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In total 552 nickel-bearing sulfide deposits and occurrences in Finland have been examined and 254 of them have been selected for more detailed classification. In age they range from Late Archean to Middle Proterozoic (Subjotnian), of which economically the most significant are the Early Proterozoic Svecofennian deposits.

The deposits have been subdivided into 62 nickel-bearing metallogenic areas according to their type, age and spatial relations:

1) Late Archean and related deposits in northern and eastern Finland (2900–2500 Ma): Ruossakero Zone, central Lapland zones, other areas in northern Finland, and Kuhmo Belt.
2) Deposits in Early Proterozoic layered intrusions (2440 Ma).
3) Deposits within the Karelian formations (2070–1900 Ma): Vuonos, Lahnaslampi and Talvivaara zones.
4) Deposits within the Svecofennian Domain or its marginal zone (1900–1860 Ma): Kotalahti Belt (including Hitura, Kotalahti and Laukunkangas zones), zones and deposits to the northeast of the Kotalahti Belt, zones and deposits to the southwest of the Kotalahti Belt, deposits within the Sulkava area, Telkkälä Belt, deposits in western Finland, Vammala Belt (including Pori and Vammala zones), zones and deposits to the east of the Vammala Belt, and zones and deposits to the southwest of the Vammala Belt.
5) Deposits in Subjotnian diabases (c. 1650 Ma).

The main tectonostratigraphic division of the eastern parts of Fennoscandian Shield into an Archean (Kola–Karelian) domain in the northeast and a Proterozoic (Svecofennian) domain to the southwest is also fundamental with respect to nickel metallogenic provinces in Finland. A general feature is that the nickel deposits of the Kola–Karelian Domain are typically associated with greenstone belts, especially in northern Finland. On the other hand, the deposits of the Svecofennian Domain are associated with mafic-ultramafic intrusions within sedimentary belts of highly metamorphosed mica gneisses, although their position does not necessarily correlate with any stratigraphic unit.

Grade and tonnage models for nickel-bearing deposits show that 10% of the 164 Svecofennian deposits have an average grade greater than 0.80% Ni and 0.40% Cu, or a size greater than 0.52 Mt of ore. At the 10% level the deposits in the Kola–Karelian Domain, hosted by komatiites, layered intrusions and Karelian formations have an average grade greater than 0.50% Ni, 0.30% Ni and 0.33% Ni, but varying grades of 0.13% Cu, 0.88% Cu and 0.30% Cu, and a size of 0.5 Mt, 55 Mt and 30 Mt respectively. At the 50% level the Kotalahti and Vammala nickel belts show an almost similar distribution of nickel and copper grades, but their average sizes are different. However, only 10% of these belts have an average grade greater than 1.06% Ni and 0.75% Ni, and 0.37% Cu and 0.47% Cu, or a size greater than 3.1 Mt and 1.0 Mt respectively.

Total geological in situ resources of Finnish nickel deposits have been estimated to be some 950 Mt with an average grade of 0.39% Ni and 0.29% Cu, which could be equivalent to a metal content of some 2.6 Mt nickel and 2.5 Mt copper. Between 1941–1994, the ore output of all nickel mines in Finland was about 42.3 Mt, at an average grade of 0.61% Ni and 0.25% Cu, which is calculated to be equivalent of some 260 300 t of nickel and 103 800 t of copper.

Based on the distribution of in situ ore resources and known ore deposits it is apparent that the overwhelming nickel potential is in the Svecofennian area, within the Kotalahti Belt and within the Vammala Belt. Economic ore deposits could also be found among the layered intrusions, whereas the Archean deposits are expected to contain only modest amounts of nickel. Current exploration in Finland could also reveal new types of economic nickel deposits.

Key words (GeoRef Thesaurus, AGI): economic geology, nickel ores, classification, ore grade, resources, metallogenic provinces, tectonostratigraphic units, Proterozoic, Archean, Finland

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INTRODUCTION

At present nickel has been recognized as one of the most strategic, and possibly also the most critical, metals for the Finnish metal industry. It has been mined and produced from domestic ores since 1941, when mining commenced at the Makola deposit. Exploration for nickel has been successful for almost 50 years, but recently, with few exceptions, the results have not been encouraging. Nickel production is now becoming dependent on imported concentrates, because domestic nickel mines operating recently were closed in early 1995. Production will continue for some time yet at the Hitura deposit, but in this case ore is mined as a raw material for nickel compounds rather than as metal. Therefore exploration for new nickel deposits in Finland is an urgent priority.

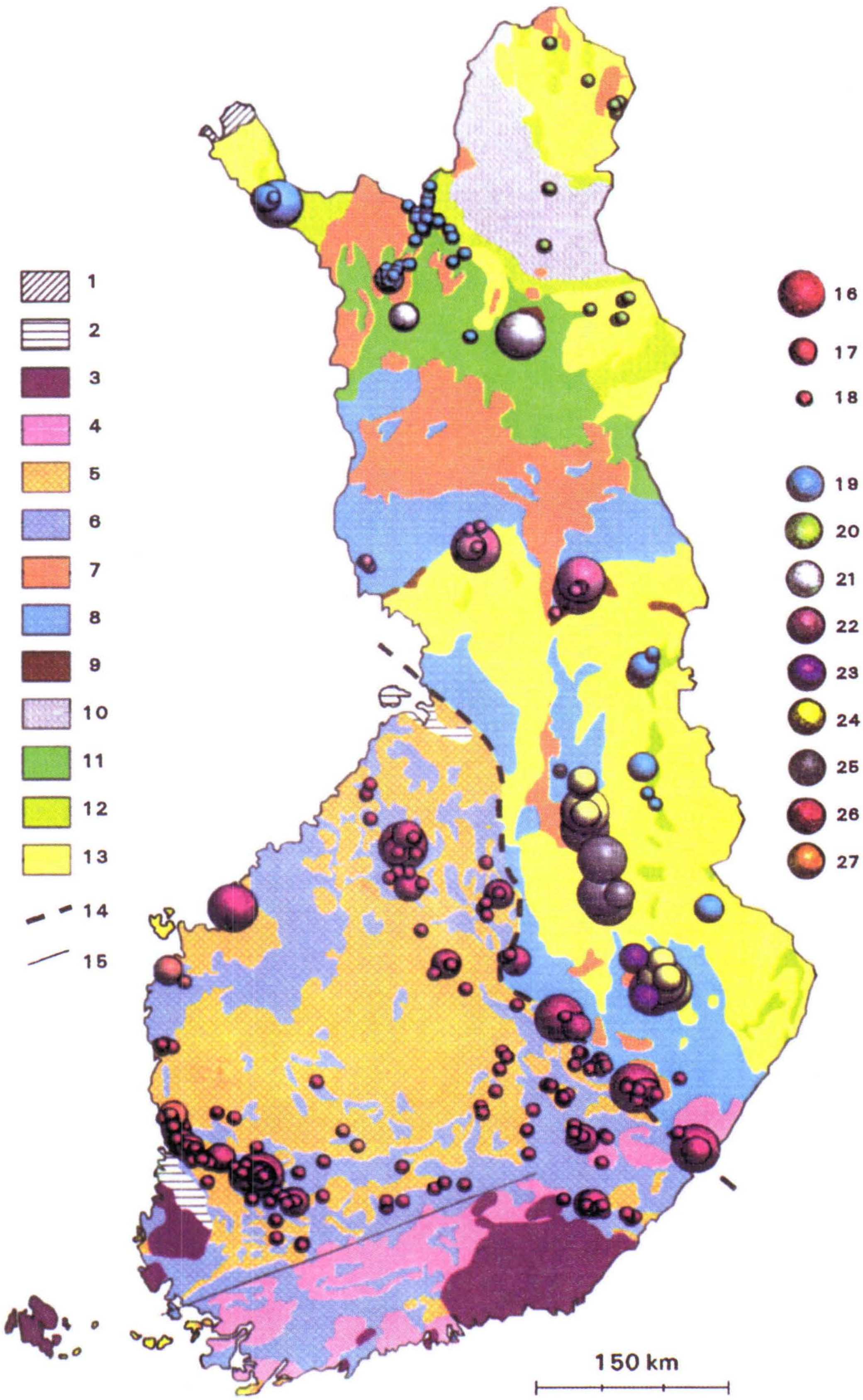
The history of Finnish nickel mining commences in the year of 1924, when the Geological Survey of Finland discovered the Pechenga (Petsamo) nickel deposits, which at that time lay within the Finnish territory (Väyrynen 1938). The area was, however, subsequently ceded to the Soviet Union in 1945. The discovery of the Makola deposit in 1937 provided the impetus for renewed mining of nickel in post-war Finland, and between 1941–1994, the total ore output of all nickel mines in Finland has been about 42.3 Mt, with an average (weighted) grade of 0.61% Ni and 0.25% Cu (Table 1), which has been estimated to equal some 260 300 t of nickel and 103 800 t of copper (sum of annual averages). Because detailed mine production statistics by the Ministry of Trade and Industry extend only to the year 1990, average metal grades in the present paper have been estimated for those mines that were still operating after that year.

Many authors have presented contributions regarding nickel exploration methods in Finland (e.g. Häkli 1971, Ketola 1982, Niemi 1989), nickel exploration results (e.g. Papunen et al. 1977), and nickel ore petrology and metallogeny (e.g. Gaál 1972, 1982, 1985, 1990, Papunen et al. 1979, Mikkola 1980, Papunen 1991, Piirainen et al. 1992, Makkonen 1992, Reino et al. 1993, Puustinen, Saltikoff & Tontti 1995, Peltonen 1995). Nickel has also been one of the most important metals portrayed in metallogenic maps of Finland (e.g. Kahma 1973, 1984, Kahma, Saltikoff & Lindberg 1976, Frietsch et al. 1987). A significant overview of nickel-copper deposits in the Fennoscandian Shield was published as a collection of papers by Papunen & Gorbunov (1985). However, no definitive metallogenic belts or zones have been delineated in these maps. This probably reflects the number of unsolved questions concerning relations of the Finnish Precambrian bedrock and the position of nickel deposits within it.

The purpose of this study is to present a revised nation-wide inventory of sulfidic nickel deposits and occurrences in Finland, to establish a consistent classification, and to draw metallogenic con-

Table 1. Nickel mine production in Finland from 1941–1994. Total mine output and ore feed output, average (weighted) grades of nickel and copper, and estimated in situ metal contents (based on annual averages).

Mine	Period	Total (t)	Ore (t)	Ni (%)	Cu (%)	Ni/Cu	Ni (t)	Cu (t)
Makola	1941–1954	422 038	414 796	0.72	0.43	1.67	2 969	1 767
Kotalahti	1957–1987	13 738 767	12 349 511	0.66	0.26	2.54	82 080	32 280
Hitura	1965–	19 387 966	8 103 660	0.55	0.20	2.75	44 707	16 035
Telkkälä	1969–1992	950 295	605 396	1.37	0.35	3.91	8 822	2 249
Kitula	1970	59 185	18 785	0.67	0.24	2.79	126	45
Kylmäkoski	1971–1974	839 586	689 616	0.36	0.27	1.33	2 504	1 887
Vuonos	1972–1977	5 495 761	5 495 761	0.20	0.04	5.00	10 939	2 198
Petolahti	1972–1973	114 608	85 738	0.47	0.38	1.24	403	325
Vammala	1974–1994	9 566 774	7 593 342	0.68	0.42	1.62	51 421	31 693
Laukunkangas	1984–1994	8 391 565	6 658 841	0.78	0.22	3.55	52 160	14 338
Hälvälä	1988–1992	535 427	249 133	1.56	0.39	4.00	3 882	976
Tainiovaara	1989	19 984	19 984	1.40	0.12	11.67	280	24
Total	1941–1994	59 521 956	42 284 563	0.61	0.25	2.44	260 293	103 817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clusions. In this context, a nickel deposit has been defined as an ore-bearing body carrying a reasonable nickel content, e.g. more than 0.1% Ni, and having some significance from the point of metallogeny or exploration. The minimum size of a nickel-bearing deposit included in this study is about 1 000 tons. The amount of ore is here defined as estimated in situ geological ore resources, and does not take into consideration costs of developing, mining, beneficiating or transporting the ore.

The basis for the present study has been the collection of comparable and comprehensive data concerning as many nickel occurrences and deposits as possible. The main source has been the National Ore Deposit Database by the Geological Survey of Finland (1994) together with other published references, such as Papunen et al. (1977, 1980), Ketola (1982), Papunen & Gorbunov (1985), Frietsch et al. (1987), Mäkinen (1987), and numerous unpublished reports submitted to the Ministry of Trade and Industry related to mining, or to exploration activities within mining concessions. In total 552 nickel-bearing deposits and occurrences were scanned and 254 of them were included in this study. Individual deposit are not described in detail, but most recent references are given within the text. During data collection, each deposit was described by its name, area, map sheet, geographical coordinates, total geological in situ ore resources, nickel and copper grades, rock type, and references. Due to deficiencies in the data, neither cobalt nor platinum group metals could be included in the database, although they are important metal components in nickel ores. Several maps published or prepared by the Geological Survey of Finland have been used in delineating of metallogenic features, such as the bedrock geological maps, aeromagnetic and gravimetric (Bouguer) maps and till geochemical maps. Grades and tonnages of the studied nickel deposits have been used for statistical summaries, for deposit modelling and for presentation of the true size of the deposits on the maps in the present paper. For this purpose, a combined variable (cf. Kahma 1977) for the bulk metal content has been used, defined as $Ni^* = Ni + (0.2 \times Cu)$, which takes into account the additional and subordinate value of the copper in nickel ore.

MAJOR TECTONOSTRATIGRAPHIC UNITS IN FINLAND WITH RESPECT TO THE LOCATION OF NICKEL DEPOSITS

Finland can geologically be divided into the Early Proterozoic Svecofennian Domain in the southwest, and into the predominately Archean Kola–Karelian Domain in the northeast (Fig. 1). The boundary between these two domains runs approximately in a NNW–SSE direction from Lake Ladoga in Russia to the northern parts of the Gulf of Bothnia (Luukkonen & Lukkarinen 1986, Karhu 1993), and further to the northwest, to Kukkola in Sweden (Öhlander et al. 1987). It may also be postulated that the boundary in this latter area could be shifted further to the southwest. Both of these two domains include several areas that have been favorable for the development of nickel deposits of various types.

Kola–Karelian Domain

The Kola–Karelian Domain, referred to as the Archean Domain by Gaál & Gorbatschev (1987), represents a craton of Late Archean age. It includes large areas made up of exclusively Archean rocks (3100–2500 Ma), but also contains intracratonic and epicratonic zones of younger, Early Proterozoic rocks (2500–1750 Ma) underlain by Archean basement. The most significant of these Proterozoic units are the Lapland Granulite Belt, the central Lapland granite batholith, and epicratonic Kare-

Fig. 1. Major geological units and nickel deposits in Finland. **Geological units:** *Phanerozoic and Late Precambrian units*: 1 — Caledonian (Paleozoic) rocks; 2 — Jotnian (Riphean) sedimentary rocks. *Intrusive units subsequent to the Svecofennian orogeny*: 3 — anorogenic rapakivi granites; 4 — Late Svecofennian granites. *Svecofennian Domain*: 5 — Early Proterozoic (Svecofennian) granitoid complex; 6 — Early Proterozoic (Svecofennian) schists. *Archean Kola–Karelian Domain*: 7 — Early Proterozoic granitoids; 8 — Early Proterozoic (Karelian) schists; 9 — Early Proterozoic layered intrusions; 10 — Lapland Granulite Belt; 11 — Central Lapland (Lapponian) greenstone belt; 12 — Archean schists; 13 — Archean gneiss (basement) complex. **Major structural features:** 14 — Boundary between the Svecofennian and Kola–Karelian domains; 15 — Häme Fault. **Nickel deposits**: Size classes: 16 — major deposit, 17 — minor deposit; 18 — occurrence. **Metallogenic types** (numbers according to deposit classification): 19 — Archean komatiitic type (1.1, 1.2 and 1.4); 20 — other deposits in northern Finland, partly Archean (partly 1.3); 21 — unclassified deposits in the central Lapland greenstone belt (partly 1.3); 22 — deposits in layered intrusions (2); 23 — deposits associated with sulfide ores (Vuonos-type) (3.1); 24 — deposits in ophiolite bodies (Lahnaslampi-type) (3.2); 25 — deposits in black schists (Talvivaara-type) (3.3); 26 — Svecofennian type (4); 27 — deposits in Subjotnian diabases (5).

lian schist belts.

Several schist belts of due Archean age are present within the Kola–Karelian Domain. Of these, the Kuhmo–Suomussalmi Schist Belt is a typical greenstone belt that includes rocks of a komatiitic affinity, and where nickel potential has been demonstrated by discovery of several subeconomic deposits. The greenstone belt at Ruossakero in northwestern Lapland is also of the same type and age. A complex situation prevails in central Lapland, where the Lapponian schist belt runs from Kolari to Kittilä, Sodankylä and Salla, continuing further to the north (Karasjok area in Norway) and to the west (Kiruna area in Sweden). The belt can be regarded the largest intracratonic greenstone belt in Finland, and it hosts several minor nickel-bearing deposits which have often a komatiitic affinity. Both Late Archean and Early Proterozoic ages have been proposed for the central Lapland greenstone belt. In supporting Gaál (1990), it must be noted that the published geological and geochronological data is insufficient to constrain a precise age. In this respect, the tectono-stratigraphic conditions in northern Finland are not fully settled, and the position and age of many nickel deposits here remains open.

A chain of Bushveld-type layered intrusive complexes of Early Proterozoic age (2440 Ma) runs across Finland, from Kemi in the west to Näränkävaara in Kuusamo in the east. The belt continues further to the east, to the Oulanka area in Russia (Turchenko 1992). The layered intrusions manifest the earliest rifting of the Archean craton, and they have been emplaced between the Archean basement and the overlying Proterozoic schists. These intrusions host large low-grade nickel-bearing deposits and, above all, economic chromium and vanadium ore deposits.

The most crucial event in the geological history of Finland was the Svecofennian orogeny which culminated at 1885 Ma, during Early Proterozoic time. A large area of crust, the Svecofennian Domain, was formed at his time, which was mostly derived from juvenile mantle material. The event also had a big impact on the Archean craton. The Early Proterozoic (2500–1750 Ma) was also a period of intracratonic sedimentation and volcanism. Consequently, a passive continental margin was formed by rifting along what is now the boundary of the Archean Kola–Karelian Domain in the central parts of Finland, and marginal basins and oceanic island-arcs were formed parallel to it during the collision (Gaál 1987, 1990, Gaál & Gorbatschev 1987).

The Early Proterozoic sedimentary basins within the Kola–Karelian Domain constitute an epicontinental cover sequence resting on the Archean basement complex. They are now represented by rocks of the so-called Karelian formations. These formations comprise the Puolanka Schist Belt in Kainuu and the Outokumpu Schist Belt in Finnish Karelia. The Kemi and Kuusamo schist belts in northern Finland have a similar character, although their setting is more intracratonic. They were evidently deposited upon the Archean craton, but intruded by the complex Proterozoic central Lapland granite batholith in the north. A common feature of all these schist belts is that they include epicontinental Jatulian and Sariolan sediments, deposited at the margins of the continental blocks. A distinctive feature of the Kemi and Kuusamo schist belts is their association with the large Early Proterozoic layered intrusions, as mentioned earlier. On the other hand, the Puolanka and Outokumpu schist belts are characterized by the presence of the so-called Outokumpu association (cf. Koistinen 1981) consisting of serpentinite, dolomite, calc-silicate rocks, mafic volcanic rocks, cherty quartzite, graphite schists and massive sulfide ores, and by isolated ultramafic bodies now converted to talc-chlorite schists (soapstones). At least some of these lithologies are ophiolitic in origin, and host distinct types of nickel deposits, which seem to be lacking within the other Early Proterozoic schist belts.

In the southwestern part of the Kola–Karelian Domain, large areas of the Archean craton are overlain by allochthonous gneisses of the Savo Schist Belt (Ekdahl 1993). Several Svecofennian type nickel deposits, including some of the largest in the country (e.g. Kotalahti and Laukunkangas) are hosted by mafic-ultramafic bodies among these schists, and thus are actually located within the Kola–Karelian Domain, albeit in its marginal zone.

Svecofennian Domain

The most significant tectonostratigraphic unit with respect to nickel deposits in Finland is the Proterozoic Svecofennian Domain. Most of the economic deposits are situated in that region, and it is these in particular that have so far been exploited until now.

Within the Svecofennian Domain, the nickel deposits are almost exclusively confined to highly metamorphosed parts of schist belts, dominated by migmatites and mica gneisses, such as around the granitoid complex of central Finland. They run roughly parallel to the eastern margin of the Archean craton (the Savo Schist Belt), and they also occur in an E–W-trending zone to the south of Tampere (including the Häme Schist Belt), to the north of Pori, and still further to the northeast, near Raahe, where they join the Savo schists. The actual basement for the Svecofennian schists has not been identified. Nickel deposits of the Svecofennian Domain are not uniformly distributed through the schist belts but constitute well-defined narrow zones. The main control on the actual location of the deposits is the distribution of nickel-bearing mafic-ultramafic intrusions, which have been strongly affected by Svecofennian tectonics.

A Late Svecofennian granite-migmatite zone (1840–1830 Ma) occupies the southern parts of Finland (Ehlers et al. 1993). This structural unit has been interpreted as an early basin of crustal extension which was the locus of an inherited zone of weakness in the Proterozoic crust. The unit has also been described as a high temperature, low pressure metamorphic zone (cf. Pietikäinen 1994). Its northern boundary appears as a sharp fault line called the Häme Fault in the present paper. This fault with the granite belt has a specific effect on the distribution of nickel deposits in southern Finland, where it abruptly truncates all nickel-bearing zones. The presence of this granite-migmatite framework also places the nickel deposits in southeastern Finland (Telkkälä and Parikkala areas) in a distinct and separate position.

Subsequent to the collision of the Proterozoic oceanic plate with the Archean craton thermal domes were formed in southern (western Uusimaa) and southeastern (Sulkava area) Finland. In the Sulkava area, high-grade metamorphism peaked about 1820 Ma ago, and the event is also reflected in the different character of the nickel deposits in this area.

Minor nickel occurrences are associated with mafic dikes of estimated Subjotnian age (1650–1550 Ma) in southern and southwestern Finland. Geotectonically the dikes might be related to the emplacement of the rapakivi granite massifs.

FRACTURE PATTERNS WITH RESPECT TO THE LOCATION OF NICKEL DEPOSITS

The concept about control of emplacement and location of nickel-bearing intrusive mafic-ultramafic bodies by fracture patterns has been widely discussed in Finland (e.g. Gaál 1985, Gaál et al. 1978, Mikkola 1982, Parkkinen 1975). Analogously, Green et al. (1985) stated that the Thompson nickel belt in Canada has been the site of successive continental rifting and rupturing, an evolving continental margin, and eventually a continental-scale strike-slip fault, over a time span from 2400 Ma to 1600 Ma. Similar findings have also been made in Labrador by Ryan et al. (1995) at the Voisey Bay nickel deposit, which is situated near the 1800 Ma collisional boundary between the Archean Nain Province and the Early Proterozoic Churchill Province, and where a crust-penetrating subvertical fault is assumed to be the feeder conduit for ultramafic mantle magmas.

According to this general fracture-related concept, emplacement of mafic-ultramafic bodies has taken place via various types of deep-seated fractures, which mark long-living zones of weakness in the crust. Due to repeated rupturing these zones carry also younger fractures. Conforming to the model, these features constitute the framework of metallogenic outlines for the nickel deposits concerned. Such a model can be readily applied for the Svecofennian Domain in Finland. The fracture lines appear as composite linear features up to hundreds of kilometers in length, and can be identified through integration of topographical, geological, geophysical and geochemical data. Quite often the location of individual mafic intrusions has been controlled by conjugate faults within a main fracture zone. A close relation has also been found between the abundance of schollenmigmatites and mafic intrusions. This feature may suggest that the intrusions were emplaced into complicated zones of tectonic weakness (c.f. Häkli & Vormisto 1985, Gaál 1985). Later in the present paper, each nickel-bearing area will be described and characterized by the presence of its fracture patterns.

Particularly near the western margin of the Archean craton, NW–SE-trending en echelon fracture patterns have been interpreted as loci for mafic-ultramafic nickel-bearing intrusions. Features of the different fault systems within the Kotalahti Nickel Belt have been discussed e.g. by Gaál (1972, 1985) and Talvitie (1975). According to Vuorela (1982) the nickel-bearing deposits, especially in central Finland, are clearly related to a maximum density anomaly of Landsat lineaments with a trend in the 315–345 degree sector. Fracture patterns within one part of the Archean basement area to the north of Kotalahti have been analyzed by Puustinen (1971), where the emplacement of the about 2600 Ma old Siilinjärvi carbonatite complex was controlled by N–S trending fractures. This area also shows a set of markedly younger NW–SE-trending fractures that overprint the older structural features.

At the southern border of the Häme Schist Belt a distinct fracture zone some 500 km long can be distinguished, following a WSW–ENE-trend from Turku to Hämeenlinna and further to the east, at least as far as Ristiina in southeastern Finland (Fig. 1). In the present paper, this fault is termed the Häme Fault. It can be discerned especially clearly from aeromagnetic maps as an intersecting and almost linear feature that seems to form a major geological discontinuity in southern Finland. As noted earlier, this discontinuity also marks the southern limit for nickel deposits in the southwestern and southern parts of the country. The fault might continue beyond Ristiina through the Sulkava thermal dome to Puruvesi. The Häme Fault has already been documented in some places (cf. Gaál 1982, 1985, 1990, Ruotoistenmäki 1992, Koistinen 1994, Tiainen & Viita 1994), but without any reference to its significance. The Häme Fault divides the Southern Svecofennian Subprovince roughly into two parts (cf. Gaál & Gorbatschev 1987) and coincides with the northern margin of the Late Svecofennian granite-migmatite zone, as defined by Ehlers et al. (1993).

CLASSIFICATION OF NICKEL DEPOSITS

Based on the age of the mafic or ultramafic host intrusions, Papunen et al. (1979) proposed the subdivision of nickel deposits in Finland into five groups. Papunen & Vorma (1985) also cited additional ore types in their list of nickel deposits. These principles are adopted and further developed in the present paper (cf. also Fig. 1), and a summary of the comprehensive classification of this will be presented below.

1. Archean and related deposits, usually associated with komatiitic and tholeiitic suites in greenstone belts (2900–2500 Ma).
2. Deposits in Early Proterozoic layered mafic intrusions (2440 Ma), emplaced between the Archean basement and overlying schists.
3.1 Deposits of Ni-Co-Fe sulfide impregnations in Karelian cherty quartzite and calc-silicate rocks, associated with the strata-bound Outokumpu-type ores (1970 Ma).
3.2 Deposits in Karelian ultramafic bodies (soapstones), tectonically emplaced during the early stage of the Svecofennian orogeny (1970–1950 Ma).
3.3 Ni-Zn-Cu sulfide deposits in black schists, associated with the Karelian evolutionary phase (2070–1900 Ma).
4. Svecofennian synorogenic deposits, hosted by ultramafic and mafic intrusions, emplaced during the main stage of the orogeny (1900–1860 Ma) within highly metamorphosed mica gneisses.
5. Deposits in postorogenic Subjotnian diabase dikes (c. 1650 Ma).

From the petrological point of view, some general observations can be made. Classification of the nickel deposits within the Archean Kola–Karelian Domain seems to be adequate. Host rocks to the deposits in the Archean domain of northern Finland are dominated by ultramafic rocks which often have a komatiitic affinity, and which according to descriptive deposit models by Cox & Singer (1986) fit into the komatiitic Ni-Cu deposits (e.g. Kambalda-type Pulju Zone) and dunitic Ni-Cu deposits (e.g. Ruossakero Zone). The 2440 Ma layered intrusions (Stillwater Ni-Cu-model deposits) can be broadly divided into the western ultramafic (Vaaralampi–Suhanko) and into the eastern mafic (Porttivaara–Kuusijärvi) zones. However, nickel deposits are absent in the Kemi and Näränkävaara areas which mark the most western and eastern ends of the entire intrusion chain.

Within the Proterozoic Svecofennian Domain, the nickel deposits make up a relatively uniform type which corresponds well to the model of synorogenic-synvolcanic Ni-Cu deposits as defined by Cox & Singer (1986). Statistically their host rocks are represented equally by gabbros and peridotites. In this context though, it should be noted that variations do exist within the Kotalahti Nickel Belt. For instance host rocks are mostly ultramafic in the northwestern part of the Belt (Hitura area) and mafic (mainly noritic) in the southeast (Laukunkangas area).

Several attempts have been made to discriminate between the different nickel deposit types in Finland. Häkli (1971) used the distribution patterns of silicate nickel abundances in mafic-ultramafic intrusives. In their study of nickel deposits in northern Finland Papunen et al. (1979) found many geological, geochemical and mineralogical features which were common to both the ore deposits and their respective host rocks. More recently, Mäkinen (1987) studied the geochemical characteristics of 35 nickel-bearing Svecofennian mafic-ultramafic intrusions. Based on factor types he divided them into three groups: (1) Kotalahti-type peridotite intrusions; Kristiskeri, Sahakoski, Hyvelä, Rottapäkki, Hälvälä, Makkola, Laukunkangas, Kotalahti and Koirusvesi, (2) Vammala-type peridotite-norite-gabbro intrusions; Oravainen, Murto, Sittamäki, Mäntymäki, Posionlahti, Ekojoki, Stormi, Haavisto, Suvitie, Kylmäkoski and Hitura, and (3) gabbro intrusions; Ahokkala, several gabbro intrusions in southern Finland, and also Parikkala. According to Mäkinen (1987) the crystallization conditions of these three intrusion types differ from each other in many respects. For instance, the Kotalahti-type intrusions were crystallized under higher P-T (plutonic) conditions and the Vammala-type intrusions under lower P-T conditions (higher crustal levels). It should also be emphasized in this context that Mäkinen (1987) did not place the Hitura and Parikkala deposits among the Kotalahti-type intrusions.

Small amounts of nickel has been found in several gabbro-type intrusions which are frequent in southern Finland, especially to the south of the Häme Fault. Many gabbroic intrusions in this region, for instance those between Forssa and Mäntsälä, have been fruitlessly explored for their nickel potential. Similar kinds of intrusions also occur in central Finland (e.g. Kangasniemi and Toivakka), where nickel concentrations were found to be very low-grade and of small size, and therefore those occurrences are not included in the present study.

REGIONAL CHARACTERISTICS OF NICKEL-BEARING AREAS

A metallogenic nickel belt is defined in the present paper as a large linearly elongated ore-bearing structure, within which certain genetically and spatially related deposits predominate. A nickel zone is a linear ore-bearing area of a lower order, within which deposits of a single type prevail. A nickel district or area has only geographic significance, and thus effectively refers to a cluster of deposits devoid of distinct marked linear features.

In total 62 nickel-bearing belts, zones and separate (undefined) deposits were distinguished during the present study. These areas were named after the largest nickel deposit in each category, or an already accepted name was used. The following list presents the main divisions identified based on their ages and spatial relations:

1. Archean and related deposits in northern and eastern Finland
   - 1.1 Ruossakero Zone
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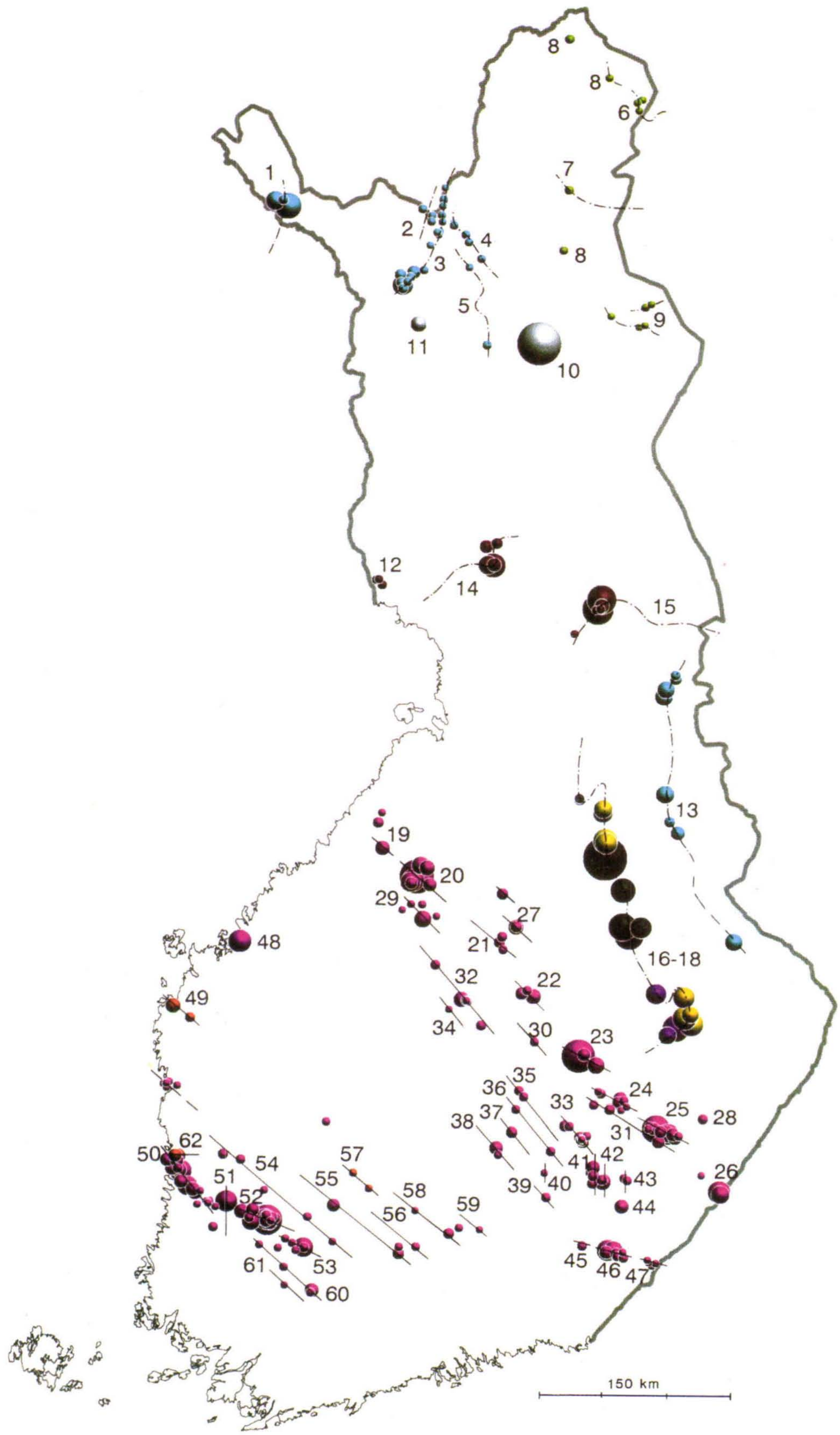

Fig. 2. Nickel-bearing zones and separate deposits in Finland. Symbol diameters refer to the total metal content in the deposits Ni* = Ni + (0.2 x Cu). Numbers correspond to deposits discussed in the text.

The distribution of the nickel-bearing areas in Finland is shown in Fig. 2, and a statistical summary with respect to their ore grades and tonnages is presented in Table 2. The location of individual deposits within their respective geological contexts was already shown in Fig. 1. The areas in the present paper are numbered and referred to on the basis of these figures and tables, and will be described later according to the main subdivisions presented in this section.

It is evident that the main part of economic nickel resources and potential lies within the Proterozoic Svecofennian Domain, near the southwestern margin of the Archean craton, and most of the operating or past mines are situated either within this marginal zone (Kotalahti Belt) or further away to the southwest of it (Vammala Belt). Because all deposits within the Karelian formations are spatially and genetically closely associated, they will be treated jointly in this context. It is also clear that the other deposits within the Archean Kola–Karelian Domain tend to be relatively large but low-grade, and that the deposits in Lapland are mostly small in size.

1. Archean and related deposits in Northern and Eastern Finland

Lapland is characterized by numerous mafic-ultramafic intrusions. In order to promote nickel exploration, two specially funded projects (Papunen et al. 1977, 1980) were carried out. Together these covered almost 200 nickel indications but unfortunately, only a few were found to be of any economic significance. The intrusions studied ranged in composition from komatiitic to tholeiitic. Especially in the central parts of Lapland, nickel deposits constitute quite uniform types of metallogenic nickel-bearing zones, and are widespread among the Lapponian greenstones, which may partly be of Late Archean age (Pulju Zone) and commonly have a komatiitic affinity. The precise position of Lapponian formations is still a subject of discussion.

1.1 Ruossakero Nickel Zone

Ruossakero Nickel Zone (1)

This nickel-bearing zone in northwestern Lapland is associated with an Archean greenstone belt composed of mafic volcanic rocks and volcaniclastic sediments, surrounded by granodioritic basement gneisses (Idman 1988, Öhlander et al. 1987). The largest of the nickel deposits, Ruossakero and Sarvisoaivi, are associated with serpentinized peridotite and dunite bodies of komatiitic composition (Isomaa 1988). Two nickel occurrences of similar type (Kurkovare and Keukiskero) have also been located to the south, in Sweden (Frietsch et al. 1987), and therefore the total length of the zone could be some 75 km. Additionally, a large differentiated gabbro-peridotite body (Tshohkkoaivi) occurs close to Ruossakero. The Ruossakero deposit has an average grade of 0.53% Ni but it has a low copper content (0.02% Cu) with a Ni/Cu ratio of 26.5.

1.2 Central Lapland nickel zones

In many instances the nickel deposits in central Lapland are associated with Lapponian greenstone belts. In almost all cases the ultramafic bodies have komatiitic composition, and several of them represent ultramafic lava flows in association with volcaniclastic sediments, graphite-bearing schists and cherts (Papunen et al. 1977). The copper contents of the nickel deposits are typically very low (0.01–0.02% Cu), with an average Ni/Cu ratio of 36.1. The Peltotunturi, Pulju, Nirroselkä and Nuttio zones trend in different directions but converge upon each other towards the north. Of these the Pulju and Nirroselkä zones are very clearly discernible from aeromagnetic maps as positive anomalies, and they show distinct geochemical nickel and copper anomalies in till. On the basis of the zinc content of chromites, Papunen et al. (1977, 1979) found that the Ruossakero, Peltotunturi and Pulju nickel zones would be potential for sulfide-bearing ultramafic bodies, whereas the Nirroselkä and Nuttio zones might include only sulfide-poor bodies.

Peltotunturi Nickel Zone (2)

The zone comprises at least three nickel occurrences, and it continues in Norway where three deposits of similar type (Raddjevarri, Njuolas and Abmujavrit) have been discovered (Frietsch et al. 1987). The Peltotunturi area is probably a zone of lower order, closely related to the Pulju Zone.

Pulju Nickel Zone (3)

This is a very distinct nickel zone (Geological Survey of Finland 1994), and it is perhaps the only

Table 2. Nickel-bearing areas in Finland. Total in situ ore resources, calculated metal contents, and arithmetical averages (non-weighted) of nickel and copper grades. No. — number corresponding to nickel-bearing areas discussed in the text; N — number of deposits in the area. Deposit type classification and corresponding numbers: **Archean and related deposits** (1): AKO = Archean komatiitic type, ARC — general Archean type, LAP — Lapponian; **Deposits in layered intrusions** (2): LIN — layered intrusion; **Deposits within the Karelian formations** (3): OKU — quartzite-skarn ore (Outokumpu-type), OPH — ophiolite (Lahnaslampi-type), BLS — black schist (Talvivaara-type); **Svecofennian deposits** (4): SFE — Svecofennian; **Subjotnian deposits** (5): SJO — Subjotnian diabase.

No.	Area	Type	N	Total ore	Metal content		Average grade			
				Mt	Ni (t)	Cu (t)	Ni (%)	Cu (%)	Ni/Cu	Cu/(Ni+Cu)
1	Ruossakero	AKO	3	6.150	31 652	1 443	0.38	0.04	12.83	0.12
1	**Ruossakero Zone**		**3**	**6.150**	**31 652**	**1 443**	**0.38**	**0.04**	**12.83**	**0.12**
2	Peltotunturi	AKO	3	0.020	36	1	0.18	0.01	29.48	0.04
3	Pulju	AKO	17	1.494	6 009	1 298	0.24	0.02	30.58	0.06
4	Nirroselkä	AKO	5	0.050	77	5	0.15	0.01	44.35	0.05
5	Nuttio	AKO	2	0.015	29	1	0.19	0.01	40.00	0.03
2–5	**Central Lapland zones**		**27**	**1.579**	**6 151**	**1 305**	**0.19**	**0.01**	**36.10**	**0.05**
6	Vätsäri	ARC	3	0.015	25	2	0.13	0.01	16.82	0.06
7	Lahessaari	ARC	1	0.010	25	15	0.25	0.15	1.67	0.38
8	Inari and Utsjoki	ARC	3	0.020	58	34	0.28	0.14	3.02	0.30
9	Seitainaapa	ARC	5	0.030	44	2	0.14	0.01	26.76	0.04
10	Keivitsa	LAP	1	250.000	650 000	1 400 000	0.26	0.56	0.46	0.68
11	Sirkka	LAP	1	0.250	800	950	0.32	0.38	0.84	0.54
12	Liakka	LIN?	3	0.030	40	77	0.13	0.26	0.66	0.62
6-12	**Other areas in Lapland**		**17**	**250.355**	**650 992**	**1 401 080**	**0.22**	**0.22**	**7.18**	**0.37**
13	Kuhmo	AKO	8	2.020	8 764	1 937	0.45	0.16	17.26	0.17
13	**Kuhmo Belt**		**8**	**2.020**	**8 764**	**1 937**	**0.45**	**0.16**	**17.26**	**0.17**
14	Vaaralampi	LIN	5	7.150	21 860	15 970	0.34	0.45	0.88	0.56
15	Porttivaara	LIN	6	121.115	123 030	216 880	0.18	0.30	0.75	0.58
14-15	**Layered intrusions**		**11**	**128.265**	**144 890**	**232 850**	**0.26**	**0.38**	**0.82**	**0.57**
16	Vuonos	OKU	3	12.300	40 770	8 590	0.37	0.14	12.35	0.21
17	Lahnaslampi	OPH	9	48.100	73 700	5 810	0.14	0.01	13.11	0.07
18	Talvivaara	BLS	6	419.010	1 045 330	558 630	0.22	0.14	1.76	0.37
16-18	**Karelian zones**		**18**	**479.410**	**1 159 800**	**573 030**	**0.24**	**0.10**	**9.07**	**0.22**
19	Perkkiö	SFE	3	0.253	559	576	0.22	0.22	1.01	0.52
20	Hitura	SFE	7	24.210	186 414	86 080	0.47	0.25	2.61	0.32
21	Ilokangas	SFE	3	0.030	142	77	0.47	0.26	1.84	0.38
22	Talluskanava	SFE	3	0.255	880	505	0.38	0.30	1.51	0.42
23	Kotalahti	SFE	3	21.270	148 808	57 280	0.62	0.21	2.91	0.26
24	Härmäniemi	SFE	9	0.120	740	191	0.59	0.19	3.27	0.27
25	Laukunkangas	SFE	10	5.236	56 416	15 037	0.55	0.23	2.24	0.35
26	Parikkala	SFE	3	3.841	12 070	11 287	0.32	0.30	1.07	0.48
19-26	**Kotalahti Belt**		**41**	**55.215**	**406 028**	**171 033**	**0.45**	**0.25**	**2.06**	**0.38**
27	Löytynmäki	SFE	3	0.180	861	555	0.38	0.33	1.20	0.51
28	Kettäjänniemi	SFE	1	0.010	50	20	0.50	0.20	2.50	0.29
27-28	**Area NE of Kotalahti Belt**		**4**	**0.190**	**911**	**575**	**0.44**	**0.27**	**1.85**	**0.40**
29	Muurasjärvi	SFE	5	0.512	1 524	1 027	0.24	0.20	1.52	0.44
30	Hyttikangas	SFE	1	0.010	15	30	0.15	0.30	0.50	0.67
31	Purstosaari	SFE	4	0.130	325	202	0.48	0.19	2.47	0.31
32	Ilmolahti	SFE	6	0.262	904	661	0.31	0.21	1.66	0.40
33	Kekonen	SFE	9	0.174	639	311	0.29	0.16	1.92	0.35
34	Pesäneva	SFE	1	0.001	4	4	0.40	0.40	1.00	0.50
35	Venetekemä	SFE	2	0.015	53	31	0.38	0.21	1.80	0.36
36	Ihastjärvi	SFE	2	0.015	49	18	0.34	0.16	4.43	0.27
37	Salmenkylä	SFE	1	0.050	85	85	0.17	0.17	1.00	0.50
38	Ohensalo	SFE	2	0.147	339	407	0.17	0.20	0.91	0.52
39	Koivakkala	SFE	1	0.010	30	15	0.30	0.15	2.00	0.33
29-39	**Area SW of Kotalahti Belt**		**34**	**1.326**	**3 966**	**2 790**	**0.29**	**0.21**	**1.75**	**0.42**

Table 2. (continued)

No.	Area	Type	N	Total ore	Metal content		Average grade			
				Mt	Ni (t)	Cu (t)	Ni (%)	Cu (%)	Ni/Cu	Cu/(Ni+Cu)
40	Kätkytsaari	SFE	1	0.001	5	1	0.50	0.07	7.14	0.12
41	Rietsalo	SFE	4	0.119	673	445	0.62	0.29	2.95	0.30
42	Niinimäki	SFE	2	0.110	1 220	420	0.84	0.26	3.93	0.21
43	Sarkalahti	SFE	2	0.015	40	15	0.30	0.13	3.00	0.27
44	Kitula	SFE	1	0.030	480	120	1.60	0.40	4.00	0.20
40-44	**Sulkava area**		**10**	**0.275**	**2 418**	**1 000**	**0.77**	**0.23**	**4.20**	**0.22**
45	Leipäsaari	SFE	1	0.005	32	15	0.63	0.29	2.17	0.32
46	Telkkälä	SFE	7	0.842	11 562	1 845	0.68	0.18	3.44	0.27
47	Kuurmanpohja	SFE	4	0.004	15	7	0.38	0.18	2.68	0.30
45-47	**Telkkälä Belt**		**12**	**0.851**	**11 609**	**1 868**	**0.56**	**0.22**	**2.76**	**0.30**
48	Oravainen	SFE	1	1.300	12 350	2 080	0.95	0.16	5.94	0.14
49	Petolahti	SJO?	2	0.110	617	678	0.41	0.47	0.80	0.56
48-49	**Western Finland**		**3**	**1.410**	**12 967**	**2 758**	**0.68**	**0.32**	**3.37**	**0.35**
50	Pori	SFE	16	3.030	16 921	8 503	0.43	0.25	2.04	0.37
51	Sääksjärvi	SFE	2	3.010	7 235	9 950	0.30	0.42	0.71	0.58
52	Stormi	SFE	14	16.524	95 510	65 396	0.42	0.25	1.92	0.37
53	Kylmäkoski	SFE	5	0.832	4 453	3 884	0.28	0.23	1.16	0.47
50-53	**Vammala Belt**		**37**	**23.396**	**124 119**	**87 734**	**0.36**	**0.29**	**1.46**	**0.45**
54	Keitaanranta	SFE	10	0.040	134	61	0.44	0.19	3.07	0.29
55	Lentola	SFE	3	0.105	412	146	0.34	0.16	3.54	0.36
56	Rieskalammi	SFE	1	0.003	15	9	0.50	0.30	1.67	0.38
57	Kuivanen	SJO?	2	0.004	16	13	0.52	0.47	1.26	0.45
58	Kalkkinen	SFE	2	0.011	78	42	0.57	0.30	1.93	0.34
59	Raivioskorpi	SFE	3	0.007	34	15	0.46	0.19	2.75	0.28
54-59	**Area E of Vammala Belt**		**21**	**0.170**	**689**	**287**	**0.47**	**0.27**	**2.37**	**0.35**
60	Särkisuo	SFE	5	0.125	428	583	0.25	0.26	1.09	0.50
61	Kiipunjärvi	SFE	1	0.005	5	6	0.10	0.11	0.91	0.52
60-61	**Area SW of Vammala Belt**		**6**	**0.130**	**433**	**589**	**0.18**	**0.19**	**1.00**	**0.51**
62	Korkeakoski	SJO	2	0.250	1 035	825	0.42	0.36	1.19	0.46
62	**Subjotnian diabases**		**2**	**0.250**	**1 035**	**825**	**0.42**	**0.36**	**1.19**	**0.46**
1-62	**TOTAL**		**254**	**950.992**	**2 566 423**	**2 481 103**	**0.39**	**0.29**	**6.22**	**0.33**

zone of high nickel potential in Lapland, even though no economic deposits have yet been found so far. In total it is about 100 km long and 1–2 km wide, and is associated with a prominent magnetic high. The zone is almost N–S-trending in its northern parts, but curves toward the southwest and branches in its southern part. As with the Ruossakero Zone, it is located adjacent to or within a deformed granitic basement area. According to Papunen (1993) the Pulju Zone contains lithologies typical of komatiitic greenstone belts, and both metasomatic and magmatic sulfides have been encountered there. The largest nickel deposits here are Hotinvaara and Iso-Siettelöjoki, with potential occurrences around Kietsimä.

Nirroselkä Nickel Zone (4)

The Nirroselkä and Pulju zones (Papunen et al. 1977) share many common features and indeed they almost coalesce at their northern ends. However, the latter zone trends NW–SE and it can be traced some 70 km along the marginal zone of the Lapland Granulite Belt. All of the nickel occurrences of the Nirroselkä Zone have approximately the same size and grade (0.15% Ni), and overall the zone seems to have a smaller ore potential than the Pulju Zone.

Nuttio Nickel Zone (5)

This roughly N–S-trending komatiitic zone is associated with a meandering discontinuous structural feature which transects tholeiitic mafic extrusive rocks for the most part (Pankka 1988, Papunen et al. 1977). It is possible that this zone divides the Lapponian tholeiitic greenstone belt of central Lapland into a younger komatiite-poor part in the west and into an older part in the east where large areas of komatiites are abundant. The southeastern part of the zone is considered to have potential for Kambalda-type ores. On average, the nickel-bearing occurrences in the Nuttio Zone are poor in copper (0.01% Cu) with a Ni/Cu ratio of 40.0.

1.3 Other nickel-bearing areas in northern Finland

Nickel deposits of various size and age have also been located in the eastern parts of northern Finland (Geological Survey of Finland 1994, Papunen et al. 1977, 1979). They usually occur in association with scattered ultramafic bodies in either the granulite belt or in the Archean basement complex. Isolated deposits occur also within the central Lapland greenstone belt and in the Kemi Schist Belt. The following examples represent the most notable nickel-bearing zones or deposits.

Vätsäri Nickel Zone (6)

This curved zone is made up of small peridotite bodies that possibly form the western continuation of the Pechenga Nickel Belt into Finland, and Melezhik et al. (1994) proposed that it continues via the Opukasjärvi Zone into northern Norway. In general, the Vätsäri deposits have Ni/Cu ratio of 16.8. The area is also characterized by small iron formations that are discernible as positive aeromagnetic anomalies.

Lahessaari Nickel Zone (7)

Small nickel-bearing ultramafic bodies (Lahessaari and several others) are present along the northeastern marginal zone of the Lapland Granulite Belt. The zone continues eastward across the Russian border (Lounajärvi), and is evident as a chain of aeromagnetic anomalies along the granulite margin.

Other nickel deposits in the Inari and Utsjoki districts (8)

Nickel-bearing occurrences have been encountered in association with the Njuohgarjavri gabbroic complex, with the volcanogenic Opukasjärvi Zone, and with the Laanila mafic dike at Ahopäät. The age of the NE–SW-trending Laanila dike (Pihlaja 1987b) might be younger than Subjotnian (ca. 998 Ma).

Seitainaapa nickel deposits (9)

Eastern Lapland is characterized by numerous isolated small mafic and ultramafic bodies within the Archean basement complex, and two probable nickel-bearing zones are delineated in the present paper. On average they have quite uniform Ni/Cu ratio of 26.8, although their content of sulfidic nickel always remain very modest.

Keivitsa nickel deposit (10)

The Keivitsa massif is an intrusion composed of pyroxenite, peridotite, gabbro and dunite (Mutanen 1995, 1989). Although it is situated very close to the southwestern contact of the 2440 Ma Koitelainen mafic-ultramafic layered intrusion, the Keivitsa intrusion is of younger age (2050 Ma). Surrounding rocks are made up of various tholeiitic and komatiitic greenstones and volcaniclastic sediments. The Keivitsa deposit seems to be an isolated nickel deposit with no known similar associated deposits in central Lapland. According to preliminary exploration results it is low-grade (0.2–0.5% Ni) with a Ni/Cu ratio of 0.5–0.6. However, because of high tonnage, its metal contents have been predicted to be substantial.

Sirkka nickel deposit (11)

The Sirkka polymetallic Ni-Cu-Co-Au deposit represents one of many nickel-bearing occurrences within the Lapponian volcano-sedimentary environment (Inkinen 1985). It is associated with typical graphite-albite-biotite rocks (Lower Proterozoic), and has a metal content of 0.32% Ni and 0.38% Cu, giving a Ni/Cu ratio of 0.8.

Liakka nickel deposits (12)

The Proterozoic Kemi Schist Belt, characterized by quartzite, dolomite, mafic volcanic rocks and phyllites, contains small mafic-ultramafic bodies (Mäkinen 1987) which may possibly be related to layered intrusions. However, their precise affinity remains uncertain. The three nickel occurrences have an average Ni/Cu ratio of 0.7. The Kukkola layered intrusion in nearby Sweden is also located very close to the western margin of the Archean craton (Öhlander et al. 1987).

1.4 Kuhmo Nickel Belt

Archean greenstone belts within the granite gneiss basement complex of eastern Finland are represented by the Kuhmo–Suomussalmi Greenstone Belt (2790 Ma) and the Ilomantsi Greenstone Belt (2750 Ma). According to Korja et al. (1994) the Kuhmo–Suomussalmi belt forms a geotectonic boundary between two Archean blocks. Typically it is composed of komatiitic mafic and ultramafic volcanic rocks with lesser amounts of felsic volcanic rocks and volcani clastic sediments. In general, it is clearly displayed in both aeromagnetic and gravimetric (Bouguer) maps as a distinct chain of anomalies. No nickel deposits have been encountered within the Ilomantsi Schist Belt.

Kuhmo Nickel Belt (13)

The most prominent nickel deposits within the Kuhmo Belt are Arola (Tuokko 1980), Hietaharju and Peura-aho (Kurki & Papunen 1985). Overall this belt, which is at least 180 km long, coincides with a regional geochemical nickel anomaly in till, reflecting the abundance of komatiites. The Tainiovaara deposit (Pekkarinen 1980) occurs in an ultramafic lens surrounded by granitic gneisses between the Kuhmo–Suomussalmi and Ilomantsi greenstone belts. However, despite its isolated location it may be correlated with the Kuhmo Belt. The Ni/Cu ratio in these deposits varies between 50.0 (Arola) and 2.4 (Peura-aho). Small-scale mining took place at Tainiovaara in 1989, when about 20 000 t of ore was extracted, containing 1.40% Ni and 0.12% Cu.

2. Deposits in layered intrusions

All of the mafic-ultramafic layered intrusions were emplaced between the Archean basement complex and the overlying sedimentary sequence at 2440 Ma, shortly after the cratonization of the Archean crust (Alapieti & Lahtinen 1989). In addition to their nickel potential, these intrusions have had great economic significance because of the chromium mining at Kemi and past mining of vanadium at Mustavaara. Small-scale pilot mining for platinum group metals has been performed at Kirakkajuppura near Kemi. A very similar layered intrusion, Koitelainen, is located within the schist belt of Sodankylä in Lapland (Puustinen 1977). Because komatiitic rocks have been encountered as xenoliths in the Koitelainen intrusion, it means that these country rocks at Sodankylä are at least older than 2440 Ma, likely to be of Archean age.

Vaaralampi Nickel Zone (14)
Porttivaara Nickel Zone (15)

The deposits within the layered intrusions (Lahtinen 1985) form a distinct nickel belt some 300 km long that can be divided into the western Vaaralampi Zone and the eastern Porttivaara Zone. With regard to host rocks the former is peridotite-dominated (Vaaralampi and Suhanko) and the latter gabbro-dominated (Porttivaara and Kuusijärvi). Both zones are associated with prominent positive aeromagnetic anomalies, and they also coincide with gravimetric and till geochemical copper anomalies. Nickel-bearing deposits usually occur as weak sulfide disseminations (0.26% Ni) in the basal marginal rocks and have rather uniform average Ni/Cu ratios, between 0.9 (Vaaralampi Zone) and 0.8 (Porttivaara Zone).

3. Deposits within the Karelian formations

The Puolanka and Outokumpu Schist Belts constitute the Proterozoic cover sequence on the Archean craton. However, some parts of these might also be considered as allochthonous. Because all rock formations within them are spatially and genetically closely associated, their nickel deposits will be treated jointly in the present study. Nickel deposits have been encountered in a specific zone associated with the Outokumpu-type sulfide ores, in the Karelian ultramafic bodies, and in sulfide-rich black schists. The total length of this nickel belt is up to 250 km, but its critical width does not exceed 10 km. In the south, the Outokumpu Cu-Zn-Co massive sulfide ore deposits (1970 Ma) are hosted by rocks of the Outokumpu association. A distinctive feature of these massive sulfide deposits is the mafic-ultramafic signature of their metals, with economic concentrations of cobalt and also nickel. The northerly continuation of the Outokumpu association includes a black schist formation that hosts Ni-Zn-Cu deposits, which are considered to represent a distal expression of Outokumpu-type mineralization. The serpentinite bodies to the east of Outokumpu (Horsmanaho) constitute a nickel-bearing ophiolite complex and similar ultramafic bodies (Lahnaslampi and Jormua) occur to the north of Talvivaara. The serpentinites have been interpreted as tectonically emplaced ophiolites, representing fragments of Precambrian oceanic crust generated some 1970 Ma ago (Koistinen 1981, Gaál 1982, Vuollo 1994). In general, the nickel zones within the Karelian formations can be discerned as aeromagnetic positive anomalies and geochemical nickel and copper till anomalies.

Vuonos Nickel Zone (16)

Concentrations of nickel in banded quartzite or cordierite-anthophyllite rock zones, enclosed within mica gneisses, have been encountered in association with the Outokumpu-type polymetallic massive sulfide deposits at Vuonos, Keretti and Kokka (Parkkinen & Reino 1985). On average, they grade 0.37% Ni and 0.14% Cu, with a Ni/Cu ratio of 12.4. In total 5.5 Mt of nickel ore at 0.20% Ni and 0.04% Cu was mined from a quartzite-skarn zone at Vuonos in 1972–1977. Like Vuonos, the Keretti nickel deposit is also hosted by banded quartzites with metal contents ranging between 0.3–1.1% Ni and 0.003–0.8% Cu.

Lahnaslampi Nickel Zone (17)

Nickel is an essential, although low grade, constituent in all soapstone deposits of the Karelian schist belts which extend from Outokumpu to the north of Talvivaara. These deposits originally represented ultramafic ophiolitic bodies (Karelian), the largest being Lahnaslampi (Tuokko 1992), Repovaara, Horsmanaho, Lipasvaara and Koivukorpi. Their average grade is 0.14% Ni and 0.01% Cu, with a Ni/Cu ratio of 13.1. The deposits are presently mined for talc, and small amounts of pentlandite concentrate is annually recovered as a by-product.

Talvivaara Nickel Zone (18)

These low-grade nickel deposits are associated with extensive sulfide-rich black schists. They are mostly located within the Puolanka Schist Belt, which is typically composed of mica schists and quartzites (Loukola-Ruskeeniemi et al. 1991). The largest deposits are at Talvivaara, Korpimäki, Pappilanmäki and Alanen, and they have an average content of 0.22% Ni and 0.14% Cu with a Ni/Cu ratio of 1.8. Recently large-scale investigations have been carried out in order to develop an appropriate technology for exploiting the Talvivaara Ni-Zn-Cu sulfide deposit.

4. Deposits within the Svecofennian domain or its marginal zone

4.1 Kotalahti Nickel Belt

The concept of the Kotalahti Nickel Belt was originally proposed by Gaál (1972) for those nickel deposits which occur in a semi-linear structure between Hitura and Parikkala. According to the findings of the present paper, it seems more likely that the belt is made up of spatially and genetically separated nickel-bearing zones. In this context, however, the name Kotalahti Nickel Belt is retained only for its historical usage and to describe its geological entity. The total length of the Kotalahti Belt is at least 450 km but the actual critical width is only up to a few kilometers. In its southern and central parts the belt is located at the western margin of the Archean craton, but diverges from it in the Talluskanava area and continues straight toward the northwest. Thus the belt is divided into the northwestern Hitura district and the Kotalahti district proper. It will also be shown later that the Parikkala deposits make up a separate nickel-bearing area.

A regional-scale gravity low runs parallel to the Kotalahti Belt. In its central parts in particular, this anomaly is very distinct, whereas further to the northwest, in the Hitura area, it spreads into several branches. This gravity anomaly has been interpreted to indicate deep fractures, the presence of large amounts of granitic material, and locally high porosity of the rocks in the area. Nickel deposits of the Kotalahti Belt are located on the northeastern flank of the gravity anomaly, where basic magma was also intruded into the crust. The nickel deposits of the Kotalahti Nickel Belt are associated with NW–SE-trending subparallel fault systems (Häkli, Papunen & Tontti 1978) which seem to have en echelon orientations. Gaál (1972, 1980, 1985, 1990) pointed out that the nickel-bearing intrusives are often associated with transcurrent faults, domes and brachyantiforms, while Tontti (1981) discussed the possible relation between intersections of N–S-trending mantled gneiss dome ridges and clusters of nickel deposits. Ekdahl (1993) proposed that the Kotalahti Belt is more specifically associated with the so-called Haukivesi shear zone, and the region between the Haukivesi and Suvasvesi shear zones. He delineated a single right lateral wrench fault from Laukunkangas to Kotalahti and Talluskanava (Haukivesi Fault) and from Talluskanava and Hitura to Perkkiö (Kinturi Fault). However, at least some of these faults belong to a younger system than the nickel-bearing zones.

Cluster and autocorrelation analyses performed by Tontti et al. (1979) showed that the nickel deposits cluster in groups having 2–7 deposits, and that the distance between the clusters is regularly 40–45 km. The results showed also that within the entire Kotalahti Belt further nickel discoveries could be anticipated. The area to the northwest of Hitura was found to be promising, and two clusters were predicted between Kotalahti and Hitura. In spite of extensive exploration however, no new findings have been made in those areas. Nevertheless next nickel mine to be opened in the Kotalahti Belt was in the southeastern Laukunkangas cluster.

Large variations can be discerned along the Kotalahti Nickel Belt. In the present study, the belt is regarded as a single metallogenic entity, and the clustering of nickel deposits within it are treated as nickel zones. Geographically the nickel zones around Hitura in the northwestern part constitute a single entity that could be regarded as a large nickel-bearing district. This was already referred to in an earlier section of the present paper with respect to the general classification of nickel deposits in Finland. The zones between Hitura and Kotalahti are not so clearly defined, and it is only between Kotalahti and Laukunkangas that a set of continuous nickel zones exists. The Parikkala area has traditionally been regarded as a part of the Kotalahti Belt, although there is an apparent gap between Laukunkangas and Parikkala. Because the area to the southeast of Laukunkangas is covered by an extensive lake area and intruded by the younger Puruvesi granite, combining the Parikkala and Laukunkangas areas may not be justified.

In general, the nickel zones of the Kotalahti Belt coincide with aeromagnetic positive anomalies, and distinct geochemical nickel and copper till anomalies. This applies particularly to the Kotalahti, Härmäniemi and Laukunkangas zones, and possibly also to the Ilokangas and Parikkala Zones. However, the area around Hitura is manifested by a regional aeromagnetic low anomaly pattern and no evident internal structure can be discerned. Similar features are also found in the general geochemical till mapping, with the exception of a major regional nickel and copper anomaly that corresponds to the northern boundary of the Hitura area.

Perkkiö Nickel Zone (19)

The Perkkiö pyroxenitic body (Geological Survey of Finland 1994) occurs within the large Ylivieska gabbro complex (1880 Ma). Because it is located some 35 km from the Hitura deposit, it can be considered as a separate and different type of nickel-bearing zone beyond the Hitura Zone. The position of small nickel occurrences to the north of Perkkiö has not been fully established.

Hitura Nickel Zone (20)

The main rock types in the area are sedimentary rocks, intercalated with various volcanic rocks and intruded by granitoids. The sedimentary sequence contains graphite-bearing and sulfide-bearing gneisses (Isohanni et al. 1985). All rocks are intensely metamorphosed and in places schollenmigmatites are present. Several NW–SE-trending subparallel fault lines occur in the vicinity of the Hitura deposits, from Kusiaiskallio to Räihänneva, and may continue through the two small deposits to the north of Perkkiö, and further beyond Perkkiö to Hitura and Kortejärvi, through Makola, and then to Pitkäneva and Ainaslampi. In addition to the prevailing NW–SE-trending faults and foliation, the schists around the Makola and Hitura deposits also exhibit N–S-trends to the north of the Pitkäneva–Ainaslampi Fault. All of the nickel deposits within the Hitura Zone are associated with ultramafic bodies (1885 Ma), with an average grade of 0.47% Ni and 0.25% Cu, corresponding to a Ni/Cu ratio of 2.6. However, the Hitura deposit itself is not typical of the entire zone, being unique with respect to its host rock composition (serpentinite), very high magnesium content, ore body morphology, and ore mineralogy (valleriite, mackinawite). As it was noted earlier in the present paper, Mäkinen (1987) found that the geochemical character of Hitura correlates rather better with the Vammala-type deposits than the Kotalahti-type deposits. The Makola ore deposit was mined between 1941–1948 and again from 1951–1954, during which time about 415 000 t of ore were extracted with an average grade of 0.72% Ni and 0.43% Cu. Mining commenced at the Hitura deposit in 1970 and has continued since then, except for minor interruptions during 1982–1984 and 1985–1988. Up until 1994 some 8.1 Mt of ore had been mined at an estimated grade of 0.55% Ni, 0.20% Cu and variable amounts of PGM. The best PGM accumulation (20 000 tonnes) yielded a mill feed with values as high as 0.034 g/t Pt, 0.041 g/t Pd and 0.015 g/t Rh, although only half of that was recovered in the concentrate. At present, nickel ore from Hitura is extracted as a material for nickel compounds.

Ilokangas Nickel Zone (21)

This nickel-bearing zone, situated some 85 km to the southeast of Hitura, is associated with the small Ilokangas and Koivujoki serpentinite bodies and with the low-grade Saarela gabbro (Ekdahl 1993). The serpentinites belong to a narrow N–S-trending mica gneiss area which is surrounded by granitoids. Because of its geographic position and its geological environment, it is questionable whether the Ilokangas Zone belongs to the Kotalahti Nickel Belt proper, as has been proposed on earlier occasions.

Talluskanava Nickel Zone (22)

About 40 km to the southeast of Ilokangas, the ultramafic bodies at Tervo form a cluster of three nickel deposits (Ekdahl 1993). Geologically the environment is manifested by the presence of areas of mica gneisses and volcanic rocks enclosed in granitoids. The largest of the deposits in this zone is located at Talluskanava.

Kotalahti Nickel Zone (23)

Migmatitic mica gneisses are the predominant country rocks in the Kotalahti area, together with amphibolites, graphite-bearing schists and synkinematic to late-kinematic granitoids. Structural and metamorphic relations suggest that the Kotalahti mafic-ultramafic intrusions were emplaced at the beginning of the Svecofennian orogenic activity 1883 Ma ago (Gaál 1980). The largest occurrence of younger mafic rocks in the vicinity of Kotalahti is the dome-shaped Valkeinen gabbro massif in the core of a brachyantiform. The very modest nickel content of this gabbro demonstrates the fact that not all mafic bodies in a given ore zone necessarily have the potential for economic nickel ores. The largest deposits in this nickel zone are Kotalahti and Sarkalahti (Mäkinen 1987, Papunen & Koskinen 1985, Niemi 1989), the former of which was mined from several ore bodies between 1958–1987, with a total production of some 12.3 Mt of ore grading 0.66% Ni and 0.26% Cu. Compared to the Hitura deposit, the PGM content at Kotalahti is very low, around 0.005 g/t Pt and less than 0.005 g/t Pd and Rh. During the last years of mining at Kotalahti, ore was also taken from an off-shoot ore body that was exceptionally rich in sulfide minerals. New nickel occurrences have recently been identified to the east of Kotalahti.

Härmäniemi Nickel Zone (24)

Härmäniemi is the largest nickel deposit in a cluster of nine small deposits (Geological Survey of Finland 1994, Niemi 1989, Häkli, Papunen & Tontti 1978), situated midway between Kotalahti and Laukunkangas. The area is characterized by the presence of mafic intrusions within granitoids in a migmatitic mica gneiss environment. In spite of extensive exploration, no economic nickel deposits have been found within this zone.

Laukunkangas Nickel Zone (25)

This zone consists of a cluster of mafic (noritic) bodies immediately to the east of the western margin of the Archean craton as drawn by Luukkonen & Lukkarinen (1986). The transverse trend of nickel deposits in the Laukunkangas Zone with respect to the main Kotalahti Belt was already noted by Gaál (1972). The zone includes the Laukunkangas (1850 Ma), Makkola, Hälvälä and Sulkavanniemi deposits (Isomäki 1994, Juhava et al. 1989, Niemi 1989, Mäkinen 1987, Grundström 1985). The Laukunkangas intrusions are located in a schollenmigmatitic mica schist belt, with intercalations of graphite-bearing schists, which is in turn surrounded by granitoids. In 1984 mining operations commenced at Laukunkangas (Enonkoski), which is the largest ore deposit in the area, and by 1994 some 6.7 Mt of ore had been taken at an estimated grade of 0.78% Ni and 0.22% Cu. Nickel was also mined from Hälvälä between 1988–1992 and some 249 000 t of ore was extracted at an estimated grade of 1.56% Ni and 0.39% Cu.

Parikkala nickel deposits (26)

Some 70 km southeast of Laukunkangas at Parikkala, near the Russian border, is a lone differentiated gabbro body dated 1890 Ma (Mäkinen 1987). The intrusion is surrounded by mica gneisses and minor granitoids. The extensive and younger post-orogenic Puruvesi granite (1800 Ma) has intruded the area between Laukunkangas and Parikkala. The nickel deposits at Parikkala comprise a cluster which was regarded by Gaál (1972) as the southeastern end of the entire Kotalahti Belt. However, the Parikkala Zone contains features that differ with respect to the other zones within the Kotalahti Belt (cf. also Papunen et al. 1979, Mäkinen 1987), and it is also located to the south of the projected eastern continuation of the Häme Fault.

Therefore the structural position of the Parikkala deposits cannot be clearly established, and they might even be associated with the Telkkälä Nickel Belt. The largest nickel-bearing deposits are situated at Ruimu and Revonmäki, which have an average content of 0.32% Ni and 0.30% Cu.

4.2 Nickel zones and deposits to the northeast of the Kotalahti Nickel Belt

Several nickel deposits have been encountered in a zone which runs subparallel and to the northeast of the Kotalahti Belt. These have been traditionally classified as Svecofennian-type deposits, although they are located to the northeast of the western margin of the Archean craton. The position of the Löytynmäki Zone in particular is not fully understood.

Löytynmäki Nickel Zone (27)

The Löytynmäki, Saarinen and Osmanki nickel occurrences (Geological Survey of Finland 1994) are situated in the same area as the Säviä Zn-Cu-bearing deposit, although the relationship between the nickel and base metal deposits seems to be spatial only. According to Ekdahl (1993) the Suvasvesi Fault should pass between Ilokangas and Saarinen, and thus it could form the boundary between the main Kotalahti Belt and the Ilokangas Zone. Although the Löytynmäki and Ilokangas zones are located close to one another, their spatial relationships are not clearly understood. The same applies also to the relationship between the Löytynmäki Zone and the Hitura Zone, and especially to the Räihänneva and Kusiaiskallio deposits.

Kettäjänniemi nickel deposit (28)

This small peridotite body is the only nickel occurrence that is situated in the southern parts of the Kola–Karelian Domain in Finland. As with some other small Svecofennian-type nickel occurrences in the area its position with respect to the cratonic margin cannot be fully ascertained.

4.3 Nickel zones and deposits to the southwest of the Kotalahti Nickel Belt

Parallel nickel zones can be located to the southwest of the Kotalahti Nickel Belt. Many of them are also controlled by similar NW–SE-trending sets of faults (cf. Vuorela 1982). All are located to the southwest of the regional gravimetric low, and therefore they occupy a separate position with respect to the Hitura Zone and thus also to the main Kotalahti Belt (cf. Gaál et al. 1978). They seem to constitute continuous nickel-bearing zones, although their overall extent is difficult to delineate precisely. For instance, the distance from the Muurasjärvi deposit to the Hyttikangas occurrence is 130 km, and it is further 60 km to the Purstosaari deposit. The situation is similar with regard to the other zones in the area, so that in this paper each nickel-bearing cluster is treated separately.

Muurasjärvi Nickel Zone (29)

Some 15 km to the south of Makola is a distinct NW–SE-trending set of faults associated with various gabbroic bodies. They form a cluster of nickel deposits (Geological Survey of Finland 1994, Nikander 1991) that are generally very small and low-grade, with the exception of the Muurasjärvi deposit itself. They are associated with different kinds of host rocks than at Hitura, and have a differing Ni/Cu ratio (1.5), and therefore they are considered to comprise a separate but parallel nickel zone. It is moreover possible that some of these nickel occurrences are located very close to the gravity low area. The zone is located in the northernmost parts of the central Finland granite complex which is characterized by isolated mica gneiss areas with mafic and granitic intrusions.

Hyttikangas nickel deposit (30)

The Hyttikangas peridotite-hosted occurrence (Geological Survey of Finland 1994) is situated some 40 km to the northwest of Kotalahti, but clearly within the Svecofennian Domain. The country rocks are mica gneisses with lesser amounts of amphibolites. It is very poor in nickel (0.15% Ni) and its Ni/Cu ratio (0.5) is also different from the Kotalahti deposits (2.9).

Purstosaari Nickel Zone (31)

Parallel to the Härmäniemi and Laukunkangas zones, and within a distance of less than 10 km to the southwest, four small ultramafic bodies, Iso-Valvatusjärvi, Tiemasoja-1, Tiemasoja-2 and Purstosaari (Geological Survey of Finland 1994), define a separate nickel zone. They are situated in an area characterized by intensely alternating mica gneisses and felsic to mafic gneisses embedded in granitic rocks. The largest of these deposits is Purstosaari, located just to the south of Laukunkangas, but within the mafic Joutsenmäki intrusion (Parkkinen 1971). The zone is also marked by a separate aeromagnetic positive anomaly and by a separate geochemical nickel and copper anomaly in till.

Ilmolahti Nickel Zone (32)

A chain of six nickel deposits can be delineated in small mica gneiss or quartz-feldspar gneiss remnants within the northern parts of the central Finland granite complex at Viitasaari (Geological Survey of Finland 1994). They are all associated with the same NW–SE-trending fault, along which they are distributed over a distance of 80 km. The chain commences with the pyroxene gabbro at Holmisperä, followed by the Ilmolahti peridotite and the Teerisuo norite (Sipilä 1986) in the southeast. All of these deposits have a quite similar Ni/Cu ratio with an average value of 1.7.

Kekonen Nickel Zone (33)

Deposits in this zone are encountered as two clusters, some 15 km apart, around the Piilukka norite body in the northwest, and around the Kiiskilänkangas, Kekonen, Saarijärvi and Rantala peridotite bodies (Makkonen 1992) in the southeast. Geologically the country rocks consist of mafic gneisses and granitic lithologies alternating with mica gneisses. A limestone sequence is also present near the Piilukka occurrence. The zone is marked by a positive aeromagnetic anomaly and a gravity high, as well as a moderate geochemical nickel anomaly in till.

Pesäneva nickel deposit (34)
Venetekemä Nickel Zone (35)
Ihastjärvi nickel deposits (36)

The Pesäneva occurrence is located some 13 km to the southwest of Muurasjärvi. It may form a contiguous nickel zone together with the Venetekemä (Niemi 1989) and Pyhäjärvi deposits and a number of other smaller nickel occurrences further to the southeast. A connecting chain of moderate anomalies is also discernible in aeromagnetic maps. Parallel to the Venetekemä Zone, a separate nickel zone can be detected which links the Ylemmäinen and Ihastjärvi deposits (Laitakari & Kohonen 1988). Except for Ihastjärvi, all of these deposits occur within a predominantly granitic setting.

Salmenkylä nickel deposit (37)
Ohensalo nickel deposits (38)

Gabbroic bodies at Salmenkylä, Ohensalo and Istruala (Geological Survey of Finland 1994, Kohonen 1988) contain small nickel occurrences and clearly resemble each other, as do many other bodies encountered in the same area. In general they are located in the eastern parts of the central Finland granitic area where only small sedimentary remnants are left. The location of these deposits is also controlled by generally NW–SE-trending faults. As with the Venetekemä deposits, there is no evidence for any association with NE–SW-trending structural features. Copper usually prevails over nickel in these deposits. Their ore potential is very modest, which was also noted by Mäkinen (1987) in his reference to Svecofennian gabbro-type nickel deposits.

Koivakkala nickel deposit (39)

The Koivakkala peridotite (Geological Survey of Finland 1994) is associated with a major gabbroic body and is situated quite close to the Häme Fault, while to the west of the Sulkava thermal dome. It contains a small nickel-bearing deposit that has a Ni/Cu ratio of about 2.0. It may also be related to the Ohensalo Zone, some 55 km to the northwest.

4.4 Nickel zones and deposits within the Sulkava area

According to Vaasjoki & Sakko (1988) the Svecofennian crust was rapidly generated by collision of a Proterozoic oceanic plate with the Archean continent between 1930 and 1850 Ma. During subsequent underplating oriented along an E–W direction, a thermal dome was formed in the Sulkava area (Korsman et al. 1988), accompanied by granulite facies metamorphism at about 1820 Ma. The area is discernible in regional geological maps (e.g. Hämäläinen & Vaasjoki 1992, Koistinen 1994) as a predominantly veined mica gneiss unit, with granitic material being especially abundant in its eastern parts. The nickel zones or isolated bodies within the Sulkava nickel area show no significant regional aeromagnetic or till geochemical anomalies. Alternatively, granulite metamorphism might have altered the redox state of some sulfide or oxide minerals, so that magnetic anomalies are weakened or obliterated. This suggests that the deposits within or near the thermal dome may be of different age than those in the Kotalahti and Laukunkangas zones. This conclusion may also be supported by the observation that some of the mafic-ultramafic intrusives seem to have been emplaced into diverging N–S-trending faults. If the emplacement of nickel-bearing ultramafic bodies had preceded the formation of the thermal dome, they would have undergone profound metamorphism and reworking. Most of the nickel deposits are found at the stratigraphic bases of the intrusions

(Makkonen 1993a, 1992). The area has been affected by several later events, as demonstrated for example by the emplacement of a carbonatite dike near Mikkeli some 1710 Ma ago (Puustinen & Karhu 1995).

Kätkytsaari Nickel Zone (40)

A narrow zone of very small nickel-bearing ultramafic bodies (Geological Survey of Finland 1994) is encountered along a N-S-trend and the composition of the rocks suggest that they may have a komatiitic affinity. This is also shown by the relatively low copper content (0.07%) and the Ni/Cu ratio of 7.1. Unlike the other nickel-bearing zones of the Sulkava thermal dome, the Kätkytsaari Zone is associated with a positive aeromagnetic anomaly and with a geochemical nickel and copper anomaly in till.

Rietsalo Nickel Zone (41)

The four small gabbroic bodies of the 25 km long Rietsalo Zone form a distinct and very narrow N–S-trending chain located inside the Sulkava thermal dome. The main deposits are at Pihlajasalo, Rietsalo and Heiskalanmäki (Makkonen 1992). Originally the entire zone may have been formed as a continuous unit, with the northern end being defined by an E–W-trending fault.

Niinimäki nickel deposit (42)

The Niinimäki deposit is associated with a solitary peridotite body in mica gneisses and granites, about 7 km to the east of the Rietsalo Zone. The deposit itself has a relatively high metal content (1.17% Ni and 0.41% Cu) which gives a Ni/Cu ratio of 2.9.

Sarkalahti nickel deposits (43)

The two gabbro bodies at Sarkalahti and Pahalampi (Makkonen 1993b) are located along the continuation of the Ilmolahti–Kekonen line. This observation is possibly meaningless because the deposits are located totally inside the Sulkava thermal dome, and may therefore be unrelated to this trend.

Kitula nickel deposit (44)

The minor Kitula deposit at Puumala is an isolated occurrence within an area of mica gneisses (Ketola 1982). Its nickel content is relatively high (Ni/Cu = 4.00), and of the same order as in the Niinimäki deposit. For a short period in 1970, at the same time as operations commenced at Telkkälä, about 19 000 t of ore at 0.67% Ni and 0.24% Cu was taken from Kitula.

4.5 Telkkälä Nickel Belt

The Telkkälä Nickel Belt is aligned in a WNW–ESE direction, close to northern contact of the anorogenic Viipuri rapakivi granite and to the south of the Sulkava thermal dome. It has a total length of at least 80 km. Generally, the mafic-ultramafic intrusions here are concordant with respect to the schistosity in the surrounding mica gneisses, mafic volcanic rocks and granitoids. The relationship between the Telkkälä Belt and the Kotalahti and Vammala belts has not been fully clarified, partly because it is situated to the south of the Häme Fault. It could also be anticipated that the Telkkälä Belt may correlate via the Ohensalo deposits with Oravainen at the Gulf of Bothnia, but the formation of the central Finland granite complex would have obliterated much of the evidence for this. Although the rapakivi contact is only a few kilometers from the Telkkälä Belt, it is believed that it has had no direct influence on the nickel deposits. All the deposits within the belt have quite uniform Ni/Cu ratios that vary between 1.0 and 3.3, except for Telkkälä and Ahokkala where it is on average 6.6. The Telkkälä Belt appears as a cluster of positive aeromagnetic anomalies within a regional gravity high.

Leipäsaari nickel deposit (45)

The small Leipäsaari deposit (Geological Survey of Finland 1994) is situated within mica gneisses between the Ahvenisto rapakivi and Hyrkkälä gabbro massives. Its is hosted by a separate gabbro body exposed on an island in Lake Kuolimojärvi.

Telkkälä Nickel Zone (46)

The Telkkälä Zone is composed of a cluster of seven deposits, of which Telkkälä and Ahokkala are the largest (Isomäki 1994, Häkli 1985). The Telkkälä deposit (at least 1820 Ma) is associated with a differentiated mafic intrusive which has also a distinct downward continuation. During the first period of mining in 1969–1970, some 211 000 t of ore at 1.08% Ni and 0.30% Cu was extracted. Later, from 1988–1992, after the discovery of new ore reserves, some 394 000 t of ore was mined at an estimated grade of 1.66% Ni and 0.41% Cu.

Kuurmanpohja Nickel Zone (47)

A cluster consisting of four coherent, but very small deposits (Geological Survey of Finland 1994) marks the eastern end of the Telkkälä Belt, about 35 km east of Telkkälä, near the Russian border. All of the deposits here are associated with gabbro bodies.

4.6 Nickel deposits in western Finland

Oravainen nickel deposit (48)

The Oravainen peridotite body is an isolated occurrence located on the sea-floor off the coast of the Gulf of Bothnia, in an area of kinzigitic gneiss with small areas of migmatitic mica gneiss, graphite schist and quartzite (Isohanni 1985). The nickel content of this pipe-like deposit is relative high (0.95% Ni), with a Ni/Cu ratio of 5.9. Because no apparent faults or similar lineaments or geochemical anomaly patterns can be detected in the area, the Oravainen deposit cannot be ascribed to any other known nickel-bearing district.

Petolahti nickel deposits (49)

A NW–SE-trending olivine diabase body at Petolahti hosts another of the isolated nickel deposits near the Gulf of Bothnia coast (Sipilä et al. 1985). The regional bedrock is mica gneiss with graphite-rich intercalations and granite veins. The small Pirttikylä deposit, located some 16 km to the southeast of Petolahti, might belong to the same linear structure. A provisional Subjotnian age (ca. 1650 Ma), similar to the Korkeakoski dike, has been tentatively assigned to the Petolahti dike (Papunen & Vorma 1985, Reino et al. 1993). The Petolahti deposit was mined in 1972–1973 and some 86 000 t of ore was extracted, with an average grade of 0.47% Ni and 0.38% Cu.

4.7 Vammala Nickel Belt

The entire WNW–ESE-trending Vammala Nickel Belt extends from the Gulf of Bothnia at Ahlainen to Vammala (Stormi) and further beyond to Kylmäkoski. Based on its metallogenic and structural features, it can be divided into the Pori, Sääksjärvi, Stormi and Kylmäkoski nickel zones, of which only the Stormi and Kylmäkoski zones are related to each other. The name Vammala Nickel Belt is thus used in the present paper to describe the whole metallogenic belt as a single entity. The Vammala Belt terminates immediately to the southeast of Kylmäkoski (cf. Saltikoff & Tontti 1990). In its central part, it is transected by a N–S-trending structural unit that can be traced from Sääksjärvi to Rausenkulma, which makes it possible that the Sääksjärvi Zone is a unique section of the Vammala Belt. In general, the fracture pattern within the Vammala Belt is not as clearly seen as it is within the Kotalahti Belt. This may be due to masking of topography by Pleistocene clay deposits, which are very common in southwestern Finland. An exception to this is the Pori Zone, which is characterized by a distinct set of NW–SE-trending and parallel linear faults. A local shear zone, called the Kynsikangas zone, has been postulated in some instances to have been the main feeder for the nickel deposits of the Pori Zone. However, it is likely that the Kynsikangas shear zone is of a younger age and has no direct relation to the nickel-bearing intrusions. Compared to the Pori Zone and the discordant Sääksjärvi area, the Stormi and Kylmäkoski zones comprise separate nickel-bearing areas in the southern parts of the W–E-running geosynclinal Häme Schist Belt. On geophysical maps they appear as broad positive aeromagnetic anomalies, combined with an obscure regional gravity high. Their geochemical nickel and copper till anomalies are not as straightforward. In general, the entire Häme Schist Belt is also characterized by an extensive regional till geochemical anomaly.

Pori Nickel Zone (50)

Deposits of the Pori Zone are located to the north of Jotnian sandstones, in a schist belt consisting of migmatitic mica gneisses with garnet-cordierite gneisses, skarn rocks and amphibolites, variably intruded by granitoids (Geological Survey of Finland 1994). The most ore potential fault system in the area is up to 15 km wide and 50 km long. Due to the location of nickel deposits in different faults, the Pori Zone could also be further subdivided into the Sahakoski and Hyvelä subzones, both of which clearly terminate against the Kynsikangas shear zone in the southeast. In total, the Pori Zone comprises sixteen nickel deposits in ultramafic bodies, of which only the small Ruoppasuo occurrence is located to the south of the main area. On average they have metal contents of 0.43% Ni and 0.25% Cu with a Ni/Cu ratio of 2.0. According to Mäkinen (1987) the deposits of the Pori Zone can be classified as Kotalahti-type intrusions. The largest nickel deposits are Sahakoski (Niemi 1989), Hyvelä (Niemi 1989, Stenberg & Häkli 1985), Harjunpää and Kalliorinne. On the aeromagnetic maps the Pori subzones are distinguished as a set of parallel positive anomalies. A regional geochemical nickel and copper anomaly is also visible in till.

Sääksjärvi nickel deposits (51)

The Sääksjärvi peridotite body is located between the Pori and Stormi zones. The general NW–SE-trending structure is cut here by a profound N–S-trending structural feature which is about 15 km wide and 70 km long. Small ultramafic bodies of similar type usually occur in association with migmatitic mica gneisses and volcanic rocks enclosed within granitoids. According to its chemical composition, the Sääksjärvi peridotite has a komatiitic affinity (Mancini 1993), which also distinguishes it from all other intrusions in the Vammala Belt. The Rausenkulma deposit to the south of Sääksjärvi may occur within the same N–S-trending structure, which is also manifested by a very uniform Ni/Cu ratio of 0.7. The aeromagnetic maps show a regional N–S trending negative anomaly pattern in the Sääksjärvi area, but the individual mafic bodies can be discerned as enhanced positive anomalies within this overall feature.

Stormi Nickel Zone (52)

In the Vammala area, a cluster containing at least fourteen nickel deposits occurs over a distance of 30 km (Mäkinen 1987, Häkli & Vormisto 1985), of which the largest deposits are Stormi, Ekojoki, Kovero-oja and Mäntymäki (Hoipola). The large number of known deposits is also a result of extensive exploration carried out near the Stormi mine. Emplacement of the host peridotite-norite-gabbro intrusions occurred 1890 Ma ago under relatively low P-T conditions. Ultramafic bodies occur within mica gneisses with intercalated garnet-cordierite gneisses, graphite-bearing schists and volcanic rocks. Granitoids are invariably present as discrete plutons. Peltonen (1995) proposed that when the ascending magmas encountered sedimentary formations containing abundant sulfidic black schists, they assimilated external sulfur, leading to the formation of an immiscible sulfide phase in the magma. Obvious fault patterns are not recognizable in this area, and on aeromagnetic maps the zone appears as an obscure cluster of anomalies. A relatively clear geochemical nickel and copper anomaly in till exists between the Stormi area and Kylmäkoski, where it is not, however, as obvious as in the northwest. Compared to the Pori Zone, the Stormi Zone has a similar average metal content of 0.42% Ni and 0.25% Cu. Test mining was first carried out at the Kovero-oja deposit already in 1975–1977 and about 460 000 t of ore at 0.43% Ni and 0.32% Cu were extracted. Full-scale mining started at the Stormi nickel deposit in 1978. Between 1975–1994 some 7.6 Mt of ore was mined from the Vammala area, with an estimated grade of 0.68% Ni and 0.42% Cu. Plans have been made recently for exploitation of the Mäntymäki deposit as well.

Kylmäkoski Nickel Zone (53)

The Kylmäkoski mafic-ultramafic bodies (Papunen 1985) are located about 35 km to the southeast of the town of Vammala. The mica gneisses in the area constitute a sedimentary belt surrounded by granitoids, and which is quite separate from the schist belt around Stormi. The Kylmäkoski Zone marks the end of the entire Vammala Nickel Belt, and there is no evidence for its continuation to the southeast. The zone comprises five nickel deposits, of which the most prominent, the Kylmäkoski (Taipale) deposit, was mined from 1971–1974. During that time some 690 000 t of ore was mined grading 0.36% Ni and 0.27% Cu.

4.8 Nickel zones and deposits to the east of the Vammala Nickel Belt

The lithological environment and the subparallel fracture pattern are the two fundamental controls on the location of nickel-bearing mafic-ultramafic bodies in this area. All of the nickel deposits in this area east of the Vammala Nickel Belt are confined to the northern part of the South Svecofennian Subprovince as defined by Gaál & Gorbatschev (1987). The ultramafic bodies are distributed among large areas of migmatitic mica gneisses. From the paleotectonic point of view Kinnunen & Saltikoff (1989) noticed that chemical sediments were deposited in a deep-sea environment within this schist belt. In the present paper, a NW–SE-trending fault system has again been invoked as controlling the location of mafic-ultramafic bodies in the region. The orientations of the faults differ slightly from the general trend of the Vammala Belt. The nickel zones seem to terminate in the southeast against the Häme Fault. All of the nickel zones show at least moderate geochemical nickel and copper anomalies in till, which also coincide with the major NW–SE-trending faults.

Keitaanranta Nickel Zone (54)
Lentola Nickel Zone (55)

The Keitaanranta Zone may have a length of up to 150 km and could perhaps be traced even further for some 70 km northwest, to Kristiinankaupunki. In total, the zone consists of ten small nickel-bearing occurrences (Geological Survey of Finland 1994), mostly associated with mafic bodies.

Usually these are enclosed within mica gneisses, or occur in association with mafic volcanic rocks, as in the northwestern part of the zone. They have a quite uniform average Ni/Cu ratio (3.1), which is of the same order as in the Lentola Zone (3.5), where two nickel occurrences have been found within mica gneisses.

Rieskalammi nickel deposit (56)
Kuivanen Nickel Zone (57)
Kalkkinen Nickel Zone (58)
Raivioskorpi Nickel Zone (59)

Each of these zones contain from 1–3 nickel occurrences in a variety of host rocks and with varying Ni/Cu ratios (Geological Survey of Finland 1994, Oivanen 1959). Nickel-bearing zones have not been fully defined in many cases in the present paper, mainly due to inadequate source data. Some deposits, at least within the Kuivanen Zone, could be associated with a Subjotnian diabase dike swarm. The occurrences further east, which are designated as forming the Raivioskorpi Zone, could also be subdivided into two separate nickel-bearing zones.

4.9 Nickel zones and deposits to the southwest of the Vammala Nickel Belt

This is a triangular nickel-bearing area delineated by the Espoonlahti Fault on the southwest and the Häme Fault from the southeast. The former fracture trend can be traced from Espoonlahti, west of Helsinki, in a NW-direction to the north of Pori. Part of it has also been referred to as the Pori Shear Zone and its main fault zone by Pietikäinen (1994). A general NW–SE-trending fracture pattern is also discernable within this nickel-bearing area. Two zones have been recognized, of which only the Särkisuo deposit and its surroundings have any metallogenic significance. The country rocks surrounding the deposits consist of mica gneisses with some mafic volcanic rocks. It has already been noted by Saltikoff & Koistinen (1989) that no nickel deposits or glacially transported nickel-bearing boulders have been encountered to the southwest of the Espoonlahti Fault.

Särkisuo Nickel Zone (60)
Kiipunjärvi nickel deposit (61)

Only a few kilometers from the Häme Fault, a cluster of five nickel occurrences (Tiainen & Viita 1994) in mafic intrusive bodies marks the southeastern end of the Särkisuo Zone. The average Ni/Cu ratio of the deposits is around 1.0, which is also the case for the Kiipunjärvi nickel occurrence. A positive aeromagnetic anomaly and a geochemical nickel and copper anomaly in till can be discerned over the Särkisuo deposit.

5. Deposits in Subjotnian diabases

Korkeakoski Nickel Zone (62)

Two small nickel deposits have been encountered in association with a Subjotnian diabase dike at Korkeakoski, about 30 km to the north of Pori (Geological Survey of Finland 1994). An age of about 1650 Ma has been proposed by Pihlaja (1987a) for this dike, located in a mica gneiss environment. It is also apparent that the Korkeakoski Zone is related only in a spatial sense to the Pori Nickel Zone. The main reason for treating it as a separate zone is its age and ore-type. The zone is clearly discernible as an E–W-trending positive aeromagnetic anomaly, and as a geochemical nickel and copper anomaly in till. As mentioned earlier, the Petolahti deposit has also been classified amongst the Subjotnian diabases. The same could well apply to the Kuivanen Zone.

LITHOLOGICAL FRAMEWORK WITH RESPECT TO THE LOCATION OF NICKEL DEPOSITS

The association between nickel deposits in mafic-ultramafic rocks and migmatitic schist belts has already been mentioned on several occasions. With regard to the Kotalahti Nickel Belt it has been shown by Tontti et al. (1979) that at a semi-regional scale, its nickel deposits are typically located in an environment consisting of mica gneiss or granodiorite/trondhjemite accompanied by minor mafic intrusive bodies. A similar result was also obtained for the Svecofennian nickel deposits of southwestern Finland by Saltikoff & Koistinen (1989).

A study of regional lithology for the present paper was performed using the geological map of Finland compiled by Simonen (1980). The map is essentially lithological, and despite some antiquat-

Table 3. Relative proportions of dominant lithologies (percentages of rocks) throughout the whole country and in the surroundings of each nickel deposit type. Deposit types are classified as in Table 2.

Rocks	Whole country	AKO 1.	ARC 1.3	LIN 2.	OKU 3.1	OPH 3.2	BLS 3.3	SFE 4.	SJO 5.
Caledonian rocks	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Jotnian rocks	0.8	0.0	0.0	0.0	0.0	0.0	0.0	2.0	0.0
Rapakivi granite	4.7	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0
Granite	14.9	1.5	0.0	0.0	0.0	1.4	3.5	5.9	10.3
Migmatitic gneiss	12.4	2.9	0.0	0.0	0.0	0.0	0.0	40.3	78.8
Granodiorite	20.1	22.0	8.1	0.0	6.7	0.0	0.0	36.0	10.9
Gabbro	2.2	1.6	0.0	0.0	0.0	0.6	0.0	6.2	0.0
Serpentinite	0.3	1.6	0.0	0.0	27.1	13.6	2.3	0.0	0.0
Amphibolite	6.1	17.7	0.0	7.2	0.0	5.4	5.8	2.9	0.0
Mica schist and gneiss	6.8	1.9	0.0	1.6	56.3	49.0	11.5	5.2	0.0
Quartz-feldspar schist	1.8	3.6	0.0	0.0	0.0	0.0	0.0	0.7	0.0
Quartzite	3.7	3.8	0.0	10.0	2.5	23.5	22.7	0.1	0.0
Layered intrusion	0.3	0.0	0.0	26.6	0.0	0.0	0.0	0.0	0.0
Granulite	3.7	0.0	50.0	0.0	0.0	0.0	0.0	0.0	0.0
Archean serpentinite	0.1	5.7	0.6	0.0	0.0	0.0	0.0	0.0	0.0
Archean amphibolite	1.3	12.3	6.3	0.0	0.0	0.0	0.0	0.0	0.0
Archean schist and gneiss	1.8	4.4	3.8	0.0	0.0	0.0	2.9	0.0	0.0
Archean migmatitic gneiss	18.8	21.2	31.3	54.7	7.5	6.5	51.3	0.3	0.0

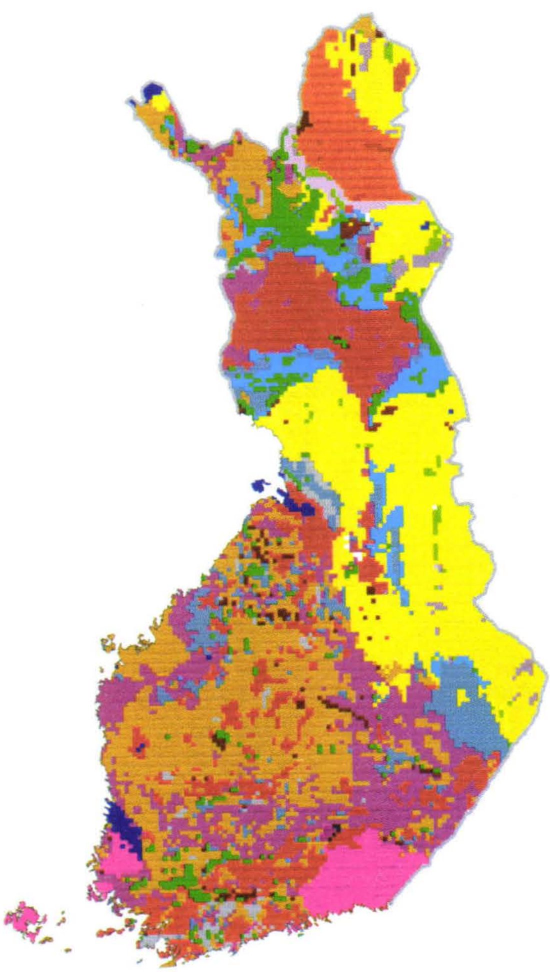

Fig. 3. Digitized (5 x 5 km cell) geological map of Finland, after Simonen (1980).

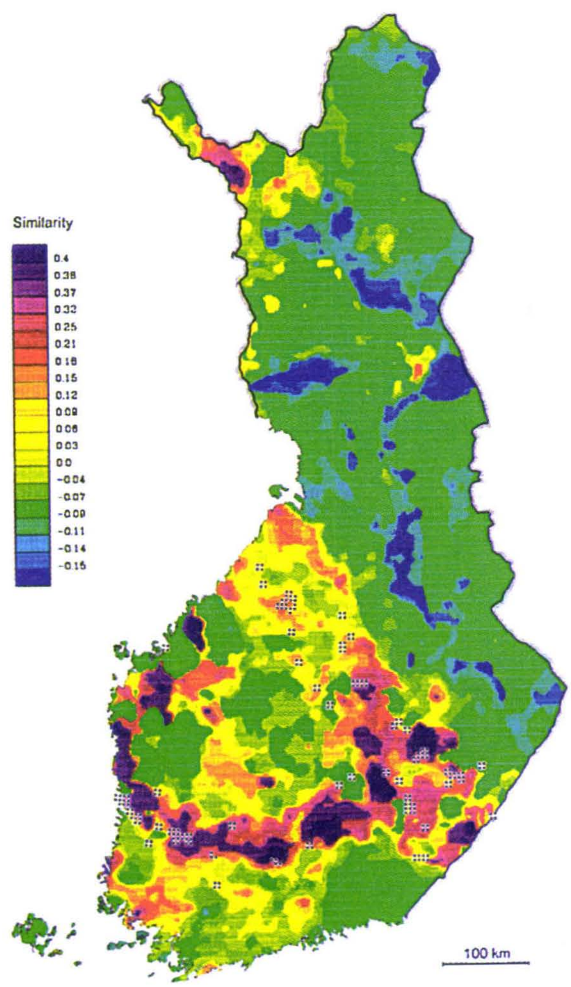

Fig. 4. Similarity analysis of Svecofennian nickel deposits using the dotted cells as the model and the data of Fig. 3 as the target. Similarity between the model and the target area: red color = high similarity; blue color = low similarity.

ed interpretations (e.g. komatiitic rocks are included among amphibolites), it provides a uniform overview of the distribution of major rock types throughout the country. This map (Fig. 3) had already been digitized in 5 x 5 km cells by Lehtonen, Tontti & Koistinen (1987), thus facilitating statistical studies on a spatial basis with a resolution quite suitable for the present study. The environment surrounding a given nickel deposit is defined here as a 10 x 10 km cell. Typical lithologies, with rough percentage estimates of the proportions of rock types in the respective cells, were picked out and summarized according to the main nickel deposits classes. The results are presented in Table 3, and it can be observed that the highly metamorphic migmatitic gneisses together with intermediate plutonic rocks dominate in the environments of the Svecofennian nickel deposits. The abundance of migmatites and the insignificance of granites when compared to the other deposit types are the most striking features for the Svecofennian deposits. On the other hand, low-grade gneisses and schists prevail around the Karelian deposits (Vuonos, Lahnaslampi and Talvivaara types).

A similarity analysis (SIMANA) developed by Koistinen (1981) was performed by applying the data in Table 3 in order to define bedrock areas similar to the model. The lithological environment of the Svecofennian deposits was used as a model (column SFE in the table, excluding rock types having zero values). The model consists of 130 5 x 5 km cells around major Svecofennian nickel deposits. The result of the analysis is shown in Fig. 4, which can be compared with the original digitized bedrock data in Fig. 3. One of the interesting features to be seen in the SIMANA map is that the Kotalahti Belt splits into the northwestern (e.g. Hitura) and southeastern (e.g. Kotalahti and Laukunkangas) parts. The northwestern part has a relatively low similarity in environment lithology (i.e. migmatitic mica gneisses) in regard to the Svecofennian model deposits, whereas the southeastern part appears as profound clusters at the boundary between the Archean and Proterozoic domains. In the western coastal region, between Pori and Kokkola, large areas can be identified that have a high similarity in regard to the model deposits.

METALLOMETRIC PARAMETERS

Metallometric parameters of ore deposits describe the amount and the intensity of the spatial concentration of particular metals during the ore forming processes. In the present paper, all nickel deposits in Finland were described in terms of their tonnage, and grade of nickel and copper (cf. Table 2). Cobalt and platinum group metals were not included in the study due to deficiencies of the original data.

Grade and tonnage models derived from known ore deposits provide the basis for quantitative assessment of undiscovered ore resources as well as serving as guides in exploration (Cox & Singer 1986). These models have usually been applied to major ore deposits, but also to deposits of small-scale mining (Bliss et al. 1990). This kind of procedure has also been adopted for the data presented in this paper. The grade and tonnage models for nickel-bearing deposits in Finland are shown in Fig. 5 and from it the following observations can be made: (1) 50% of the total 164 Svecofennian deposits have an average grade of 0.38% Ni and 0.20% Cu, and a size of 10 000 tonnes. Only 10% of these have an average grade greater than 0.80% Ni and 0.40% Cu, or a size greater than 520 000 tonnes. (2) For the deposits in the komatiites, layered intrusions and Karelian formations, 10% have an average grade of 0.30–0.50% Ni, but respective grades are variable, being 0.13% Cu, 0.88% Cu and 0.30% Cu, while corresponding sizes are 0.5 Mt, 55 Mt and 30 Mt. (3) In general the Kotalahti, Telkkälä and Vammala belts show rather uniform distributions of nickel and copper grades, but they differ in size. Only 10% of these belts have respective average grades greater than 1.06% Ni, 1.30% Ni and 0.75% Ni, and 0.37% Cu, 0.35% Cu and 0.47% Cu, or sizes greater than 3.1 Mt, 0.3 Mt and 1.0 Mt. (4) Modelling also showed that the average nickel and copper grades of the Pori and Stormi zones are similar within the Vammala Belt.

The ratios of Ni/Cu for major nickel-bearing areas in Finland are given in Fig. 6. Although ratios of Ni/Cu represent a simple statistical parameter, they are suitable for a general description and discrimination for nickel deposits. A potential objection might be that these average values represent a wide range of nickel deposits, from productive mines to small occurrences. The following observations can nevertheless be made: (1) Archean or related nickel zones are very low in copper and their nickel contents rarely exceed 0.5% Ni. (2) Deposits in layered intrusions and within the Karelian formations both show a tendency toward higher copper contents in relation to nickel. (3) Deposits from all Svecofennian areas have a quite uniform Ni/Cu. (4) The Svecofennian deposits have a tendency toward higher nickel contents, up to about

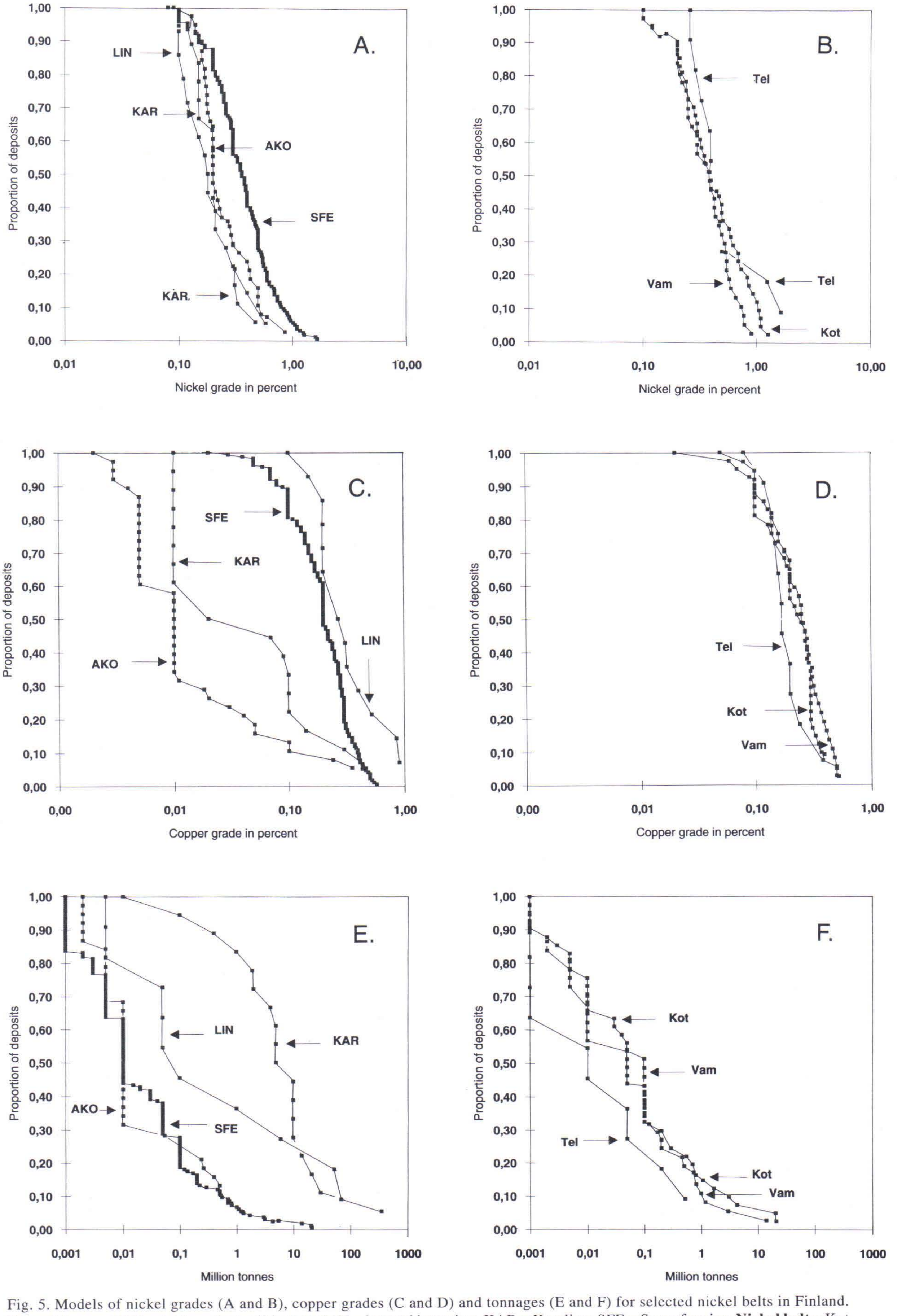

Fig. 5. Models of nickel grades (A and B), copper grades (C and D) and tonnages (E and F) for selected nickel belts in Finland. **Deposit types:** AKO = Archean komatiitic type; LIN = layered intrusion; KAR = Karelian; SFE = Svecofennian. **Nickel belts:** Kot = Kotalahti; Tel = Telkkälä; Vam = Vammala.

1.7% Ni, at a range of 0.2–0.3% Cu. These conclusions are consistent with the results obtained from grade and tonnage models.

A plot of the nickel deposits classified according to a combination of metallometric parameters is presented in Fig. 7. This largely supports the above conclusions, and the following observations can therefore be made: (1) Most of the deposits in the Archean formations and those in central Lapland are extremely nickel-dominated. (2) Deposits in central Lapland are predominantly small and low-grade, and only the Ruossakero Zone and Archean komatiite deposits of Kuhmo Belt show considerable size and grade. (3) In contrast, the deposits in the layered intrusions are large, low-grade and have an almost identical low Ni/Cu ratios. (4) Within the Karelian formations the low-grade and nickel-dominated ophiolite (Lahnaslampi-type soapstones) deposits are clearly distinct from the black schist (Talvivaara-type) and quartzite-skarn (Vuonos-type) deposits. (5) Deposits of the Svecofennian-type reveal a larger diversity in size, grade and metal ratios. (6) The most intriguing detail is the division of the Kotalahti Belt into three different parts, namely the northwestern part (Hitura), which lies totally inside the Svecofennian

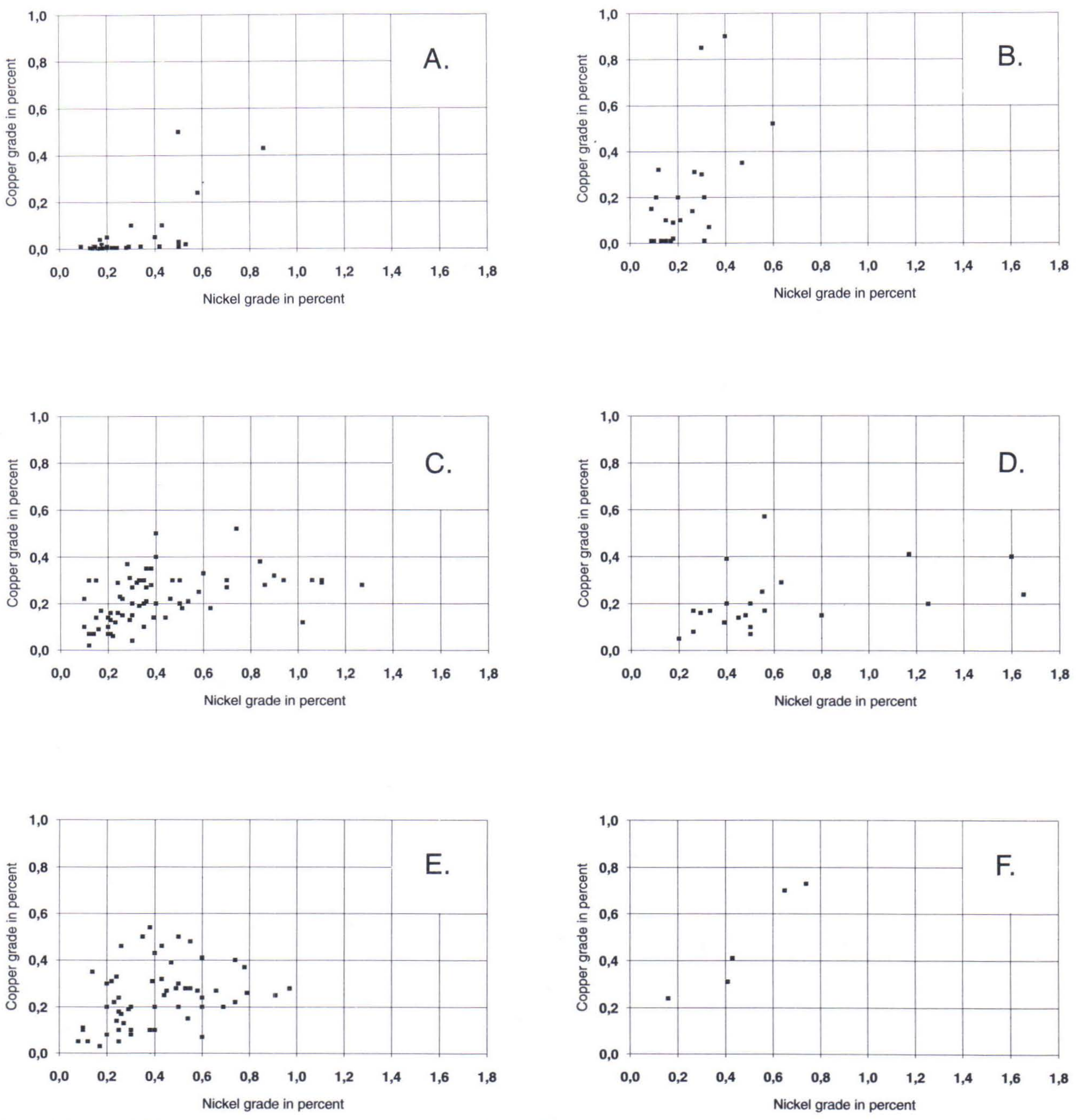

Fig. 6. Average Ni/Cu ratios of major nickel-bearing areas in Finland. **Deposit types:** A — Archean komatiitic type; B — layered intrusions and deposits in Karelian formations; C — Kotalahti Nickel Belt and deposits to the southwest; D — deposits in the Sulkava area and Telkkälä Nickel Belt; E — Vammala Nickel Belt, and deposits to the east and southwest; F — Subjotnian diabases.

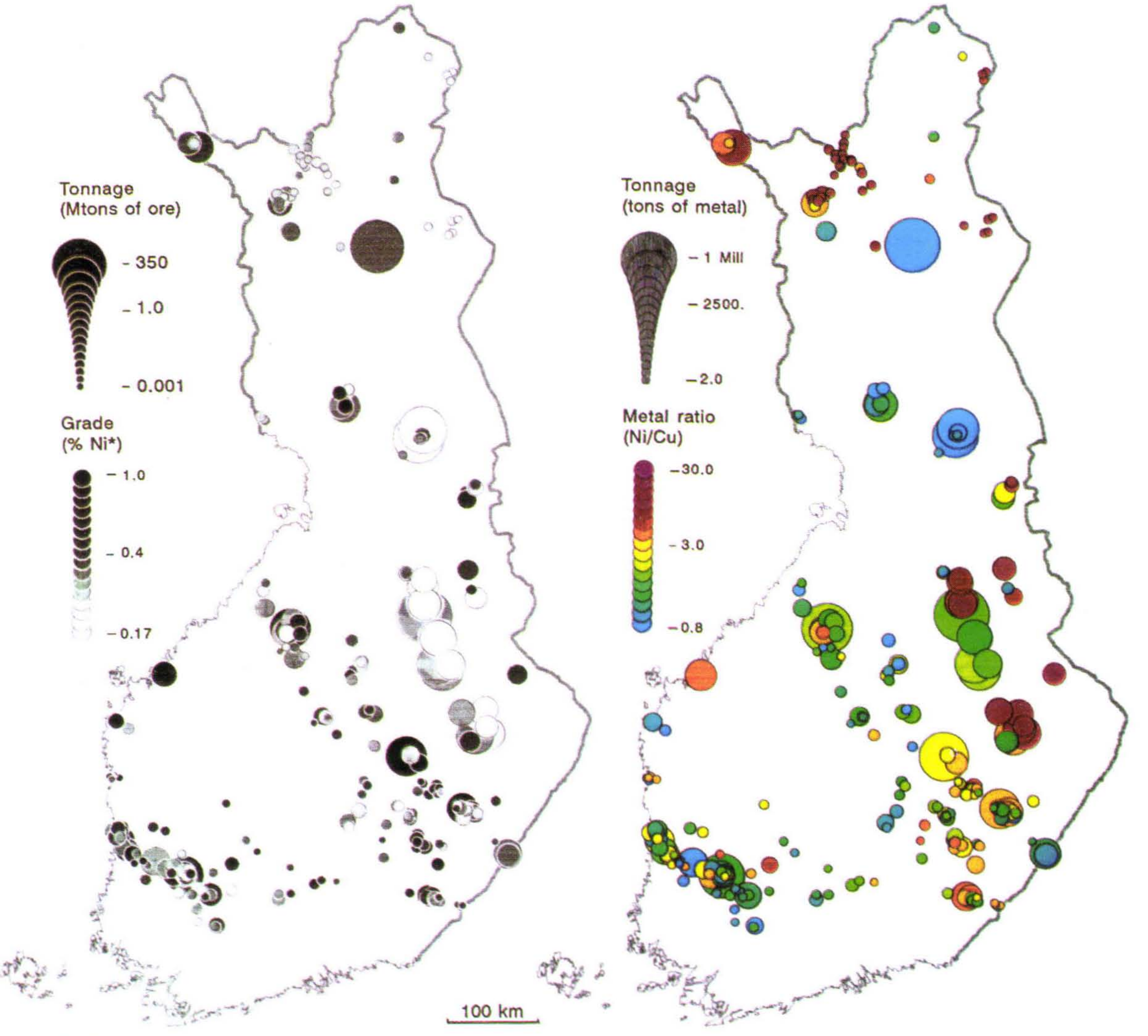

Fig. 7. Combination of metallometric parameters for nickel deposits in Finland. a — tonnage (in tonnes of ore) and grade (in percents of nickel equivalent); b — metal content (tonnes of nickel equivalent) and metal ratios (Ni/Cu). Nickel equivalent defined as Ni* = Ni + (0.2 x Cu).

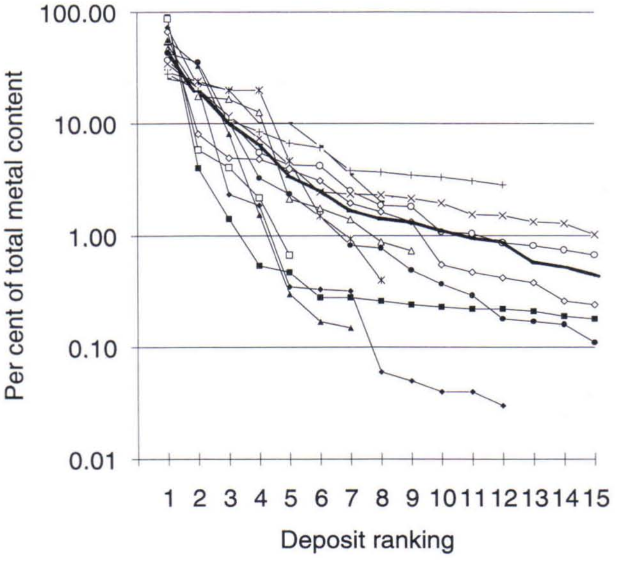

Fig. 8. Deposits in major nickel-bearing areas ranked according to their percentage contribution to the total nickel and copper content. The heavy line represents average values in each deposit ranking class.

Domain and resembles the Stormi and Kylmäkoski zones of the Vammala Belt; the central part (from Kotalahti to Laukunkangas) which is located at the margin of the Archean craton and shows a tendency toward higher Ni/Cu ratios, just as in the deposits to the south; and the separate deposits at Parikkala. These facts complicate the simple concept of a long and uniform Kotalahti Nickel Belt in the sense initially proposed by Gaál (1972).

Quantitative analysis of total metal contents for major nickel-bearing areas is shown in Fig. 8. Ranked in order of size, the largest deposit in each area contains on average 51.4% of the total nickel and copper metal content and the second largest some 19.4%. Remaining deposits range downwards in decreasing proportions of 10.1%, 6.5% and 3.4%. These empirical observations could be used for evaluating the undiscovered potential of new areas (cf. Sangster 1980), but this has not been tested in the present study.

DISCUSSION AND CONCLUSIONS

The main tectonostratigraphic subdivision of the eastern part of the Svecofennian Shield into the Archean Kola–Karelian and Proterozoic Svecofennian domains is also the most prominent discriminant with respect to the metallogeny of nickel in Finland. A general observation is that the nickel deposits of the Kola–Karelian Domain are generally associated with greenstone belts, whereas the deposits of the Svecofennian Domain are associated with highly metamorphosed sediments, typically mica gneisses, although they are not necessarily restricted to any particular stratigraphic unit. Classifications for magmatic nickel sulfide deposits have been proposed by several authors (cf. Naldrett 1989, 1979, Naldrett & Cabri 1976) in which the deposits can be viewed in terms of their associated mafic or ultramafic bodies and the tectonic settings into which these were emplaced. These general concepts can be applied for most of the nickel deposits mentioned in the present paper.

The schist belt of central Lapland (Lapponian), with tholeiitic volcanic rocks, ultramafic komatiitic lavas intercalated with cherts and volcaniclastic sediments is a very typical greenstone complex. In addition to the komatiitic Ni-Cu deposits (central Lapland nickel zones), and the distinctive Keivitsa Ni-Cu deposit, it contains polymetallic mineralization, including the Cu-Zn-Au-Ag volcanogenic massive sulfide deposits at Pahtavuoma, Saattopora and Riikonkoski, the banded iron formations at Porkonen–Pahtavaara, and the komatiitic Au deposit at Pahtavaara. However, as noted before, the age of central Lapland is not well established and thus the exact position of some nickel deposits remains open.

The Archean Kuhmo–Suomussalmi greenstone belt in eastern Finland is totally surrounded by the granite gneiss basement complex. The komatiite association with its subeconomic nickel deposits is typical of Archean greenstone belts.

Extensive layered mafic-ultramafic intrusions were emplaced at 2440 Ma between the Archean basement and overlying sedimentary rocks. Although these intrusions are best known for their Cr-V-Ti-PGM deposits, some of them include large but low-grade sulfidic nickel deposits.

The sedimentary basins within the Kola–Karelian Domain include a Proterozoic cover sequence (Karelian formations) resting on the basement complex. These schist belts are characterized by the so-called Outokumpu association, extensive graphite-bearing shales and ophiolite bodies. In addition to the Cu-Zn-Co volcanogenic massive sulfide deposits at Outokumpu, all of these formations host specific types of nickel deposits. Nickel has been mined from a quartzite-skarn bed at Vuonos and is presently recovered from ophiolites as a by-product of talc mining.

Within the Svecofennian Domain, two major factors controlling the location of nickel deposits are the distribution of highly metamorphosed mica gneiss belts and the presence of various linear fracture patterns. These controlling features have previously been noted, explicitly or implicitly, by several authors. However, their relative importance has been interpreted in various ways.

The concept of a long and narrow Kotalahti Nickel Belt, extending through the country from Parikkala to Hitura, was introduced by Gaál (1972). The belt was also believed to be connected with a deep fracture system, called the Suvasvesi fault. New discoveries have subsequently shown that the belt is rather different than originally envisaged, and now it seems probable that it comprises several more or less independent segments. The southeastern end at Parikkala is apparently isolated, although it might connect with the Telkkälä Belt. The central part, from Laukunkangas to Kotalahti coincides with the marginal zone of the Archean Kola–Karelian Domain. The only true Svecofennian part, namely the group of zones around Hitura, is not really a linear entity at all. This heterogeneity of the entire Kotalahti Belt as a whole can be imagined even in its metal contents and ratios as is shown by Fig. 7.

Several authors, including Häkli et al. (1979), Papunen et al. (1979) and Gaál (1985) have proposed that the nickel deposits of the Vammala Belt, small occurrences to the east of it, the Kotalahti Belt, and the Oravainen deposit might form a ring-shape structure around the central Finland granitoid complex. Ekdahl (1993) further suggested that the ring might run even from Skellefte in Sweden through Oravainen to Vammala, and possibly to the southern parts of the Savo area. This feature was also defined as a deformed synorogenic nickel belt subparallel to the Tampere–Skellefte zone, just as the Kotalahti Belt is associated with the Vihanti–Pyhäsalmi base metal district. However, according to the results obtained in the present study and by Saltikoff & Tontti (1990), there is little evidence in support of such a ring structure.

A continuation of the Vammala Belt from Kylmäkoski to Heinola in the east has been drawn on the maps by Mikkola (1980) and Kahma (1984). Gaál (1985) proposed that the belt might even extend as far as Porvoo and could be up to 280 km long and 60 km wide. According to the results obtained in the present study, however, this seems improbable. The finding corresponds to the geomathematical analysis of an areal nickel favorability in which the Vammala Belt occupies only a part of the Häme Schist Belt (Saltikoff & Koistinen 1989). This is also demonstrated by the Häme Fault line which marks the southern limit of the nickel deposits. Mäkinen (1987) stated that the Kynsikangas shear zone splits the Vammala Belt into a western zone where Kotalahti-type intrusions were emplaced under higher P-T conditions, and an eastern zone where Vammala-type intrusions were emplaced under lower P-T conditions.

Within the Svecofennian Domain, tholeiitic volcanic belts are interpreted as representing an island arc system (1930–1880 Ma) that dominates the tectonic pattern and records transitions between mature continental island arcs and primitive oceanic island arcs (Gaál 1990). The continental island arcs are the sites of the economically most significant mineralizations, such as the base metal sulfide deposits in the Vihanti-Pyhäsalmi and Orijärvi Zn-Cu-Pb districts. The Kotalahti Nickel Belt and the Vihanti–Pyhäsalmi base metal belt formed during a contemporaneous metallogenic process and, when combined into a single entity, has been traditionally designated the Lake Ladoga–Gulf of Bothnia Ore Zone (Kahma 1973).

The nickel deposits within the eastern part of the Svecofennian Domain are evidently associated with NW–SE-trending linear fault patterns which are mostly parallel to the Lake Ladoga–Gulf of Bothnia zone. These linear structures can be detected on regional aeromagnetic, gravimetric and till geochemical maps and tend to correlate with clusters of nickel deposits. Within these clusters the nickel-bearing mafic-ultramafic bodies are very small, effectively occurring as enclaves in a migmatitic mica gneiss environment. The neosome of the gneisses is usually trondhjemitic and the surrounding granites are very sparse. According to Saltikoff & Koistinen (1989) the mica gneiss-dominated Häme Schist Belt in southwestern Finland is the most favorable environment for nickel occurrences with respect to regional lithology. This conclusion supports the results by Tontti et al. (1979) in central Finland, where the presence of mica gneiss in a particular district was found to be the most consistent critical characteristic feature of the nickel-bearing areas.

The formation of the thermal dome in the Sulkava area, and also possibly the large central Finland granitoid area, occurred after the emplacement of mafic-ultramafic bodies of the Kotalahti and Laukunkangas zones. This event, combined with the formation of the rapakivi granite massive, has modified or even destroyed many earlier tectonic features. The original distribution of nickel-bearing areas has possibly also been affected during these episodes. This is demonstrated for instance by the separate location of the Oravainen deposit at the Gulf of Bothnia, and also by the location of the Telkkälä Belt to the south of the Häme Fault. The role of this discontinuity in the distribution of nickel deposits in southern and southeastern Finland is probably greater than is understood at present. Although a general tectonic control has been the main feature controlling the location of nickel-bearing bodies within the Kotalahti Belt, a favorable paleotectonic lithological environment is also of vital importance, since magma may become contaminated prior to emplacement as well as during crystallization (cf. Peltonen 1995, Mäkinen 1987). This feature has possibly also played a role in the evolution of the Kotalahti and Laukunkangas magmas, because these intrusions are located close to the Archean craton, in contrast to the intrusions of Hitura and Stormi.

Contributions to understanding the metallogeny of nickel have direct applications in mineral exploration. The main conclusion is that nickel-bearing deposits tend to be located in certain linear belts or zones, and hence the ore potential and the economic importance of such linear zones is emphasized. Based on the present knowledge of the distribution of in situ ore resources and known ore deposits in those belts it is apparent that the overwhelming nickel potential is in the Svecofennian area, within the Kotalahti Belt and within the Vammala Belt (cf. also Reino et al. 1993). Economic ore deposits could also be found among the layered intrusions, whereas the Archean deposits are expected to contain only modest amounts of nickel, although being typical Kambalda-type ores. Current exploration could also generate new ideas on nickel metallogeny in Finland and new economic deposit types may be revealed.

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