (Mutanen 1997), altered and mineralized zones could be the cause of observed reflectivity beneath the known deposit. Due to poor data quality at shallow depths, the 3D seismic data does not show any reflectivity at the depths of the known deposit. Nevertheless, we argue that the deeper, horizontal to gently dipping reflections are potential exploration targets in the area. It should, however, be noted again that the SOM results also indicate that unmineralized but altered olivine pyroxenites in contact with unmineralized and unaltered olivine pyroxenites could be the cause of reflections in the seismic data (Figs 8 and 9).

The origin of sulphur in the Kevitsa ore has been attributed to host rock contamination which took place by incorporation of metasedimentary material in the ultramafic magma (Mutanen 1997; Standing et al. 2009). Adding sulphur to the magma would have facilitated the crystallization of Ni and Cu in the sulphide phase instead of the silicate phase. Host rock contamination is also supported by the presence of graphite as the metasedimentary host rocks are (partly) sulphide-bearing carbonaceous black schists. In the case of host rock contamination, volatile components (S, C, H₂O, Cl), as well as other elements typical for metasediments (e.g. Al, Na, K and Si), would have been mixed in the crystallizing magma. Traces of these are reported by Mutanen (1997). Water provided by the host rock contamination is a necessary component in the alteration reactions, and it is feasible to think that the alteration started immediately after crystallization of the mafic minerals and continued until relatively low temperatures. The contamination model predicts that the ore mineral content should correlate with alteration.

According to Mutanen (1997), the main part of the intrusion was only marginally affected by contaminants and evolved autonomously. Here we pay attention to the observation by Standing et al. (2009) that compositional heterogeneity and variation, interpreted as smaller scale magmatic layering, could not be detected outside the Kevitsa resource area and, further, that the horizontal to gently dipping reflections are constrained mainly to the Kevitsa resource area (Koivisto et al. 2015). Therefore, a plausible hypothesis is that the formation of the ore deposit was controlled by the availability of contaminants and, where available, crystallization of the metals took place in the sulphide phase, and the ambient magmatic rock was also altered accordingly. The model allows for cyclic intrusions of several pulses of magma, but the final composition and mineralization would have depended on the availability of sulphur, volatiles and other contaminants from the host rock. As a result, the reflectivity would be a useful proxy for the mineralized and altered rocks in a less-altered environment.

Interpreting the deeper reflections observed in the 3D seismic data as altered and possibly mineralized zones would require that the mineralized and altered zones are somehow layered. Such a layering would be a natural result of adding cyclic, contaminated magma pulses to the intrusion. Thus, the observed reflectivity might originate from the altered pulses that could be associated with higher sulphide content (although this is not seismically required) in contact with less-altered unmineralized parts of the intrusion. However, as currently there is no understanding of the detailed distribution of alteration within the Kevitsa resource area, future work is required to further understand the relationship between the mineralization and alteration in detail.

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