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RESEARCH ARTICLE

Post-VMS mineralization deformations (1880–1820 Ma) of the Skellefte district (Sweden): insights from the spatial pattern of VMS occurrences

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Abstract In the last two to three decades or so, the spatial pattern of mineral occurrences of a deposit-type has been studied to derive insights to mineralization controls and assist mineral exploration. In the Skellefte district, Fry plots of volcanogenic massive sulfide (VMS) mines/prospects reveal patterns that are likely due to post-mineralization deformation events. The fractal dimensions of the spatial patterns of the present-day VMS mines/prospects and that of the 'original' VMS deposits support the concept that spatial patterns of mineral deposits are spatially-invariant. Therefore, analysis of the spatial pattern of mineral deposits is useful not only in research about pre- and syn-mineralization geological settings but also post-mineralization geological settings.

Keywords fractal, Fry analysis, mineral deposits, structural history, orogenic belts

1 Introduction

The spatial pattern of known occurrences of a mineral deposit-type provides insights to geological controls on mineralization (cf. Carlson, 1991; Cheng and Agterberg, 1995; Vearncombe and Vearncombe, 1999; Weinberg et al., 2004; Raines, 2008; Carranza, 2009a; Zuo et al., 2009a). However, the present-day spatial pattern of mineral occurrences of a deposit-type is the product of pre-, syn- and post-mineralization deformation events. Therefore, it can be hypothesized that, in the analysis of the structural history of ancient orogenic belts, mineral deposits are useful markers of deformation events. In this paper, we demonstrate, in the Skellefte district (SD) of Sweden, that analysis of the spatial pattern of mineral occurrences of a deposit-type can be useful to infer post-mineralization geological settings.

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2 Skellefte district

The discussions of the geology and mineralization of the SD given below are summarized from Carranza and Sadeghi (2010).

The SD (Fig. 1), according to early researchers (e.g., Weihed et al., 1992; Allen et al., 1996; Billström and Weihed, 1996; Nironen, 1997), is a volcanic arc that was formed during the Svecofennian period in a zone situated between a Proterozoic sedimentary basin to the south and an Archean craton to the north. Now it is regarded by many recent researches (e.g., Allen et al., 2002; Juhlin et al., 2002; Weihed et al., 2005) as a part of a strongly extensional Palaeoproterozoic intra-arc region developed on a mature arc or continental crust overlying a subduction zone that dipped to the north and was later accreted to the Archean continent after about 1870 Ma. Some recent researchers (e.g., Rutland et al., 2001a, b; Skiöld and Rutland, 2006) argue, however, that the formation of the Skellefte volcanic arc took place in a rift setting on a pre-1900 Ma basement complex with original rocks emplaced in a back-arc marginal basin, which were accreted in an early episode of deformation. Notwithstanding which hypothesis is true, the ancient geological environment of SD was permissive for volcanogenic massive sulfide (VMS) mineralization (cf. Galley et al., 2007).

There are more than 80 polymetallic mineral occurrences in the SD and most of them have been classified as VMS deposits, which are typically stratabound, pyritic, base-metal-rich mineralizations hosted mostly in younger felsic volcanic rocks of the Skellefte Group (cf. Rickard

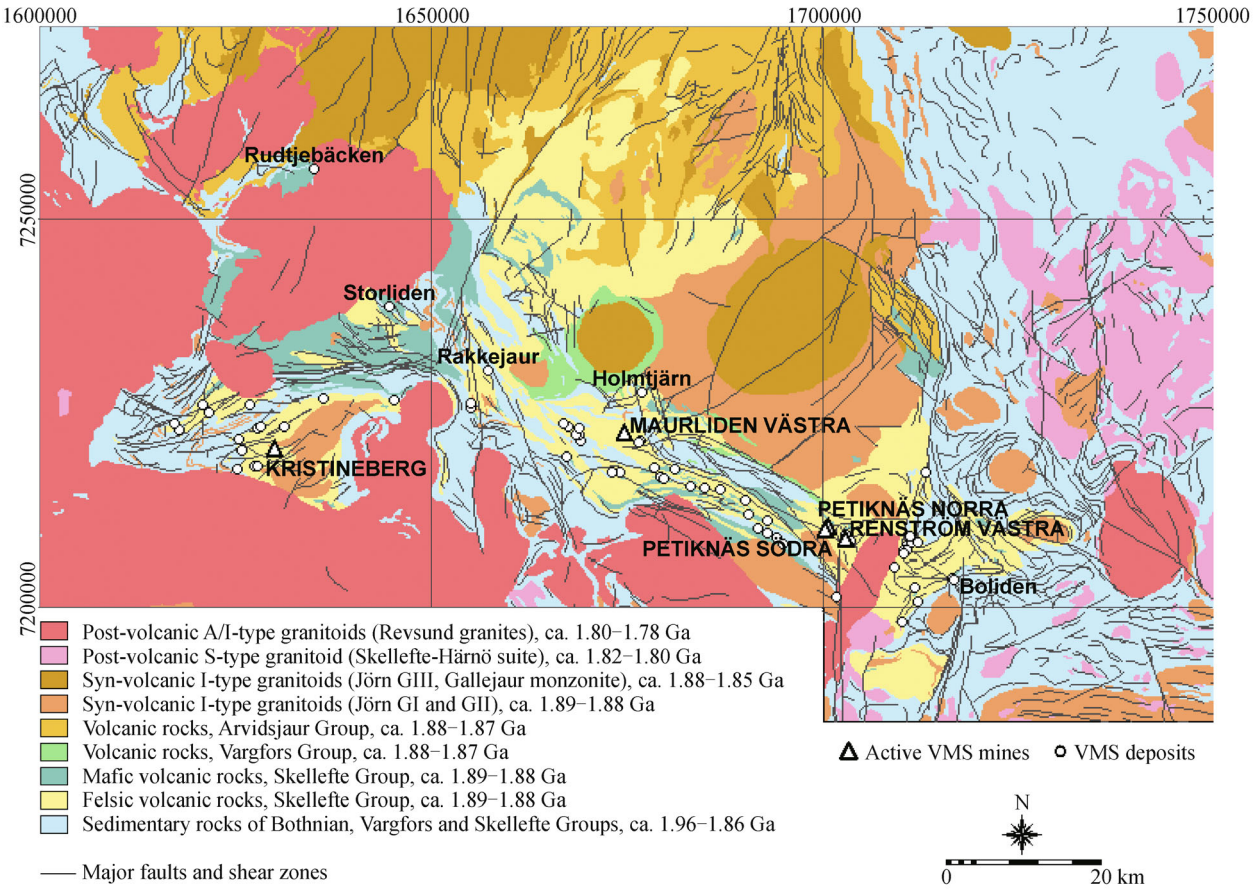

Fig. 1 Skellefte district: simplified geological map (adapted from Kathol and Weihed, 2005) and the locations of VMS mines/deposits. Map coordinates are in meters (Swedish RT90 coordinate system).

and Zweifel, 1975; Weihed et al., 1992; Allen et al., 1996; Billström and Weihed, 1996). The internal stratigraphy of the Skellefte Group, with a total thickness of at least 3 km, is extremely variable but it consists mainly of volcanic rocks of dacitic-rhyolitic compositions with intercalations of volcanic rocks of andesitic-basaltic compositions in the upper parts of the volcanic pile (Allen et al., 1996). Radiometric ages of 1890–1880 Ma have been obtained from the Skellefte Group volcanic rocks (Welin, 1987; Billström and Weihed, 1996; Weihed et al., 2002). It has been proposed that the formation of all the VMS deposits took place within less than 10 Ma through a period of intense extensional arc volcanism that resulted in the formation of the Skellefte Group (Allen et al., 1996). It has been further proposed that the formation of most of the VMS deposits likely took place in the second half (i.e., 1885–1880 Ma) of the 10 Ma age interval for the emplacement of the Skellefte Group (Billström and Weihed, 1996). Some VMS deposits are hosted in basal sedimentary rocks of the overlying Vargfors Group (cf. Rickard and Zweifel, 1975; Allen et al., 1996), but those are linked with the Skellefte volcanism as this lasted through the formation of the early Vargfors sedimentary rocks (Allen et al., 1996).

Prior to the formation of the Skellefte Group, the earliest Svecokarelian deformation-metamorphism (D1) occurred before about 1910 Ma (Rutland et al., 2001a, b; Skiöld and Rutland, 2006). During the Svecofennian (or Svecokarelian) orogeny in 1900–1800 Ma, the D2 and D3 deformation events have affected the pre-existing rocks and mineralizations (Lundberg, 1980; Weihed et al., 1992; Allen et al., 1996; Bergman Weihed, 2001). Structures linked with D1 were overprinted by structures linked with D2 and/or D3, in some parts of the SD. The compressional D2 deformation is constrained between 1879 and 1867 Ma (Skyttä et al., 2012). The D3 E–W shortening likely occurred during 1870–1820 Ma (Bergman Weihed, 2001). It follows that pre-, syn- and post-mineralization deformation events have affected the present-day spatial pattern of VMS occurrences in the SD.

3 Spatial pattern analysis

For the analysis of the spatial pattern of occurrences of a mineral deposit-type, the two mostly used methods are fractal analysis (Carlson, 1991; Cheng and Agterberg, 1995; Weinberg et al., 2004; Carranza, 2009a; Zuo et al.,

2009a) and Fry analysis (Vearncombe and Vearncombe, 1999; Stubley, 2004; Carranza, 2009a). We applied both of these methods to 69 mines/prospects classified as VMS deposits by the Geological Survey of Sweden (Fig. 1).

3.1 Fractal analysis

A fractal is a pattern made up of parts with geometries, aside from size or scale, which are similar to the whole pattern (Mandelbrot, 1982). The fractal dimension (D) of the spatial pattern of a set of points can be quantified by the box-counting method. In a GIS, this entails making raster maps of deposit occurrences using various pixel sizes (δ) and then counting in every raster map the number of pixels with one or more deposits [$n(\delta)$]. The values of δ and the matching values of $n(\delta)$ are plotted on a log–log graph. Every line segment fitted by least-squares regression through the plots can be described by a power–law equation as $n(\delta) = C\delta^{-D}$ (Mandelbrot, 1985), where C is the constant of proportionality between $n(\delta)$ and δ, and the box-count fractal dimension D varies between 0 and 2.

The smallest δ that contains at least one VMS mine/prospect, which is 0.2 km (Fig. 2), was determined using locations of all the known VMS mines/prospects in the SD and the method for objective selection of suitable unit cell size in data-driven modeling of mineral prospectivity (Carranza, 2009b). Then, the spatial pattern of the VMS mines/prospects has three box-count fractal dimensions (Fig. 2(a)): (a) for δ of at most 1 km, D is 0.07; (b) for δ ranging from 1 to 8 km, D is 0.44; and (c) for δ of at least 8 km, D is 0.98. These are interesting results because most, if not all, previous researches in this subject (e.g., Carlson, 1991; Cheng and Agterberg, 1995; Weinberg et al., 2004; Raines, 2008; Carranza, 2009a; Zuo et al., 2009a, b) have reported that the spatial patterns of certain types of mineral deposits have two – a local-scale and a regional-scale – box-count fractal dimensions (Agterberg et al., 1993). However, the line segment for δ of at most 1 km (Fig. 2(a)) likely implies "roll-off" effect (Blenkinsop and Sanderson, 1999), which can be due to (a) portrayal of mineral occurrences as points in regional-scale maps, (b) omission of small mineral occurrences around mines/prospects from the analysis or (c) the existence of undiscovered mineral occurrences. Yet, even if the hypothesis of roll-off is true, the D of the line segment in the middle of the plot (Fig. 2 (a)) implies that VMS mines/prospects in the SD form clusters within spatial scales of at most 8 km whereas the D of the bottom line segment implies that clusters of VMS mines/prospects in SD follow linear trends within spatial scales of at least 8 km.

The VMS mines/prospects hosted in felsic volcanic rocks of the Skellefte Group are situated within 9 km of each other (Carranza and Sadeghi, 2010). Therefore, at spatial scales of at most 8 km, the clustering of VMS mines/prospects in the SD can be linked to discrete (mostly felsic) vent areas or volcanic centers within the Skellefte Group (cf. Lundberg, 1980; Vivallo, 1987; Weihed et al., 1992; Allen et al., 1996). At spatial scales of at least 8 km, the alignment of clusters of VMS mines/prospects in the SD can be linked to the mainly WNW–ESE linear trend of the volcanic rocks of the Skellefte Group and/or to WNW- and ENE-trends of major shear zones and faults cutting the volcanic rocks of the Skellefte Group (Fig. 1).

3.2 Fry analysis

This is a geometrical method of spatial autocorrelation analysis of a type of point objects (Fry, 1979). It entails translations (also known as Fry plots) of point objects whereby every point object is used as translation origin (Vearncombe and Vearncombe, 1999). Subtle patterns in the spatial pattern of point objects can be enhanced in a Fry plot, whereas trends in the spatial pattern of point objects can be described by orientations and distances between pairs of Fry points. To analyze trends of any two neighboring deposits, it is edifying to use the shortest

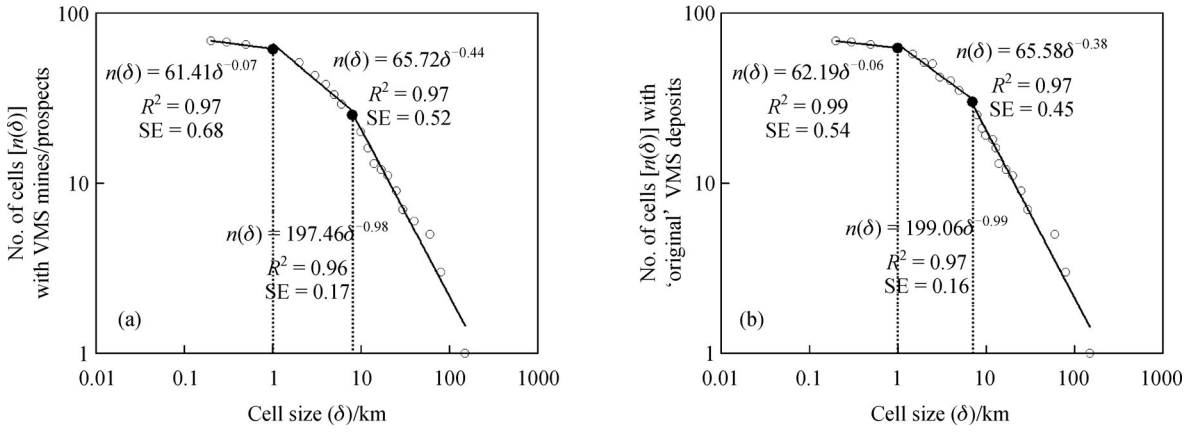

Fig. 2 Box-count fractal analyses of the spatial patterns of (a) VMS mines/prospects and (b) 'original' VMS deposits (Fig. 3(a)). Black dots represent breakpoints of fitted lines, R^2 is coefficient of regression and SE is standard error.

distance within which there is highest likelihood of one deposit occurrence next to any other deposit (Carranza, 2009a).

Three *en echelon* and evenly spaced WNW-trending corridors with an average width of about 10 km describe the Fry plots of the VMS mines/prospects (Fig. 3(a)). The trends and widths of the corridors of Fry points are likely due, respectively, to the WNW trend and the roughly 10 km average map width of the felsic volcanics of the Skellefte Group in the middle parts of the SD where most of the known VMS deposits exist (Fig. 1). All pairs of Fry points of the VMS mines/prospects show a major WNW–ESE trend (90°–120° or 270°–300°), which is likely due to the mainly WNW-trending volcanic rocks of the Skellefte Group and/or to the WNW-trending major shear zones and faults cutting the volcanic rocks of the Skellefte Group (Fig. 1). For pairs of Fry points within the shortest distance (20 km) where there is highest likelihood of a neighbor VMS mine/prospect next to any one of the VMS mines/prospects (Fig. 3(a)), there is a subsidiary NNE–SSW trend (0–20° or 180°–200°). This is likely linked to fault controls on VMS mineralization at spatial scales of at most 8 km defined from the box-count fractal analysis.

4 Discussion and conclusions

Carranza and Sadeghi (2010) have discussed the implications of the results of box-count fractal analysis and Fry analysis of the VMS mines/prospects in the SD terms of mineralization controls and prospectivity for undiscovered VMS deposits. Here, the focus of the discussion is on three WNW-trending corridors of Fry points (Fig. 3(a)), which require explanation because there are no obvious patterns in the geological map (Fig. 1) that readily explain their even spacing and *en echelon* formation. We propose and illustrate (Fig. 4) that these patterns in the Fry plots are likely due to post-VMS-mineralization events as discussed below.

During and immediately after the formation of most of the VMS deposits within 1885–1880 Ma (Billström and Weihed, 1996), the southern parts of the Skellefte Group volcanics likely had a continuous WNW-trend and, thus, there was a straight WNW-trending corridor of ‘original’ VMS deposits (Fig. 4(a)). Then, during the D2 deformation phase (1880–1860 Ma), the oblique NW-directed convergence (Bergman Weihed, 2001) likely resulted in a major NW-trending fault or shear zone cutting through the WNW-trending parts the Skellefte Group volcanics (Fig. 4(b)). Rocks to the west of the major NW-trending fault or shear zone moved and rotated counter-clockwise, whereas rocks to the east of this fault stayed because they were obstructed by the Jörn batholith (cf. Bergman Weihed, 2001). Thus, the western parts of the Skellefte Group volcanics was dismembered and its trend became approximately E–W. Finally, during the D3 deformation

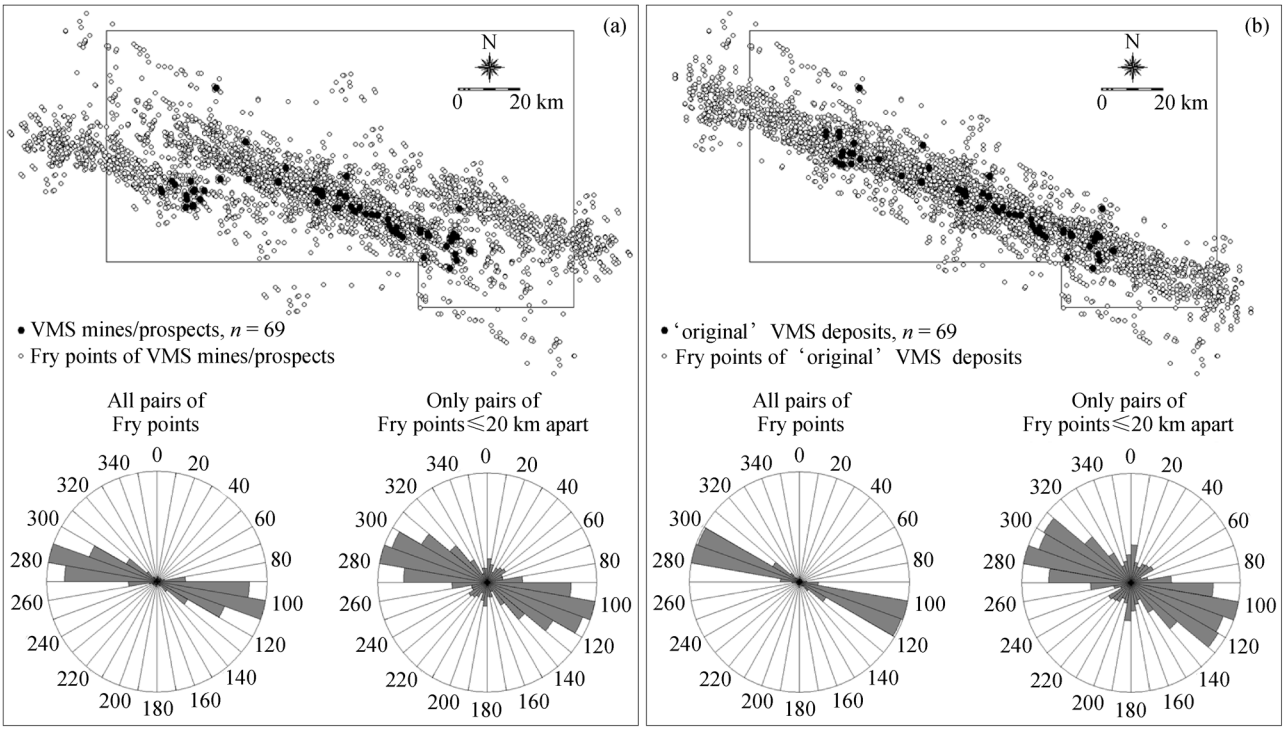

Fig. 3 Fry analyses of (a) VMS mines/prospects and (b) ‘original’ VMS deposits (Fig. 4(a)). The distance of either 20 km in (a) or 16 km in (b), determined through point pattern analysis (Boots and Getis, 1988), is minimum distance within which there is maximum probability of one deposit next to any other deposit in each set of VMS occurrences.

phase (1870–1820 Ma), the E–W shortening (Bergman Weihed, 2001) resulted in further counter-clockwise rotation of the rocks in the southwestern portion of the Skellefte such that the trend of western parts of the Skellefte Group volcanics became approximately ENE (Fig. 4(c)).

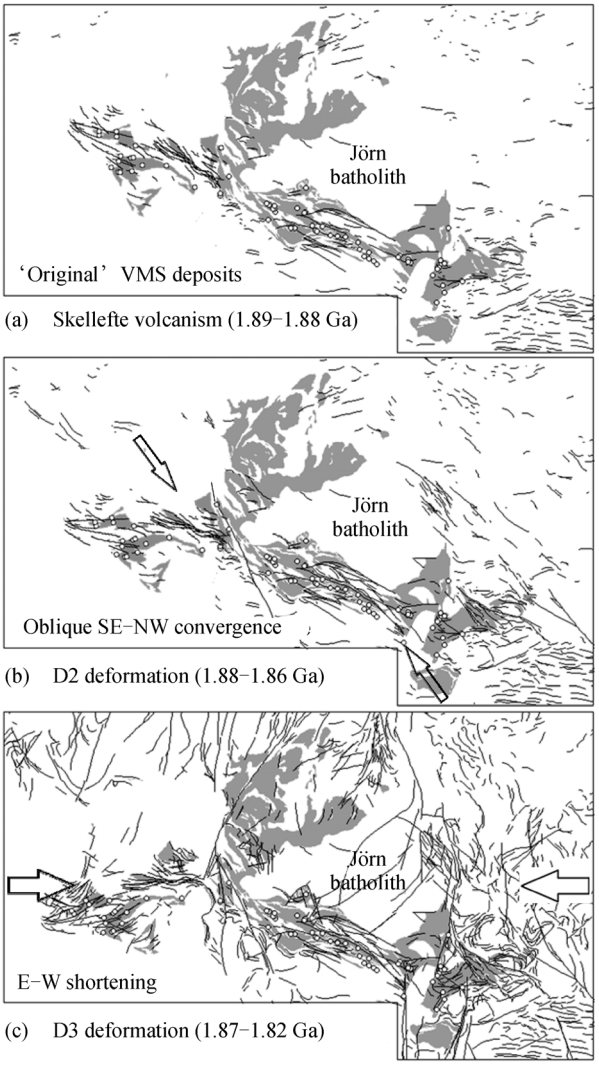

Fig. 4 Hypothesized 'original' VMS deposit locations (small open circles) and post-VMS-mineralization deformations (portrayed by arrows) in the Skellefte district. See text for explanation. Linear features are major faults and/or shear zones, whereas grey-shaded areas are Skellefte Group felsic volcanics, which are used for spatial reference only.

We found that the box-count fractal dimensions of the spatial pattern of 'original' VMS deposits (Fig. 2(b)) are strongly similar to those of the spatial pattern of the present-day VMS mines/prospects (Fig. 2(a)). This is interesting because it supports the concept that mineral deposits are fractals (cf. Turcotte, 1997), meaning that their geometrical and topological properties are spatially-invariant even after deformation (or spatial transformation). In addition, the 'original' VMS deposits result in one WNW-trending corridor of Fry points (Fig. 3(b)), which can be explained by a straight WNW-trending zone of extension faults where volcanism with accompanying VMS mineralization ensued. These results of spatial analyses support our hypothesis of a straight WNW-trending corridor of 'original' VMS deposits prior to D2 (Fig. 3(a)).

Our explanation for the *en echelon* and evenly-spaced WNW-trending corridors in the Fry plots of the whole set and subsets of VMS deposits in the SD can be supported further by results of recent researches. Firstly, based on magnetic fabrics, Skyttä et al. (2010, p. 1134) proposed a strongly similar schematic model of post-VMS mineralization deformations in the SD. Secondly, new zircon data for igneous activity at about 1890 Ma in the western SD (Skyttä et al., 2011) supports the notion of a laterally (sub)continuous volcanic belt that was later split and deformed by tectonic events as proposed by Skyttä et al. (2010). Therefore, analysis of the spatial pattern of mineral deposits provides stimulus as well as adjunct information in research regarding not only pre- and syn-mineralization geological settings but also post-mineralization geological settings. The results presented here are a great example of using mineral deposit distributions to derive geological insights for reconstruction of structural/tectonic histories of orogenic belts.

References

Agterberg F P, Cheng Q, Wright D F (1993). Fractal modeling of mineral deposits. In: Proceedings APCOM Symposium, 24th, Canadian Institute of Mining, Metallurgy, and Petroleum Engineers, volume 1, Montreal: Canadian Institute of Mining, Metallurgy and Petroleum Engineering, 43–53

Allen R L, Weihed P, and the Global VHMS Research Project Team (2002). Global comparison of volcanic-associated massive sulphide districts. In: Blundell D J, Neubauer F, Von Quadt A, eds. The Timing and Location of Major Ore Deposits in an Evolving Orogen. London: Geological Society [London] Special Publications 204, 13–37

Allen R L, Weihed P, Svenson S Å (1996). Setting of Zn-Cu-Au-Ag massive sulfide deposits in the evolution and facies architecture of a 1.9 Ga marine volcanic arc, Skellefte district, Sweden. Econ Geol, 91 (6): 1022–1053

Bergman Weihed J (2001). Palaeoproterozoic deformation zones in the Skellefte and Arvidsjaur areas, northern Sweden. In: Weihed P, ed. Economic Geology Research, volume 1, 1999–2000. Uppsala: Sveriges Geologiska Undersökning Research Paper C 833, 46–68

Billström K, Weihed P (1996). Age and provenance of host rocks and ores in the Paleoproterozoic Skellefte District, northern Sweden. Econ Geol, 91(6): 1054–1072

Blenkinsop T G, Sanderson D (1999). Are gold deposits in the crust

fractals? A study of gold mines in the Zimbabwe craton. London: Geological Society [London] Special Publications, 155: 141–151

Boots B N, Getis A (1988). Point Pattern Analysis. Sage University Scientific Geography Series, No. 8. Beverly Hills: Sage Publications

Carlson C A (1991). Spatial distribution of ore deposits. Geology, 19(2): 111–114

Carranza E J M (2009a). Controls on mineral deposit occurrence inferred from analysis of their spatial pattern and spatial association with geological features. Ore Geol Rev, 35(3–4): 383–400

Carranza E J M (2009b). Objective selection of suitable unit cell size in data-driven modeling of mineral prospectivity. Comput Geosci, 35 (10): 2032–2046

Carranza E J M, Sadeghi M (2010). Predictive mapping of prospectivity and quantitative estimation of undiscovered VMS deposits in Skellefte district (Sweden). Ore Geol Rev, 38(3): 219–241

Cheng Q, Agterberg F P (1995). Multifractal modeling and spatial point processes. Math Geol, 27(7): 831–845

Fry N (1979). Random point distributions and strain measurement in rocks. Tectonophysics, 60(1–2): 89–105

Galley A G, Hannington M D, Jonasson I R (2007). Volcanogenic massive sulphide deposits. In: Goodfellow W D, ed. Mineral Deposits of Canada: A Synthesis of Major Deposit-Types, District Metallogeny, the Evolution of Geological Provinces, and Exploration Methods. Montreal: Geological Association of Canada, Mineral Deposits Division, Special Publication No. 5, 141–161

Juhlin C, Elming S Å, Mellqvist C, Öhlander B, Weihed P, Wikström A (2002). Crustal reflectivity near the Archaean-Proterozoic boundary in northern Sweden and implication for the tectonic evolution of the area. Geophys J Int, 150(1): 180–197

Kathol B, Weihed P (2005). Description of Regional Geological and Geophysical Maps of the Skellefte District and Surrounding Areas. Uppsala: Sveriges Geologiska Undersökning Ba 57

Lundberg B (1980). Aspects of the geology of Skellefte field, northern Sweden. Geol Foren Stockh Forh, 102(2): 156–166

Mandelbrot B B (1982) The Fractal Geometry of Nature. New York: Freeman

Mandelbrot B B (1985). Self-affine fractals and fractal dimension. Phys Scr, 32(4): 257–260

Nironen M (1997). The Svecofennian Orogen: a tectonic model. Precambrian Res, 86(1–2): 21–44

Raines G L (2008). Are fractal dimensions of the spatial distribution of mineral deposits meaningful? Nat Resour Res, 17(2): 87–97

Rickard D T, Zweifel H (1975). Genesis of Precambrian sulfide ores, Skellefte District, Sweden. Econ Geol, 70(2): 255–274

Rutland R W R, Kero L, Nilsson G, Stølen K (2001a). Nature of a major tectonic discontinuity in the Svecofennian province of northern Sweden. Precambrian Res, 112(3–4): 211–237

Rutland R W R, Skiöld T, Page R W (2001b). Age deformation episodes in the Palaeoproterozoic domain of northern Sweden, and evidence for a pre-1.9 Ga crustal layer. Precambrian Res, 112(3–4): 239–259

Skiöld T, Rutland R W R (2006). Successive ~1.94 Ga plutonism and ~1.92 Ga deformation and metamorphism south of the Skellefte district, northern Sweden: substantiation of the marginal basin accretion hypothesis of Svecofennian evolution. Precambrian Res, 148(3–4): 181–204

Skyttä P, Bauer T E, Tavakoli S, Hermansson T, Andersson J, Weihed P (2012). Pre-1987 Ga development of crustal domains overprinted by 1.87 Ga transpression in the Palaeoproterozoic Skellefte district, Sweden. Precambrian Res, 206–207: 109–136

Skyttä P, Hermansson T, Andersson J, Weihed P (2011). New zircon data supporting models of short-lived igneous activity at 1.89 of the western Skellefte District, central Fennoscandian Shield. Solid Earth Discuss, 3(1): 355–383

Skyttä P, Hermansson T, Elming S Å, Bauer T (2010). Magnetic fabrics as constraints on the kinematic history of a pre-tectonic granitoid intrusion, Kristineberg, northern Sweden. J Struct Geol, 32(8): 1125–1136

Stubley M P (2004). Spatial distribution of kimberlite in the Slave craton, Canada: a geometrical approach. Lithos, 77(1–4): 683–693

Turcotte D L (1997). Fractals and Chaos in Geology and Geophysics (2nd edition). Cambridge: Cambridge University Press

Vearncombe J, Vearncombe S (1999). The spatial distribution of mineralization: applications of Fry analysis. Econ Geol, 94(4): 475–486

Vivallo W (1987). Early Proterozoic bimodal volcanism, hydrothermal activity, and massive sulphide deposition in the Boliden-Långdal area, Skellefte District, Sweden. Econ Geol, 82(2): 440–456

Weinberg R F, Hodkiewicz P F, Groves D I (2004). What controls gold distribution in Archean terranes? Geology, 32(7): 545–548

Weihed P, Arndt N, Billström K, Duchesne J C, Eilu P, Martinsson O, Papunen H, Lahtinen R (2005). Precambrian geodynamics and ore formation: the Fennoscandian Shield. Ore Geol Rev, 27(1–4): 273–322

Weihed P, Bergman J, Bergström U (1992). Metallogeny and tectonic evolution of the Early Proterozoic Skellefte district, northern Sweden. Precambrian Res, 58(1–4): 143–167

Weihed P, Billström K, Persson P O, Bergman Weihed J (2002). Relationship between 1.90–1.85 Ga accretionary processes and 1.82–1.80 Ga oblique subduction at the Karelian craton margin, Fennoscandian Shield. Geol Foren Stockh Forh, 124: 163–180

Welin E (1987). The depositional evolution of the Svecofennian supracrustal sequence in Finland and Sweden. Precambrian Res, 35: 95–113

Zuo R, Agterberg F P, Cheng Q, Yao L (2009a). Fractal characterization of the spatial distribution of geological point processes. Int J Appl Earth Obs Geoinf, 11(6): 394–402

Zuo R, Cheng Q, Agterberg F P, Xia Q (2009b). Evaluation of the uncertainty in estimation of metal resources of skarn tin in Southern China. Ore Geol Rev, 35(3–4): 415–422