



Rare earth element distribution and mineralization in Sweden: An application of principal component analysis to FOREGS soil geochemistry

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ABSTRACT

This paper presents results of statistical analyses and spatial interpretations of distributions of rare earth elements (REEs) in Sweden using the Forum of European Geological Surveys (FOREGS) geochemical database of topsoil, subsoil and stream sediment compositions. Raster maps depicting spatial distributions of individual REEs were created by interpolation of uni-element data and then principal component (PC) analysis was carried out on the REE data to identify geochemical anomalies associated with bedrock lithology and known mineralizations. The spatial distributions of REEs in Sweden are studied using only the Swedish data subset and the entire European data set. The light rare earth elements (LREEs) La, Ce, Nd and Sm show good correlations among each other but not with Eu. The heavy rare earth elements (HREEs) including Tb, Dy, Ho, Er, Tm, Yb and Lu also show good correlations among each other but not necessarily with the LREE. La, Ce and Nd are the most abundant REEs in all the studied media (topsoils, subsoils and stream sediments), with average median concentrations of 25.3 mg/kg, 53.6 mg/kg and 23.9 mg/kg, respectively. The total explained variances of the first two PCs of each of the REE dataset for topsoils, subsoils, and stream sediments are 95.4%, 95.8% and 95.2%, respectively. Biplots of the first two PCs of each of the REE dataset for topsoils, subsoils, and stream sediments commonly reveal two distinct groupings – HREEs and LREEs – whereas biplots of PC1 versus PC3 of these datasets commonly reveal three distinct groupings – Eu, Ce and other REEs. The main difference between the distribution patterns of LREE and HREE is likely due to enrichment of the LREEs in the Archean bedrock underlying northern Sweden. HREE concentrations in the Archean to Paleoproterozoic metasediments are rather low. Color composites of PC maps produced from the topsoil and subsoil datasets clearly reflect the Archean rocks in northern Sweden and outline the second phase of the Svecokarelian orogen.

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1. Introduction

The FOREGS (Forum of European Geological Surveys) Geochemical Baseline Mapping Program was originally planned as the European contribution to the global geochemical dataset, and as a guideline for carrying out such a complex international survey on the continental scale (Salminen et al., 2005). The main objectives of FOREGS were to provide a basis for formulating policies and legislation concerning the management of harmful elements and to define their corresponding safety levels (Salminen et al., 2005). Therefore, the FOREGS initiated a program to construct a standardized geochemical database with the aim of compiling the first geochemical atlas of Europe (Fedele et al., 2008). As a result, a large geochemical database is now available free for public use (De Vos et al., 2006;

Salminen et al., 2005). The FOREGS database covers 26 countries and contains descriptions for various environmental media (soils, stream and floodplain sediments, and water) that were chemically analyzed for more than 70 elements including the rare earth elements (REEs).

The REEs comprise 15 chemically similar metallic elements, which are a key group of trace elements for the geochemical study of earth systems (Prego et al., 2009; Taylor and McLennan, 1985). The REEs are commonly divided into the light rare earth elements (LREEs) with lower atomic weights and larger atomic radii (lanthanum to europium), and the heavy rare earth elements (HREEs) with higher atomic weights and smaller atomic radii (gadolinium to lutetium). This gradual decrease of atomic radii with increasing atomic number is a characteristic feature of REEs and it is known as contraction of lanthanides. Scandium and yttrium are often grouped with the REEs because the former is chemically similar to the latter (Hedrick, 1997; Walters et al., 2011). In particular, yttrium is often grouped with the HREEs because of its similar chemical properties (Samson and Wood, 2004).

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The REEs are not found as native elements but as a variety of minerals, e.g., oxides (fergusonite), carbonates (bastnäsite), phosphates (monazite), and silicates (allanite). At least 100 minerals can incorporate REEs into their crystal structures while approximately 10 of these minerals contain significant REE concentrations. Currently, only bastnäsite, monazite, and xenotime are the primary REE-bearing minerals of economic importance (Richardson and Birkett, 1996).

The REEs are incompatible during most magmatic processes and, thus, concentrate in the final products of magma differentiation (e.g., evolved granites and pegmatites). The REEs have been considered relatively immobile during metamorphism and, in the surficial environments, are not easily affected by alteration (Öhlander et al., 1996). However, some studies have indicated that the REEs can be mobile during weathering processes, e.g., in till cover in northern Sweden (Öhlander et al., 1991, 1996).

The most significant economic concentrations of REE-bearing minerals worldwide are hosted in or associated with alkaline igneous rocks and carbonatites. Within hydrothermal systems, REE-bearing minerals are associated with quartz and fluorite-bearing veins and as breccia filling. REE-bearing minerals also occur in skarns, in pegmatite and are sometimes concentrated in placer and laterite clay deposits. The geological setting of economic concentrations of REE-bearing minerals is usually within, or a combined variety of these rock types and mineralizing events. REEs are also extracted as a by-product during uranium and niobium milling process (Pell, 1996).

During the last few decades, rare earth metals have found many applications in metallurgy, electronics, the high-tech industry, medicine, military, and many other areas of modern life. There is, therefore, a need to define the natural background levels of REEs in order to distinguish their natural variations related to geology and mineralization from anthropogenic input and contamination (Fedele et al., 2008).

The main objective of this paper is, therefore, to analyze the distributions of REEs in Swedish subsols, topsoils, and stream sediments using the FOREGS database to identify patterns that could be related to bed-rock geology and mineralization. For this, we apply the principal component analysis to study the structure and spatial distribution of the Swedish REE data in respect to the regional geology (underlying bed-rock type) and mineralizations.

2. Geological and tectonic setting of Sweden

Geographically, Sweden can be divided into seven geological regions, each with a distinct tectonic history and geochemical character (Fig. 1). Most of these regions belong to the Fennoscandian Shield, which includes the Archean rocks of northern Sweden, the Svecokarelian Orogen, post Svecokarelian rocks of the Trans-Scandinavian Igneous Belt, the Blekinge–Bornholm Province and the Sveconorwegian Orogen. Impinging on the western side of Sweden, and incorporating many reworked components of the Fennoscandian Shield, is the Caledonian Orogen; whereas younger intrusives and outliers in the sedimentary cover in southern Sweden are collectively grouped here as the Phanerozoic Rocks.

Archean Rocks occur exclusively in northern Sweden (Norrbotten County) and are composed of ca. 3.5–2.5 Ga tonalite–trondhjemite–granodiorite gneisses, paragneisses, greenstone, granulite and migmatitic amphibolites. Most of these units were generated during the Saamian orogeny (3.1–2.9 Ga), amalgamated by collision at ca. 2.0–1.9 Ga, then reworked during Proterozoic tectonic events to form collisional belts such as the Lapland granulite belt (Hölttä et al., 2008). The southernmost outcrops of Archean rocks occur between Luleå and Piteå, near Boden, and towards Jokkmokk; however, they are thought to underlie the Palaeoproterozoic rocks located southwards. Products of mafic volcanism associated with the breakup of the early Archean crust in the early Palaeoproterozoic are preserved in the greenstone belts of northern Sweden.

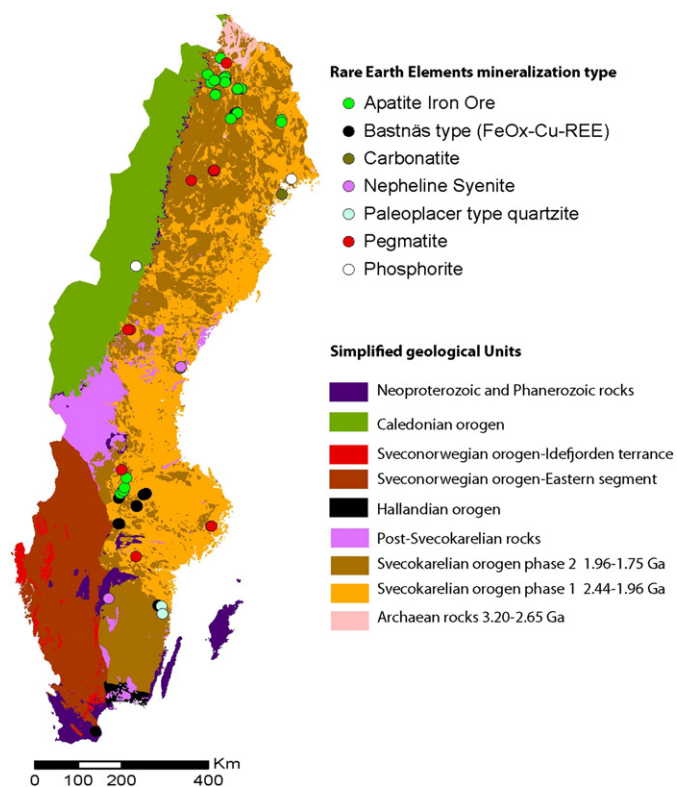


Fig. 1. Simplified geological map of Sweden with main types of REE deposits (based on data from Geological Survey of Sweden).

The majority of Sweden consists of rocks of the Svecokarelian Orogen, formed during the Palaeoproterozoic in two distinct phases, one during 2.44–1.96 Ga and the other 1.96–1.75 Ga. Earlier phases of the orogen were marked by mafic volcanism probably associated with the breakup of the early Archean crust. The majority of the orogen is assembled from a series of island arc terranes and interlying sedimentary basins accreted onto the Archean continental core. All units were variably metamorphosed with grades reaching amphibolites–granulite facies, with many rock units showing extensive migmatization. Thus, before ca. 1.7 Ga, almost the entire Fennoscandian Shield experienced extensive metamorphic and magmatic activities, which resulted in magmas ranging from anatectic S-type granites to various mantle-derived melts, and the formation of migmatites and shear zones (Högdahl et al., 2004; Korsman et al., 1999). The youngest events in the Svecokarelian orogen are the deposition of the Jotnian sandstone in the Bothnian Gulf at ca. 1.5–1.2 Ga and much of the region has been extensively intruded by basic dykes.

The Trans-Scandinavian Igneous Belt (TIB) is situated to the west of the Svecokarelian domain and stretches from southernmost Sweden northwards, beneath the Caledonian mountain chain and up to the coastal regions in northern Norway (Högdahl et al., 2004). Within the Caledonides, the TIB rocks outcrop in tectonic windows, e.g., the Grong-Olden Culmination. The belt consists largely of undeformed granitoids and associated volcanic rocks formed in at least three different episodes (TIB 1, TIB 2, and TIB 3) between ca. 1.85 and 1.65 Ga, with youngest intrusions at ca. 1.4. In places, the TIB is partly covered by the Jotnian sandstone and cut by diabase dykes (1.25–1.2 Ga and 1.0–0.9 Ga).

The Blekinge–Bornholm province is located in southern Sweden. Early amphibolites, felsic metavolcanics, mica schists, and gneisses (ca. 1.77–1.69 Ga) were intruded by tonalite–granodiorite plutons and were not affected by the Sveconorwegian orogeny. Mesoproterozoic rapakivi granites (1.5–1.25 Ga), pegmatites, gabbros, mafic dykes and associated bimodal volcanic rocks represent younger units (Bingen et al., 2008; Lahtinen et al., 2008).

The Sveconorwegian orogen predominantly consists of bedrock originally formed during the Gothian orogeny (1.7–1.55 Ga), cut by late Mesoproterozoic igneous rocks (ca. 1.1–0.9 Ga), and subsequently deformed and metamorphosed under amphibolite to granulite–eclogite facies conditions into gneisses, granulites, eclogites, and migmatites. Rare supracrustal rocks (greywacke, quartzite, shale) occurring with minor mafic to felsic volcanics in southwestern Sweden have been metamorphosed under greenschist to amphibolites facies conditions. The Sveconorwegian units are intruded by several generations of diabase with the youngest ones dated at ca. 615 Ma (Göteborg diabase). The orogen is divided into several N–S-trending segments separated by ductile deformation zones such as the Mylonite Zone separating Eastern and Western segments (Andersson et al., 2002).

Neoproterozoic rocks in Scandinavia are represented by sedimentary successions of marine and fluvial sandstones, conglomerates, and carbonates occurring within the Caledonides. Dolerite dyke swarms (ca. 600 Ma) cut voluminous siliciclastic successions and mark the opening of the Paleozoic lapetus Ocean. Ediacaran glaciations resulted in tillite formation and postglacial marine sediments (Nystuen et al., 2008). Outside the Caledonides, Neoproterozoic rocks occur locally in southern Sweden by the lake Vättern (sandstone, shale, dolomite, and conglomerate) and in central Sweden (Alnö carbonatite complex) (Nystuen et al., 2008).

The Caledonian orogen was formed during the Early–Mid Paleozoic (Ordovician to Devonian) when North America and Greenland

(Laurentia) collided with Scandinavia (Baltica). In Sweden, the current exposures are mainly composed of Neoproterozoic to Paleozoic (mostly Silurian) marine to fluvial sediments and volcanoclastic successions, which were deposited at the continental margin of the lapetus Ocean between ca. 700 and 400 Ma (Gee et al., 2008). Together with slices of older basement, these rocks were thrust several hundred kilometers eastwards onto the Fennoscandian shield in several large thrust sheets (nappes) (Gee et al., 2008). Within Caledonian nappes, the metamorphic grade varies from lower greenschist to granulite–eclogite facies (Gee et al., 2008).

Outside the Caledonides, the majority of Phanerozoic Rocks are remnants of the Cambro-Silurian sedimentary cover (550–400 Ma old sandstones, shales, and limestones) that once covered much on central and northern Europe. These are found in southern and central Sweden, e.g., near Östersund, Siljan, Billingen-Kinnekele, Skåne, and on the islands of Götland and Öland. Cambrian to Permian diabase dykes, porphyritic monzonite, and ultramafic intrusions outcrop in central (Västergötland), western (Bohuslan), and southern (Skåne) Sweden. Triassic through Cretaceous shallow marine sandstones, siltstones shales, and limestones occur only in the south of the country.

All geological regions in Sweden have a variable but generally rather thin soil layer dominated by glacial debris from the last glaciation and marine or post-glacial deposits. The composition of glacial debris is mainly sandy till, especially common above the pre-isostatic rebound coastline. In central Sweden, heavy glacial or postglacial clays are

Table 1
Basic statistics of REE concentrations (in mg/kg) in European and Swedish samples.

Europe								Sweden							
	Media	Samples	Min	Max	Mean	Median	SD		Media	Samples	Min	Max	Mean	Median	SD
La	Subsoil	790	0.78	155	27.7	25.6	16.1	La	Subsoil	51	12.30	47.10	25.19	21.40	8.61
	Topsoil	852	1.10	143	25.9	23.5	15.8		Topsoil	51	6.92	34.30	17.42	16.90	6.69
	Stream	853	1.30	553	41.0	32.5	44.8		Stream	51	15.80	125.00	43.05	37.60	22.82
Ce	Subsoil	790	1.04	379	56.8	53.7	32.9	Ce	Subsoil	51	22.70	101.00	55.91	48.80	18.81
	Topsoil	852	2.45	267	52.2	48.2	31.3		Topsoil	51	13.80	83.00	37.67	34.80	15.69
	Stream	853	2.20	1080	83.0	66.6	88.6		Stream	51	36.60	301.00	94.80	77.40	54.31
Pr	Subsoil	790	0.14	32.9	6.50	6.04	3.66	Pr	Subsoil	51	2.93	11.40	5.94	5.37	2.04
	Topsoil	852	0.29	31.6	6.02	5.60	3.64		Topsoil	51	1.64	8.16	4.10	3.91	1.63
	Stream	853	0.30	125.0	9.22	7.35	10.20		Stream	51	4.38	36.10	11.38	9.76	6.53
Nd	Subsoil	790	0.46	111	24.2	22.4	13.40	Nd	Subsoil	51	12.00	41.10	21.86	19.20	7.37
	Topsoil	852	1.14	132	22.4	20.8	13.52		Topsoil	51	6.71	31.80	15.14	14.50	6.12
	Stream	853	1.10	524	36.6	28.2	41.30		Stream	51	17.30	139.00	44.68	37.90	25.29
Sm	Subsoil	790	<0.10	18.2	4.66	4.38	2.47	Sm	Subsoil	51	2.30	8.33	4.30	3.80	1.47
	Topsoil	852	0.23	30.0	4.28	3.96	2.63		Topsoil	51	1.37	6.01	2.98	2.76	1.15
	Stream	853	0.20	106.0	6.91	5.40	7.55		Stream	51	3.49	24.60	8.53	7.25	4.75
Eu	Subsoil	790	<0.05	4.66	0.92	0.84	0.52	Eu	Subsoil	51	0.36	1.58	0.84	0.78	0.28
	Topsoil	852	0.05	6.99	0.85	0.77	0.56		Topsoil	51	0.24	1.29	0.65	0.63	0.23
	Stream	853	0.05	7.06	1.15	1.01	0.73		Stream	51	0.57	3.39	1.37	1.25	0.58
Gd	Subsoil	790	<0.1	16.0	4.52	4.24	2.33	Gd	Subsoil	51	2.25	7.89	4.25	3.82	1.46
	Topsoil	852	0.2	36.0	4.20	3.85	2.66		Topsoil	51	1.15	6.40	3.07	2.89	1.12
	Stream	853	0.2	90.5	6.32	5.06	6.45		Stream	51	4.05	26.80	8.75	7.31	4.69
Tb	Subsoil	790	<0.02	2.36	0.68	0.64	0.34	Tb	Subsoil	51	0.36	1.17	0.67	0.61	0.21
	Topsoil	852	0.03	7.01	0.64	0.60	0.42		Topsoil	51	0.22	1.08	0.49	0.47	0.18
	Stream	853	0.02	14.50	0.96	0.79	0.93		Stream	51	0.65	4.26	1.28	1.03	0.68
Dy	Subsoil	790	<0.10	12.7	3.79	3.66	1.84	Dy	Subsoil	51	2.02	7.23	3.79	3.55	1.19
	Topsoil	852	0.18	44.9	3.58	3.42	2.40		Topsoil	51	1.48	6.18	2.95	2.94	0.94
	Stream	853	0.11	78.2	5.40	4.53	4.81		Stream	51	3.78	25.30	7.06	5.78	3.68
Ho	Subsoil	790	<0.02	2.58	0.75	0.74	0.37	Ho	Subsoil	51	0.37	1.47	0.78	0.75	0.24
	Topsoil	852	0.03	9.16	0.72	0.68	0.48		Topsoil	51	0.28	1.34	0.61	0.60	0.20
	Stream	853	0.04	16.70	1.09	0.92	0.97		Stream	51	0.74	5.49	1.47	1.20	0.79
Er	Subsoil	790	<0.10	7.42	2.20	2.18	1.06	Er	Subsoil	51	1.21	4.39	2.34	2.24	0.70
	Topsoil	852	0.12	26.00	2.10	1.98	1.37		Topsoil	51	0.95	3.96	1.88	1.80	0.58
	Stream	853	0.07	46.00	3.18	2.67	2.79		Stream	51	2.14	17.30	4.36	3.47	2.44
Tm	Subsoil	790	<0.02	1.08	0.33	0.31	0.16	Tm	Subsoil	51	0.17	0.65	0.36	0.36	0.11
	Topsoil	852	<0.02	4.03	0.31	0.30	0.20		Topsoil	51	0.13	0.57	0.28	0.28	0.08
	Stream	853	0.02	6.43	0.47	0.40	0.40		Stream	51	0.35	2.68	0.65	0.53	0.37
Yb	Subsoil	790	<0.05	7.37	2.17	2.13	1.02	Yb	Subsoil	51	1.28	4.37	2.48	2.40	0.75
	Topsoil	852	0.09	25.00	2.09	1.99	1.29		Topsoil	51	1.08	4.19	2.01	1.98	0.59
	Stream	853	0.10	42.8	3.09	2.58	2.65		Stream	51	2.26	18.70	4.56	3.76	2.55
Lu	Subsoil	790	<0.02	1.06	0.32	0.31	0.15	Lu	Subsoil	51	0.18	0.59	0.36	0.35	0.10
	Topsoil	852	<0.02	3.21	0.31	0.30	0.18		Topsoil	51	0.17	0.58	0.30	0.30	0.08
	Stream	853	<0.02	6.04	0.48	0.39	0.40		Stream	51	0.34	3.01	0.71	0.57	0.42

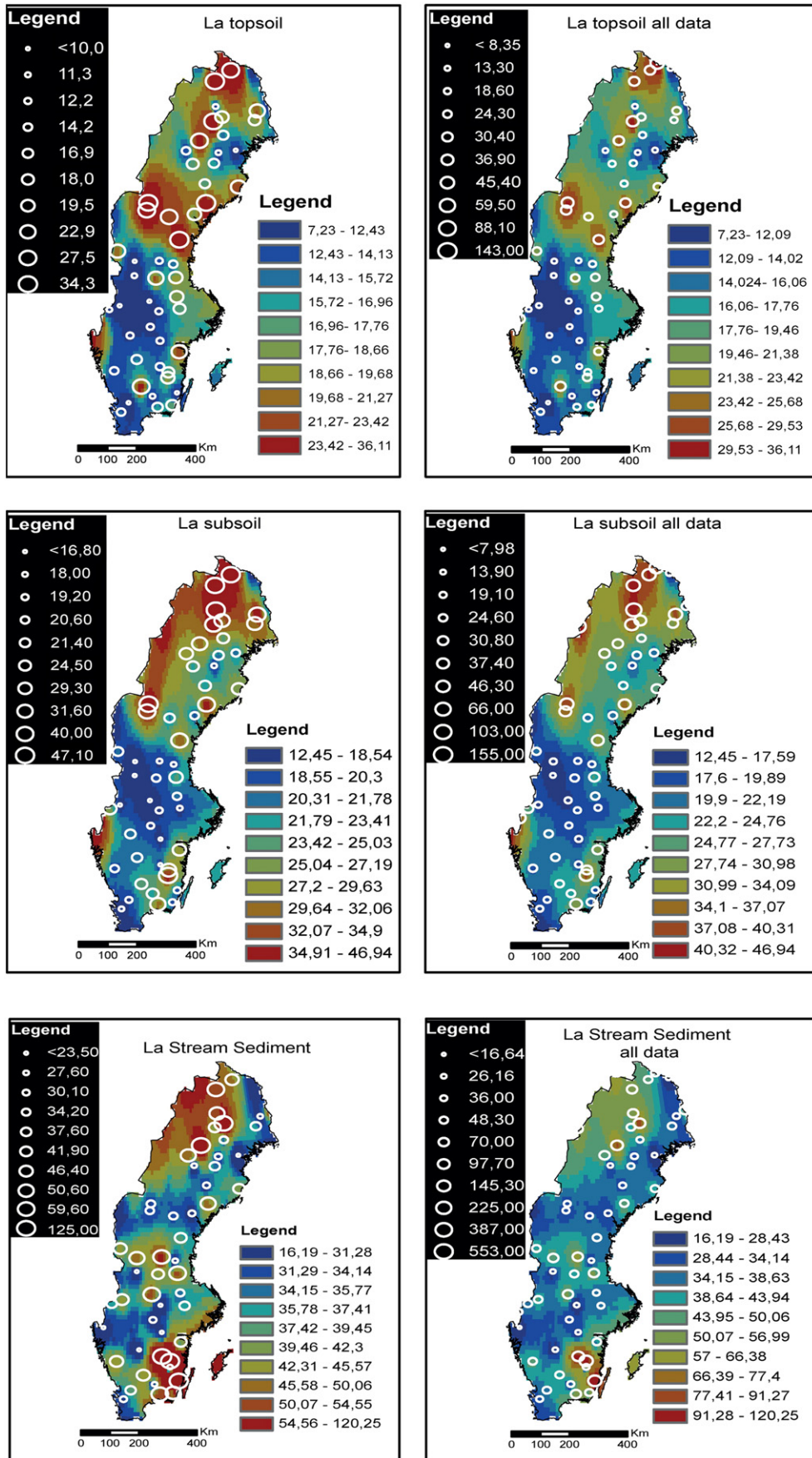


Fig. 2. Geochemical maps of La in topsoils, subsoils and stream sediments in Sweden. Symbol sizes and color scales for maps on the left are based on Swedish datasets, whereas those for map on the right are based on the whole European datasets.

common while peat lands occur frequently, especially in the northeast. Glacial deposits are strongly influenced by ice movement and post glacial reworking by melting waters. As a result, most of the deposits, especially till cover and fluvial sediments, have been displaced and redeposited. Ice transport distances are, however, short and rarely exceed 5–10 km in northern and central Sweden. In southern part of the country, displacement is more variable and can reach up to 60–80 km (Sohlenius et al., 2009).

3. REE mineralizations in Sweden

In Sweden, in many of the REE-bearing deposits were identified for the first time during the latter parts of the 19th century, most notably from the world famous Ytterby mine, from which the element ytterbium (Yb) derived its name. The elements cerium (Ce) and lanthanum (La) were discovered in minerals from Bastnäs and the Bastnäs region is still considered the most promising area for REE exploration in Sweden. REE-bearing mineral deposits occur in a broad range of igneous, sedimentary, and metamorphic rocks. Environments in which REEs are enriched can be broadly divided into two categories (Walters et al., 2011): (i) primary deposits associated with igneous and hydrothermal processes and (ii) secondary deposits concentrated from primary sources by sedimentary processes and weathering. Primary deposits include REEs associated with carbonates and/or alkaline igneous rocks, REEs associated with iron oxide–copper–gold (IOCG) deposits and hydrothermal deposits (unrelated to alkaline igneous rocks). Secondary deposits include marine placers (including coastal dune deposits formed by aeolian processes), alluvial placers, paleoplacers, lateritic deposits, and ion-adsorption clays (Walters et al., 2011). The main categories of REE mineral deposits in Sweden (Fig. 1), based on genetic sources, are described below.

- Hydrothermal *Bastnäs-type (FeO-Cu-REE)*. The main occurrences of the Bastnäs-type deposits are located in the Bergslagen mining district and are related to hydrothermal skarn mineralization in south-central Sweden (Holtstam and Andersson, 2007). Based on characteristic assemblages, the Bastnäs type deposits can be divided into two subtypes: LREE-enriched deposits located mainly in the Riddarhyttan-Bastnäs area, and deposits showing enrichment in LREE and Y+HREE mainly located in the Norberg district (Holtstam and Andersson, 2007).
- REEs associated with *apatite iron ore*. The magnetite–apatite deposits of the Kiruna district and surrounding regions of northern Sweden form the type locality for the magnetite–apatite end member of the IOCG deposit class (Barton and Johnson, 1996; Hitzman et al., 1992). The characteristic feature of these deposits is a close association with sodic and potassic alteration (Frietsch et al., 1997; Martinsson, 1997) and anomalously high concentrations of the REEs (e.g., Frietsch and Perdahl, 1995). The main occurrences of REEs related to apatite iron ore is situated in Norbotten County in the northern part of Sweden (the Kiirunavaara and Malmberget deposits) and in the Bergslagen mining district in central Sweden (e.g., Grängesberg). REEs usually reside in apatite (e.g., in the Kiirunavaara ore), which contain between 2000 and 7000 ppm REEs with a weak to moderate LREE/HREE enrichments and negative EU anomalies (Frietsch and Perdahl, 1995; Smith et al., 2007).
- REE related alkaline *carbonatite complexes*. Carbonatites are igneous carbonate rocks in which the modal percentage of carbonate exceeds 50% (Le Maitre, 2002). If the dominant carbonate is calcite, the rocks are classified as calcite carbonatites and are called sövite (coarse grained) or alvikite (fine grained) (Eckermann, 1948; Hornig-Kjarsgaard, 1998). Carbonates are considered

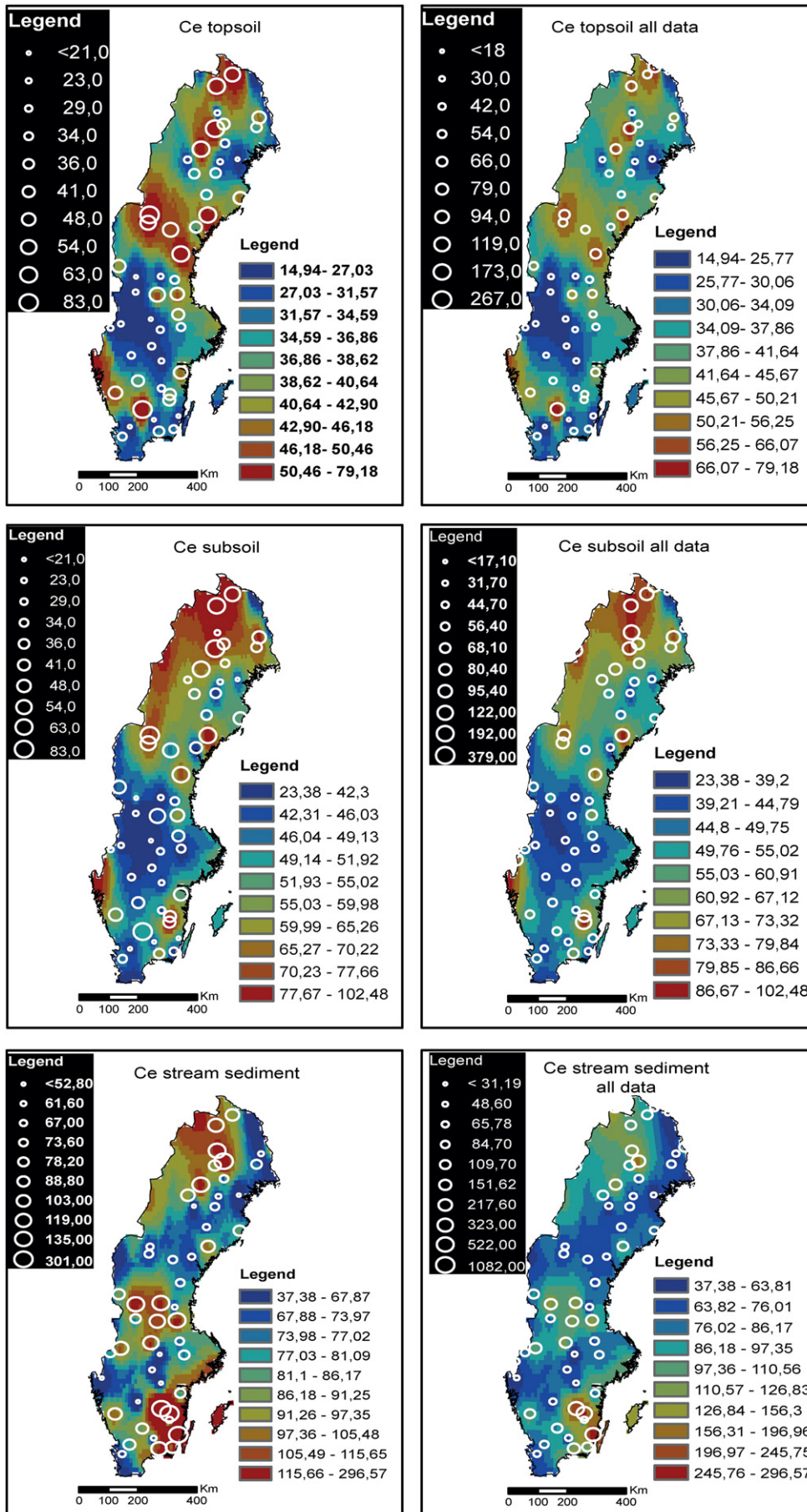
results of extreme fractionation of magmas. This process concentrates incompatible elements, including the REEs, into the final magmatic component, sometimes to economic levels (Hornig-Kjarsgaard, 1998). The LREEs show progressively greater degrees of enrichment over the slightly less mobile and heavier REEs. This, sometimes, result in extreme LREE/HREE enrichments (Balashov and Pozharitskaya, 1968; Eby, 1975; Kapustin, 1966; Kjarsgaard, 1998; Möller et al., 1980; Viladkar and Pawaskar, 1989; Von Maravic and Morteani, 1980). Some of the highest concentrations of REEs as a whole, and one of the strongest enrichments of LREEs over HREEs have been identified in sövite from the Alnö complex in Sweden (Hode Vuorinen and Hälenius, 2005; Kjarsgaard and Hamilton, 1989).

- REE-U rich phosphorite* in Jämtland in central Sweden (Täsjö). At the Caledonian front, in the lower allochthon, the Täsjö uranium and REE mineralization is hosted by Paleozoic calcareous sandstone and shales with phosphorite overlying alum shale, which contains 0.03–0.07% U₃O₈ and 0.11–0.24% total REE (Browne, 2008; David Gee, personal communication).
- Peralkaline nepheline syenite*. Quartz undersaturated alkaline plutonic rocks with (Na₂O + K₂O) > Al₂O₃. The Norra Kärr deposits are hosted in an agpaitic complex (peralkaline nepheline-syenite) located by the lake Vättern in southern Sweden, 300 km southwest of Stockholm. The rocks comprising the Norra Kärr intrusion are very rare on a global scale, and include variety of rare minerals, particularly rich in REEs, zirconium, niobium, yttrium, and hafnium. According to the Tasman Metals Ltd report (2011), the size of the deposit has been estimated as 60.5 Mt averaging 0.54% total rare earth oxide with 53% of that being heavy rare earth oxide.
- Pegmatites* containing U and REE bearing minerals are common but generally too small or too low in grade to be commercially exploited. Production of REEs from pegmatites mined for other minerals, such as feldspar or mica, is possible however. Allanite bearing pegmatites are relatively common and generally have high LREE/HREE ratios (Castor and Hedrick, 2006). Smeds (1990) carried out a comprehensive study on accessory minerals related to pegmatites in Sweden and classified pegmatites occurring in Svecokarelian rocks into two main groups: tourmaline ± Li-mineral bearing pegmatite occurring in low- to medium-grade metamorphic rocks; and pegmatite bearing Y-REE-mineral type, which can be formed in several settings.
- Paleoplacer type quartzite*. The most important placer deposits containing significant quantities of REE minerals are tertiary or quaternary in age. Orris and Grauch (2002) have identified more than 360 placer deposits worldwide. However, deposits as old as Precambrian (paleoplacers) are known and are found only in a few countries (Castor and Hedrick, 2006). The most important REE-bearing mineral in placer deposits is monazite, with minor quantities of xenotime, fergusonite, euxenite, samarkite, allanite, knopite, pyrochlore, and loparite (Möller, 1986). Several considerably older deposits containing REE-bearing minerals of possible Paleoproterozoic origin occur in southern Sweden in Västervik county (e.g., the Klockartorpet and Trostad mineralizations), and normally consist of a metamorphosed Proterozoic conglomerate containing REE bearing minerals.

4. FOREGS data—sampling and analytical methods

The field sampling, laboratory sample preparations and analytical methods of the FOREGS data are described in detail in Sandström et al. (2005). The FOREGS sampling grid (Salminen et al., 1998; Tarvainen et al., 2005) was based on the Global Terrestrial Network grid cells developed for the purpose of Global Geochemical Baselines Mapping (Darnley et al., 1995).

Fig. 3. Geochemical maps of Ce in topsoils, subsoils and stream sediments in Sweden. Symbol sizes and color scales for maps on the left are based on Swedish datasets, whereas those for map on the right are based on the whole European datasets.



All soil, stream, and floodplain sediment samples were prepared for analysis at the Geological Survey of the Slovak Republic. The REEs were determined in topsoils (0–25 cm depth), subsoils (the C soil horizon), and stream sediments by ICP-MS at the Geological Survey of Finland (topsoil and subsoil samples) and at the Geological Survey of France (stream and floodplain sediment samples).

4.1. REE baseline levels in Sweden based on FOREGS data

In this study, we present interpolated maps of the FOREGS REE data. These maps were prepared with ArcView software, using the inverse distance weighted (IDW) algorithm to generate a regular grid. In Table 1, the basic statistics of REEs in different sample media from Europe and Sweden are compared. The geochemical data have also been interpolated through inverse distance weighting (IDW) algorithm, which preserves the information contained in point sample data. This resulted in maps portraying geochemical distribution trends that broadly match geological and other features (Cheng et al., 2001; Fedele et al., 2008; Lima et al., 2008). In general, the distribution patterns of most REEs in Sweden are similar to those in Europe. Typically, the lowest REE concentrations occur in soils and sediments overlying siliciclastic sediments (e.g., Dala sandstone in central-western Sweden) and carbonates of different age (Proterozoic to Quaternary). In contrast, high REE concentrations occur in northern Sweden (Norrbotten), northeastern Sweden (Västerbotten), central-northwestern Sweden (Jämtland), southeastern Sweden (Småland) and southwestern Sweden close to the border with Norway (Bohuslan).

The La data in Europe subsoils have a median of 25.6 mg/kg and maximum value of 155 mg/kg, with values higher than the median only over the Italian alkaline magmatic province (IAMP), in northern Portugal, and Spain (the Iberian Massif) (Fedele et al., 2008). In Sweden, La values in subsoils are lower than elsewhere in Europe (Fig. 2), with a median of 21.40 mg/kg and a maximum value of 47.10 mg/kg (Table 1). The highest La concentrations in Sweden are observed in stream sediments (up to 125 mg/kg), which have a median of 37.60 mg/kg that is higher than the median for stream sediments in Europe. The most possible sources of high La levels in soils and stream sediments are leucogranites, pegmatites, and clay-rich soils (secondary La concentrations). Migmatized bedrock with well-developed leucosome is another possible source of high La in soils and sedimentary cover.

The Ce concentrations in Europe and Sweden are similar in terms of median values. The highest values of Ce in European subsoils and topsoils are 379 mg/kg and 267 mg/kg, respectively. The median Ce values in Europe are 56.8 mg/kg and 48.2 mg/kg in topsoils and subsoils, respectively. The Ce concentrations in Swedish topsoils and subsoils have maximum values of 101 mg/kg and 83 mg/kg, respectively, with corresponding median values of 48.8 mg/kg in topsoils and 34.80 mg/kg in subsoils. The Ce concentrations in European stream sediments show maximum value of 1080 mg/kg and median of 66.6 mg/kg, whereas Ce concentrations in Swedish stream sediments show 301 mg/kg and 77.40 mg/kg for maximum and median values, respectively. Thus, Ce contents in various environmental media are quite similar in European and Swedish scales. High Ce values occur over granitic and metamorphic rocks of Northern Portugal and Spain, in IAMP, in karstic areas of Slovenia and Croatia, on the Massif Central, in SW Norway and northern Sweden. In Sweden, high Ce concentrations reflect both the type of bedrock and some mineralizations. High Ce contents (Fig. 3) in central Sweden (Dalarna and Jämtland), in Småland (SE Sweden), and Bohuslan (SW Sweden) correlate with evolved granites. The Ce anomalies in northern Sweden can be related to iron mineralizations, e.g., Kiruna type of apatite-iron deposits.

Maximum values of Pr in European vary from 32.9 mg/kg in topsoils to 125 mg/kg in stream sediments. Maximum values of Pr in European vary from 32.9 mg/kg in topsoils to 125 mg/kg in stream sediments.

The same changes in Swedish FOREGS data, from 11.40 mg/kg to 36.1 mg/kg from subsoil to stream sediment. The median value of Pr in Europe and Sweden is almost the same and ranges in median value from 6 mg/kg to 7.3 mg/kg and 5.3 mg/kg to 9.7 mg/kg in Europe and Sweden, respectively. Pr anomalies in Sweden overlap to large extent with Ce anomalies and they show highest levels in the northern part of the country.

The Nd concentrations in European subsoils have a median of 22.4 mg/kg and maximum of 111 mg/kg. In Sweden, Nd values in subsoils are lower than elsewhere in Europe, with a median of 19.2 mg/kg and a maximum of 41.1 mg/kg. The highest Nd concentrations in Sweden are observed in the stream sediments (up to 139 mg/kg) with a median around 37.90 mg/kg. The Nd concentrations in Swedish topsoils are also low compared to European levels. Much lower Nd concentrations in topsoils in the southern part of Sweden may be related to the glacial deposits over crystalline bedrock of Paleoproterozoic rocks. Positive Nd anomalies point to the occurrences of crystalline rocks, while the low values in Dalarna and southern part of Sweden correlate with sedimentary rocks, e.g., Dala sandstone, Cambro-Silurian limestone and shale, and younger Mesozoic sedimentary rocks in Skåne in southern part of Sweden.

The Sm concentrations in Swedish subsoils range between 2.3 and 8.33 mg/kg, and the median of 3.80 mg/kg is slightly lower than in European subsoils (4.38 mg/kg). The Sm concentrations in Swedish topsoils range from 1.37 to 6.01 mg/kg, and the median of 2.76 mg/kg is lower than in European subsoils (3.96 mg/kg). The Sm contents in Swedish stream sediments vary from 3.49 to 24.60 mg/kg, whereas European stream sediments contain 0.2–106 mg/kg Sm. The median value of Sm in Swedish stream sediments (7.25 mg/kg) is slightly higher than that of European stream sediments (5.4 mg/kg). Locally, Sm contents are high in stream sediments in northern parts of Europe. Generally, values of Sm over Europe are quite low (<10 mg/kg) and Sm anomalies follow the pattern observed for Nd (Fedele et al., 2008).

In Swedish subsoils, Eu contents range from 0.36 to 1.58 mg/kg and the median is 0.78 mg/kg. In European subsoils, Eu contents range from 0.05 to 4.66 mg/kg and the median is 0.84 mg/kg. Concentrations of Eu in Swedish topsoils vary from 0.24 to 1.29 mg/kg with a median of 0.63 mg/kg. In contrast, concentrations of Eu in European topsoils vary from 0.05 to 6.99 mg/kg with a median of 0.77 mg/kg. In Swedish stream sediments, Eu values range between 0.57 and 3.39 mg/kg, and the median is 1.25 mg/kg. The highest Eu concentrations occur in northern Sweden where soils overly Archean and Paleoproterozoic basement rocks, in central Jämtland, Västerbotten, and in Bohuslan where soils are underlain by younger evolved granitoids (Fig. 4).

European subsoils have a median Gd concentration of 4.24 mg/kg and a maximum Gd value of 16 mg/kg. Swedish subsoils have Gd values of 2.25 to 7.89 mg/kg with a median of 3.82 mg/kg. Swedish topsoils have Gd contents of 1.15 to 6.40 mg/kg, with median of 2.89 mg/kg. This is slightly less than median Gd content of European topsoils (3.85 mg/kg). The highest Gd concentrations in Sweden are observed in the stream sediments (up to 26.80 mg/kg) with a median of 7.31 mg/kg. The areas with high Gd concentrations in Sweden overlap with Eu anomalies. In northern Sweden, high Gd contents correlate with Palaeoproterozoic granite and pegmatite; whereas in the southern part of Sweden, high Gd contents correlate with occurrences of post-orogenic granites within the Fennoscandian Shield and young Neoproterozoic granitoids (ca. 900 Ma old) in Bohuslan.

The Tb values in Swedish subsoils vary between 0.36 and 1.17 mg/kg, and the median is 0.61 mg/kg. In Swedish topsoils, Tb contents vary from 0.22 to 1.08 mg/kg and the median is 0.47 mg/kg. The median Tb values in European topsoils and subsoils are almost the same as those in Sweden. In stream sediments, Tb contents range from 0.65 to 4.26 mg/kg and the median is 1.03 mg/kg. This is slightly higher than the median Tb value in European stream sediments (0.79 mg/kg). The higher concentrations of

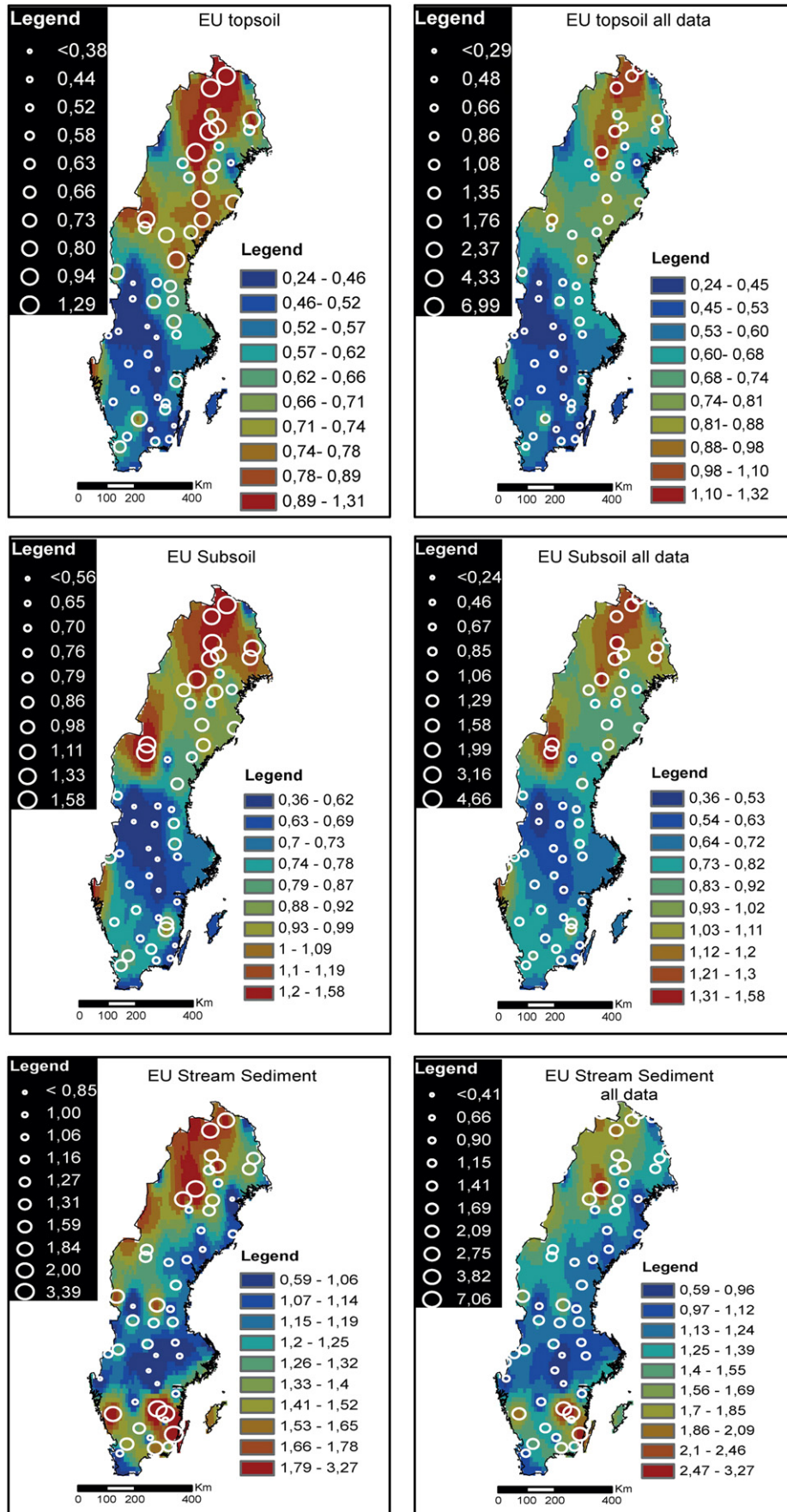


Fig. 4. Geochemical maps of Eu in topsoils, subsoils and stream sediments in Sweden. Symbol sizes and color scales for maps on the left are based on Swedish datasets, whereas those for map on the right are based on the whole European datasets.

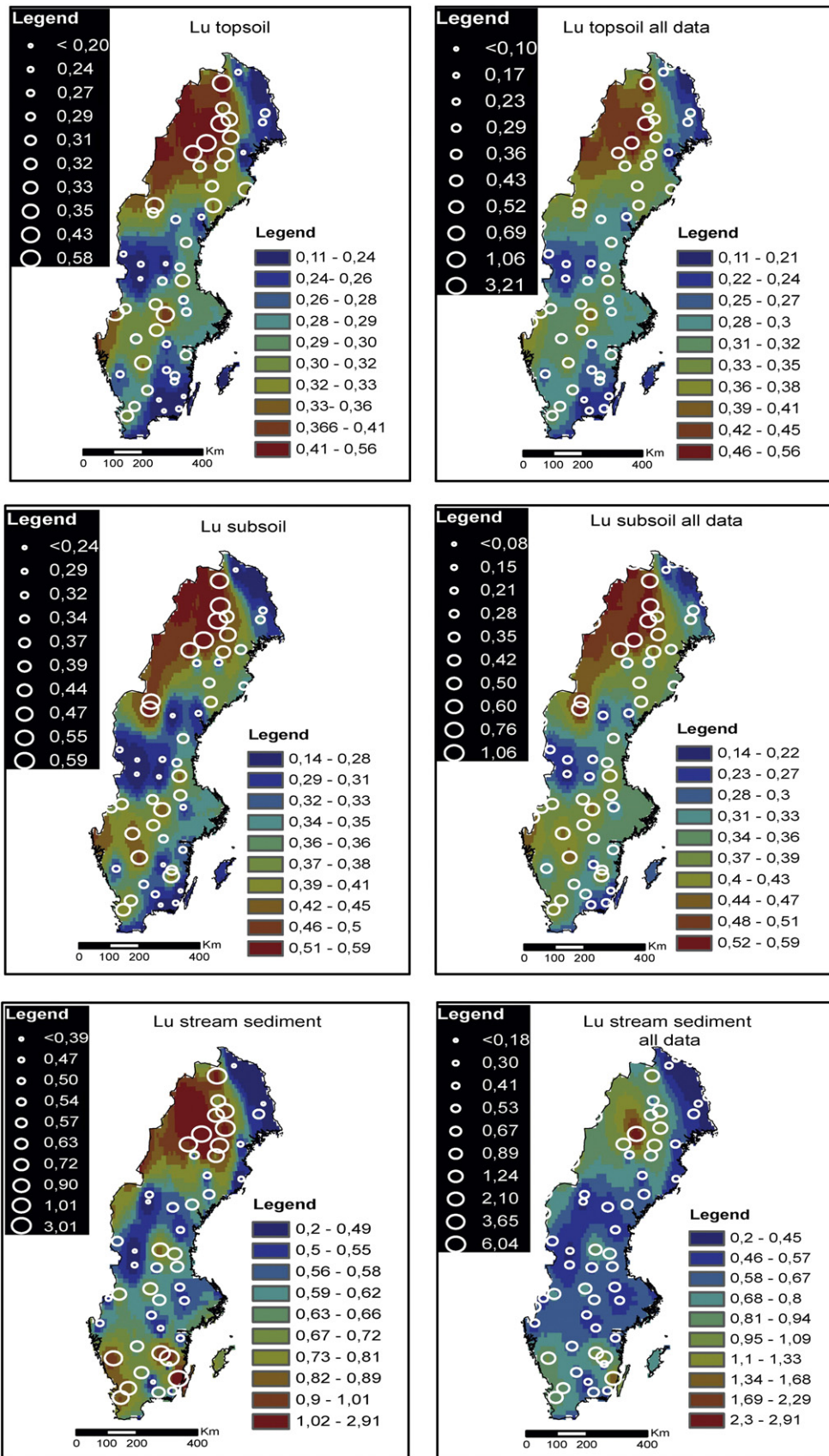


Fig. 5. Geochemical maps of Lu in topsoils, subsoils and stream sediments in Sweden. Symbol sizes and color scales for maps on the left are based on Swedish datasets, whereas those for map on the right are based on the whole European datasets.

Table 2

Pearson correlation matrices for the topsoil, subsoil and stream sediment REE data. Values greater than 0.90 are indicated in bold.

	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
<i>Topsoils (n = 51)</i>														
La	1.00													
Ce	0.93	1.00												
Pr	0.99	0.90	1.00											
Nd	0.98	0.90	0.99	1.00										
Sm	0.94	0.86	0.97	0.98	1.00									
Eu	0.83	0.77	0.85	0.89	0.88	1.00								
Gd	0.88	0.82	0.92	0.94	0.97	0.89	1.00							
Tb	0.83	0.77	0.87	0.91	0.94	0.87	0.98	1.00						
Dy	0.75	0.70	0.79	0.83	0.87	0.83	0.93	0.97	1.00					
Ho	0.69	0.64	0.73	0.78	0.82	0.81	0.90	0.94	0.97	1.00				
Er	0.65	0.61	0.68	0.73	0.77	0.77	0.86	0.91	0.95	0.98	1.00			
Tm	0.58	0.54	0.63	0.67	0.71	0.70	0.82	0.86	0.92	0.96	0.96	1.00		
Yb	0.55	0.53	0.58	0.64	0.67	0.69	0.79	0.84	0.90	0.95	0.96	0.97	1.00	
Lu	0.45	0.45	0.49	0.54	0.57	0.60	0.70	0.76	0.85	0.91	0.93	0.96	0.96	1.00
<i>Subsoils (n = 51)</i>														
La	1.00													
Ce	0.95	1.00												
Pr	0.98	0.95	1.00											
Nd	0.97	0.92	0.99	1.00										
Sm	0.92	0.89	0.96	0.98	1.00									
Eu	0.85	0.79	0.89	0.90	0.90	1.00								
Gd	0.86	0.84	0.91	0.93	0.97	0.88	1.00							
Tb	0.82	0.81	0.89	0.91	0.96	0.86	0.98	1.00						
Dy	0.71	0.71	0.79	0.82	0.89	0.78	0.93	0.97	1.00					
Ho	0.67	0.66	0.74	0.77	0.85	0.76	0.90	0.94	0.98	1.00				
Er	0.60	0.59	0.68	0.72	0.80	0.69	0.85	0.90	0.95	0.97	1.00			
Tm	0.58	0.58	0.67	0.70	0.79	0.70	0.85	0.89	0.94	0.96	0.97	1.00		
Yb	0.55	0.55	0.63	0.67	0.76	0.65	0.81	0.88	0.92	0.96	0.97	0.97	1.00	
Lu	0.51	0.51	0.58	0.62	0.70	0.63	0.76	0.83	0.90	0.93	0.94	0.94	0.95	1.00
<i>Stream sediments (n = 51)</i>														
La	1.00													
Ce	0.97	1.00												
Pr	0.99	0.96	1.00											
Nd	0.98	0.94	1.00	1.00										
Sm	0.94	0.89	0.97	0.99	1.00									
Eu	0.87	0.81	0.90	0.92	0.92	1.00								
Gd	0.90	0.83	0.94	0.96	0.99	0.90	1.00							
Tb	0.84	0.76	0.89	0.92	0.96	0.88	0.99	1.00						
Dy	0.76	0.66	0.81	0.85	0.91	0.84	0.96	0.99	1.00					
Ho	0.72	0.62	0.78	0.82	0.89	0.81	0.94	0.97	0.99	1.00				
Er	0.68	0.57	0.74	0.78	0.85	0.77	0.91	0.96	0.99	1.00	1.00			
Tm	0.64	0.53	0.70	0.74	0.82	0.75	0.89	0.94	0.97	0.99	1.00	1.00		
Yb	0.60	0.48	0.66	0.70	0.79	0.73	0.86	0.91	0.96	0.98	0.99	1.00	1.00	
Lu	0.59	0.47	0.65	0.69	0.78	0.71	0.85	0.91	0.95	0.97	0.98	0.99	0.99	1.00

Tb are found in regions with igneous rocks, mostly granitic to pegmatitic in composition. In the southern part of Sweden, some anomalies may relate to the glacial deposits overlying crystalline bedrock.

The median for Dy is 3.55 mg/kg in subsoil and range vary from 2.02 mg/kg to 7.23 mg/kg. In topsoil the median Dy value is 2.94 mg/kg; content in topsoil vary from 1.48 mg/kg to 6.18 mg/kg, while the median Dy at Europe is 3.66 mg/kg and 3.42 mg/kg in subsoil and topsoil, respectively. The median Dy content in stream sediment is 5.78 mg/kg and the range of concentrations varies between 3.78 mg/kg and 25.30 mg/kg. Dy concentrations in soil are much higher in northern Sweden than in the south. High Dy values in soil are located mainly in the crystalline basement and loess/paleoplacer area of northern Sweden. Dy pattern in subsoil and topsoil is very similar. High Dy values also occur in stream sediment in the northern part of Sweden and mostly have a good correlation with Th and U.

The Ho contents of Swedish subsoils range from 0.37 to 1.47 mg/kg with a median of 0.75 mg/kg, which is similar to the median Ho content of European subsoils. The values of Ho in Swedish topsoils are similar to those of the subsoils and the highest Ho concentrations are found in areas with crystalline basement rocks in northern Sweden. Concentrations of Ho in soils have strong correlations with concentrations of Gd, Tb, and Dy. The median Ho value in Swedish

stream sediments is 1.20 mg/kg, which is slightly higher than the median Ho value in European stream sediments. Anomalies of Ho occur in northern and southern parts of Sweden, where they are related to granitic–pegmatitic lithologies enriched in U and Th.

The Er concentrations in Swedish subsoils range from 1.21 to 4.39 mg/kg with median of 2.24 mg/kg, whereas Er contents of topsoils vary from 0.95 to 3.96 mg/kg with a median of 1.80 mg/kg. The Er contents of Swedish stream sediments vary from 2.14 to 17.30 mg/kg with a median of 3.47 mg/kg, whereas the median Er value in European sediments is 2.67 mg/kg. The Er median in Swedish stream sediments is higher than that in Swedish soils (3.47 mg/kg). High Er values in Swedish soils are found mainly on the crystalline basement with granitic composition and in paleoplacer areas in northern Sweden (Salpeteur et al., 2005). The distribution of Er anomalies in Sweden is similar to that of heavy REE elements.

The Tm contents of Swedish subsoils vary from 0.17 to 0.65 mg/kg with median of 0.36 mg/kg, whereas in Swedish topsoils Tm values vary from 0.13 to 0.57 mg/kg with median of 0.28 mg/kg. The spatial distribution of Tm is very similar to other heavy REEs and controlled mainly by the crystalline bedrock underlying the soils. The median Tm value in Swedish stream sediment is 0.53 mg/kg, which is slightly higher than that of European stream sediments. A reason for this is

the strong correlation of REEs with U and Th in granite–pegmatite rocks and felsic volcanics in the northern part of Sweden.

The spatial distribution of Yb is similar to that of Tm and Er, but areas with elevated values of these elements are generally smaller. The median Yb values in Swedish subsoils and topsoils are 2.40 mg/kg and 1.98 mg/kg, respectively. The concentrations of Yb in stream sediments, which range from 2.26 to 18.70 mg/kg with a median of 3.76 mg/kg, are higher than in the soils. High Yb values in soils are located mainly in regions underlain by the crystalline basement of mainly granitic composition and in areas with high-grade metamorphic rocks (amphibolites, migmatites, granulites, and eclogites) with garnet is a common phase. Paleoplacer area in northern Sweden tends to have higher Yb concentrations as well (Salpeteur et al., 2005). There are strong correlations of Yb with U and Th in stream sediments, possibly because these elements form substitutions in heavy minerals commonly found in stream sediments (e.g., garnet).

The Lu values in Swedish subsoils range from 0.18 to 0.59 mg/kg with median of 0.35 mg/kg, whereas Lu values in topsoils vary between 0.17 and 0.58 mg/kg with median of 0.30 mg/kg (Fig. 5). The median Lu values in Swedish subsoils and topsoils are almost similar to those in European subsoils/topsoils. Low Lu concentrations in Swedish soil occur in areas with metavolcanic rocks and younger granitoids in central and northern Sweden. High Lu contents have been noted in the Paleoproterozoic granite–pegmatite series in northern and southeastern Sweden. The Lu contents of Swedish stream sediments range from 0.34 to 3.01 mg/kg with a median of 0.57 mg/kg, which is higher than for European stream sediments (0.39 mg/kg). The spatial distribution of Lu in stream sediments shows similar trends to the other media and there are strong correlations among Lu, Yb, and Tm.

4.2. Principal component analysis of REE data

Principal component (PC) analysis has been a conventional multivariate technique that is used for studying geochemical data (Carranza, 2008; Howarth and Sinding-Larsen, 1983). PC analysis reduces a large number of variables to a smaller number, allowing the user to determine which components (groups of variables) account for variation in multivariate data (Güller et al., 2002). PC analysis has been applied frequently to process and interpret geochemical and other types of spatial data (e.g., Carranza, 2008; Cheng et al., 2011; Grunsky, 2010; Harris et al., 1997). PC analysis has also been used in GIS for integration and interpretation of image data (e.g., Carranza and Hale, 2002; Chavez and Kwarteng, 1989; Crósta et al., 1989). The foundation of PC analysis is the correlation (covariance) matrix, which measures the interrelationships among multiple variables. The first PC explains most of the variance within the original data, and each subsequent PC explains progressively less of the variance. A multivariate dataset can usually be reduced to two or three PCs that account for the majority of the variance within the dataset.

Pearson correlation analysis was performed on the FOREGS REE data for the individual sampling media (Table 2). The results show strong correlations among LREEs (e.g., La with Ce, Pr, and Sm) in all media. The results also show strong correlations among HREEs (e.g., Er with Lu, Yb, and Tm).

Subsequently, PC analysis was performed on the average values of the different sampling media. The results reported in Table 3 show that PC1 and PC2 explain 82.60% and 12.77%, respectively, of the total variance in topsoils. For subsoils, PC1 and PC2 explain 83.72% and 12.11%, respectively, of the total variance in the data. For stream sediments, PC1 and PC2 explain 86.46% and 11.68%, respectively, of the total variance in the data. All REEs have negative loadings on PC1 of data for individual sampling media (Table 3). The LREEs have largest loadings on PC2 of data for individual sampling media. For data of each sampling media, Ce has largest loading on PC3 whereas Eu and Yb have negative loading on this component.

The datasets for the individual sampling media show similar multivariate structures. The PC1 and PC2 of the individual datasets show the contrast between LREEs and HREEs, whereas the PC1 and PC3 of the individual datasets show three distinct clusters (one comprising most REEs, one for Ce and one for Eu) (Figs. 6–8). Plots of loadings of REEs on PC2 and PC3 of individual datasets show mainly two distinct clusters (Fig. 9), one comprising most REEs and the other represent Eu anomalies. However, Ce forms a distinct cluster in the subsoil and topsoil datasets. This indicates that Ce in topsoils and subsoils are closely related probably in origin and dispersion. The result for stream sediment is slightly different from subsoil and topsoil, which may relate to the origin for each elements and any other weathering or mineralization.

5. Discussion

The geochemical maps of REE distribution in Sweden show the possible sources of metals in relation to the type of the underlying rock

Table 3
Correlations among elements and principal components.

Elements	PC1	PC2	PC3	PC4
<i>Topsoils</i>				
La	−0.075	0.258	0.439	0.048
Ce	−0.071	0.245	1.330	−0.738
Pr	−0.078	0.234	0.113	0.348
Nd	−0.080	0.199	−0.038	0.083
Sm	−0.081	0.164	−0.346	0.757
Eu	−0.078	0.097	−1.075	−1.959
Gd	−0.084	0.059	−0.364	0.531
Tb	−0.085	−0.005	−0.430	0.641
Dy	−0.083	−0.096	−0.285	0.424
Ho	−0.082	−0.159	−0.199	0.180
Er	−0.079	−0.194	0.033	−0.011
Tm	−0.077	−0.241	0.226	0.102
Yb	−0.075	−0.260	0.324	−0.396
Lu	−0.069	−0.317	0.606	−0.311
Eigenvalue	11.565	1.788	0.237	0.159
Cumulative variance (%)	82.605	95.377	97.071	98.213
<i>Subsoils</i>				
La	−0.858	0.485	0.081	−0.088
Ce	−0.837	0.460	0.228	−0.084
Pr	−0.910	0.401	0.039	−0.026
Nd	−0.929	0.349	−0.005	0.024
Sm	−0.967	0.208	−0.026	0.089
Eu	−0.882	0.249	−0.377	−0.112
Gd	−0.977	0.083	−0.034	0.144
Tb	−0.989	−0.022	−0.023	0.107
Dy	−0.960	−0.207	0.008	0.106
Ho	−0.946	−0.294	0.011	0.026
Er	−0.909	−0.383	0.033	0.009
Tm	−0.902	−0.391	−0.006	−0.026
Yb	−0.882	−0.442	0.059	−0.042
Lu	−0.845	−0.479	0.031	−0.185
Eigenvalue	11.723	1.696	0.209	0.118
Cumulative variance (%)	83.734	95.849	97.349	98.196
<i>Stream sediments</i>				
La	−0.880	0.458	0.052	0.059
Ce	−0.804	0.571	0.106	0.095
Pr	−0.920	0.387	0.031	0.009
Nd	−0.942	0.331	0.015	−0.018
Sm	−0.976	0.195	0.013	−0.073
Eu	−0.907	0.207	−0.367	0.022
Gd	−0.992	0.063	0.041	−0.091
Tb	−0.994	−0.062	0.021	−0.083
Dy	−0.974	−0.209	0.005	−0.070
Ho	−0.961	−0.267	0.027	−0.019
Er	−0.941	−0.333	0.029	0.008
Tm	−0.921	−0.385	0.015	0.049
Yb	−0.899	−0.432	−0.004	0.061
Lu	−0.891	−0.438	0.016	0.093
Eigenvalue	12.108	1.636	0.154	0.154
Cumulative variance (%)	86.485	98.174	99.274	99.661

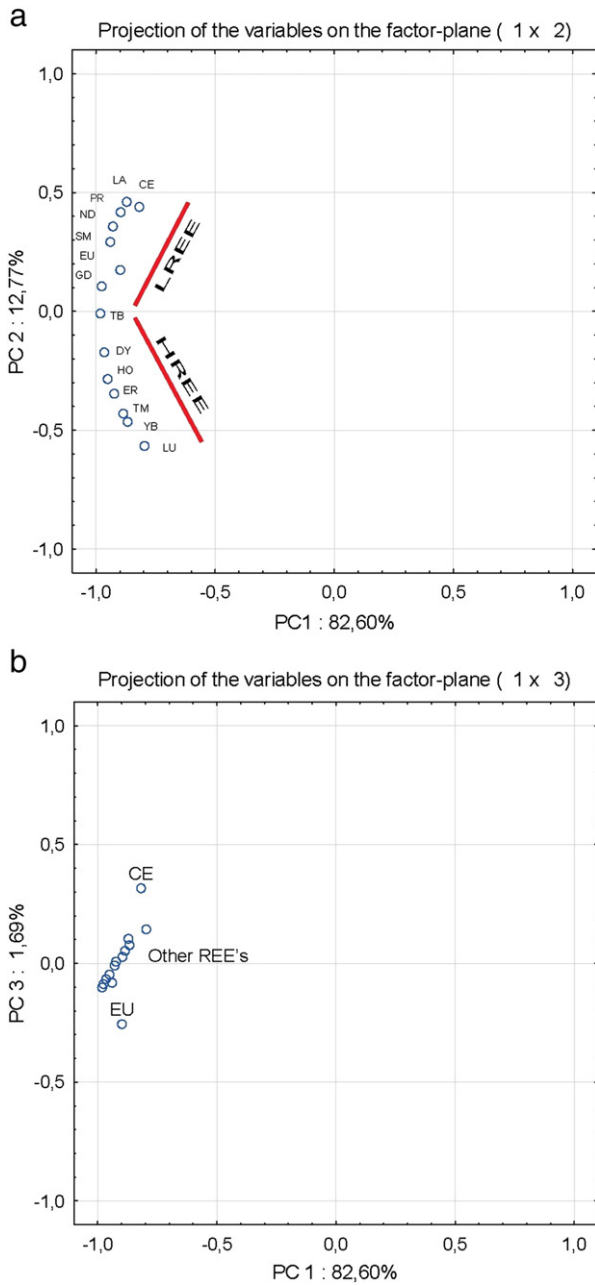


Fig. 6. Principal component analysis of Swedish topsoil dataset. Correlations of elements with PCs: (a) PC1 versus PC2; (b) PC1 versus PC3.

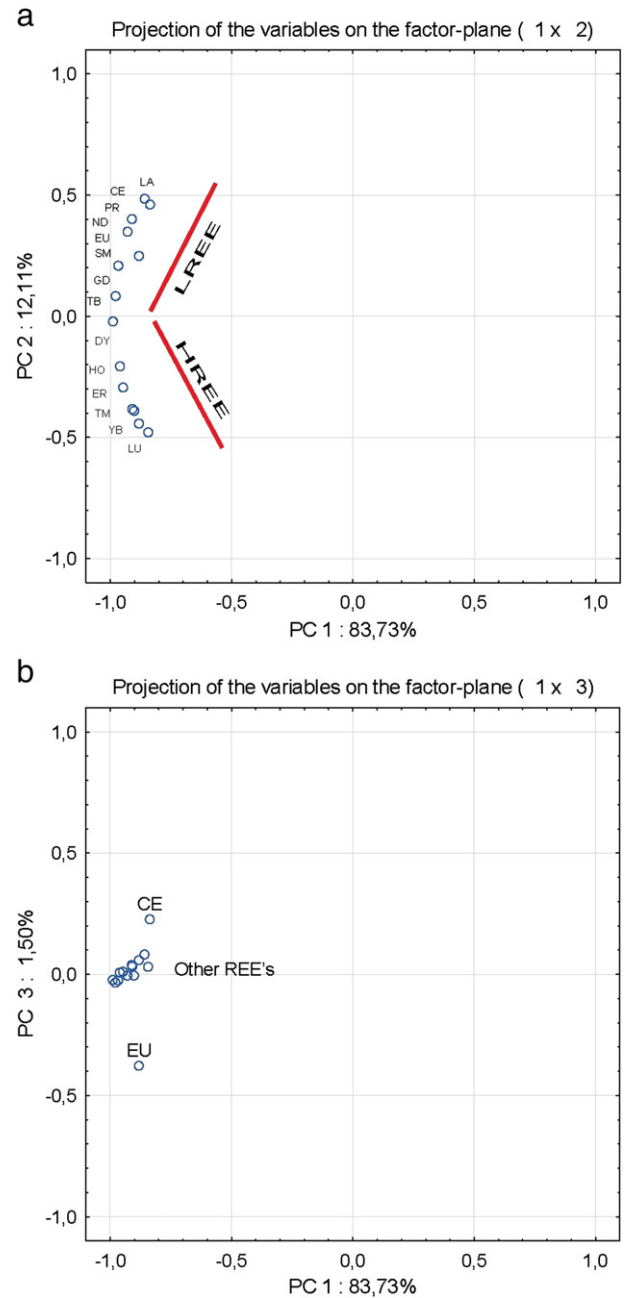


Fig. 7. Principal component analysis of Swedish subsoil dataset. Correlations of elements with PCs: (a) PC1 versus PC2; (b) PC1 versus PC3.

types. In northern Sweden, the large REE anomaly probably has a complex origin; the high REE concentrations correlate with underlying crystalline rocks of the Fennoscandian Shield, and granitic intrusions and high grade metamorphic rocks within the Caledonides. Another potential source of REEs is hydrothermally altered igneous and metavolcanic rocks, which host important ore deposits (Fe, Cu, Zn etc). The high REE concentrations in Jämtland in west northern part of Sweden at Caledonian region originate from granites of the autochthonous basement rocks (the Grong-Olden Culmination) which form a tectonic window within the Caledonides. In addition to the REEs, these lithologies are known to host uranium mineralization. Higher REE concentrations close to the Baltic coast in central Sweden can be related to the high-grade migmatites and large igneous intrusions (e.g., Ljusdal Batholith). In southern Sweden, the high REEs are related to evolved post-orogenic granites and pegmatites of Sveco-karelian (SE Swede) and Sveconorwegian (SW Sweden) age.

The geochemical maps and correlation matrices show a general decoupling between LREE and HREE. The main reason for this difference is that the LREE are highly incompatible in the magmatic and metamorphic environments, which dominate Swedish bedrock geology, while HREE are somewhat more compatible. The LREEs concentrate in highly evolved rocks and the final products of magma differentiation (accessory minerals), while HREE tend to substitute for major elements in some rock forming and metamorphic minerals (e.g., clinopyroxene and garnet).

The median concentration of REE followed the order Ce>La>Nd>Pr>Sm>Gd>Dy>Er>Yb>Eu>Ho>Tb>Tm>Lu in subsoils, Ce>La>Nd>Pr>Sm>Gd>Dy>Yb>Er>Eu>Ho>Tb>Tm>Lu in topsoils, and Ce>La>Nd>Pr>Sm>Gd>Dy>Er>Yb>Ho>Tb>Eu>Lu>Tm in stream sediments. The REE patterns are generally similar by having higher LREE concentrations, a slightly negative Eu anomaly and depletion in HREE concentrations in all media. The

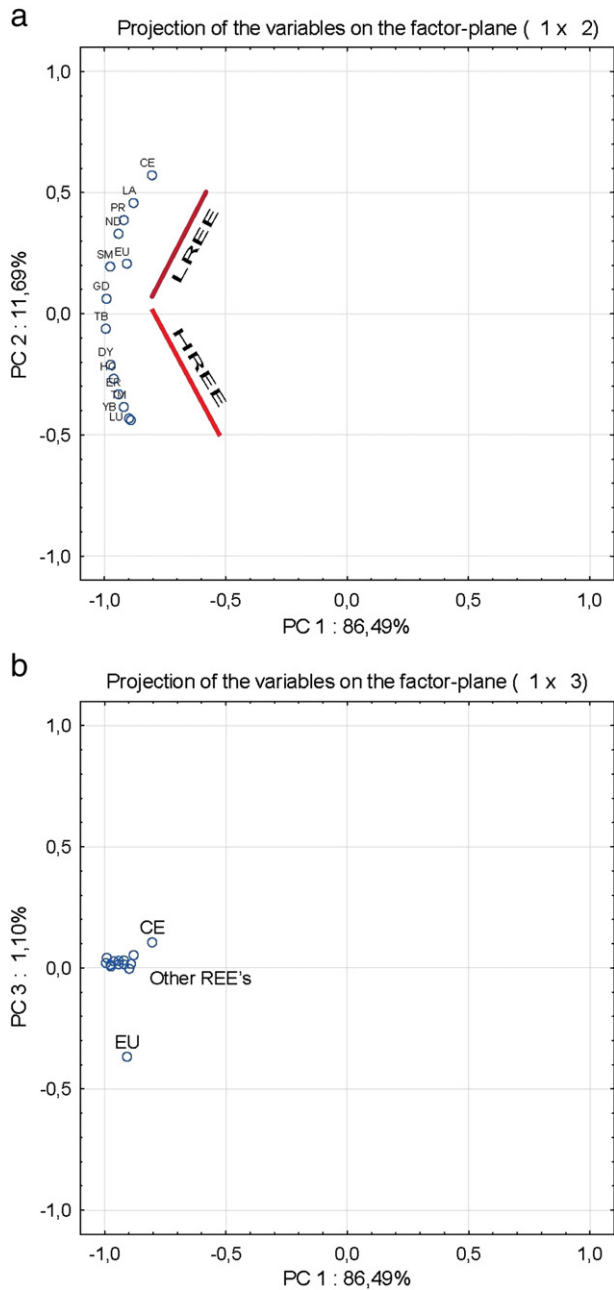


Fig. 8. Principal component analysis of Swedish stream sediment dataset. Correlations of elements with PCs: (a) PC1 versus PC2; (b) PC1 versus PC3.

main difference between the distribution pattern for LREE and HREE is the enrichment of the LREE in Archean rocks in northern Sweden while HREE concentrations in the oldest rocks and located southeastwards (along the border with Finland) Archean to Paleoproterozoic metasediments are rather low. Enrichment of HREE in southern Sweden occurs in soils overlying high grade metamorphic rocks of the Sveconorwegian terrane. High-grade rocks (garnet migmatites, granulites, and eclogites) are responsible for elevated Yb and Lu contents in the Middle and Upper Allochthons in the Caledonides (e.g., in the Seve Nappe). The main REE negative anomaly occurs in Dalarna (central Sweden) where Mesoproterozoic quartzitic sandstone exhibits quartz-dominated, strongly depleted composition. Soils overlying Cambro-Silurian sedimentary rocks (shale, limestone, marl etc) in central and southern Sweden, Golland, and Öland also have low REE concentrations. Skåne in southernmost Sweden with the youngest

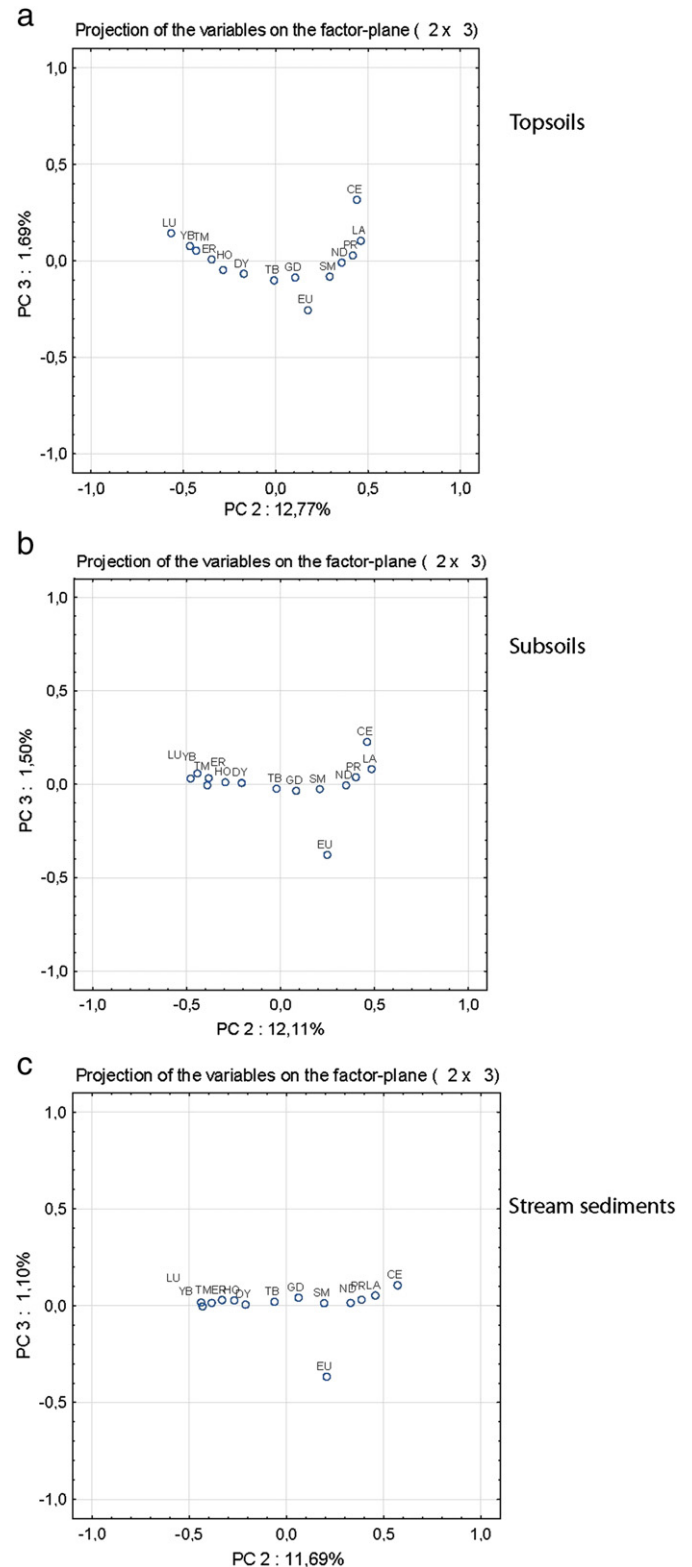


Fig. 9. Principal component analysis of individual Swedish datasets. Correlations of elements with PC2 and PC3: (a) topsoils; (b) subsoils; and (c) stream sediments.

sedimentary cover in Sweden, closely related to the continental Europe, shows low REE concentrations in all sample types.

In nature, the REEs generally act together. Therefore, multivariate methodologies can be applied to this series of elements to identify and examine anomalies. PC analysis aids interpretation of geochemical data in terms of geological process, such as differentiation (partial

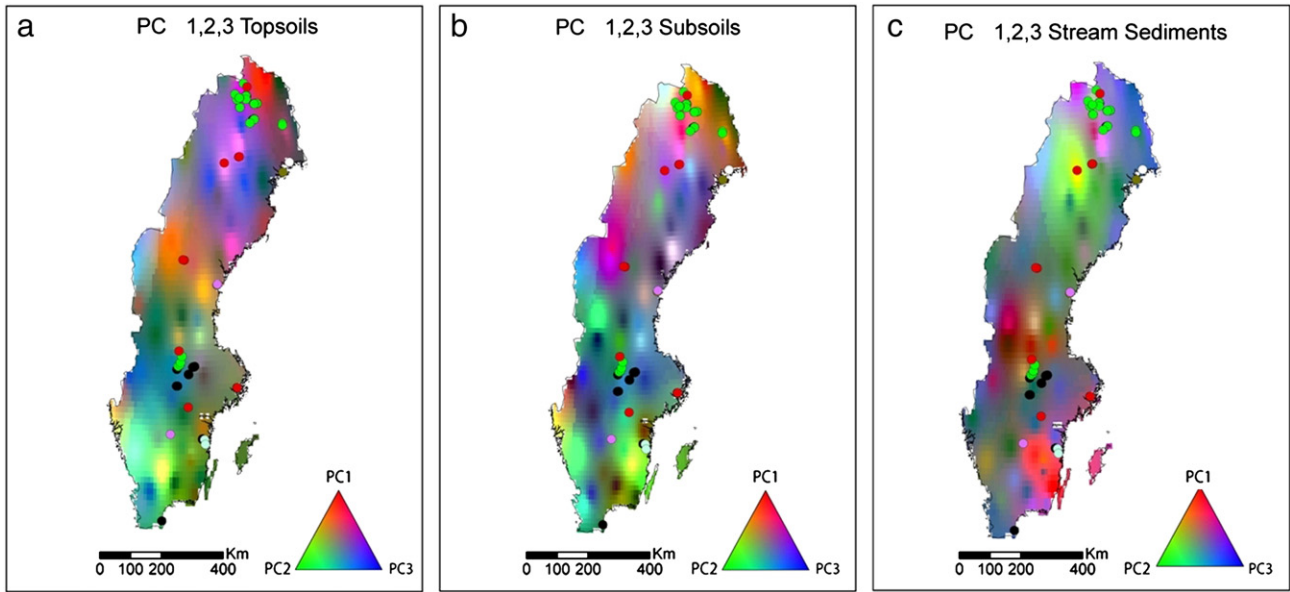


Fig. 10. Color composite images of PC1 (red), PC2 (green) and PC3 (blue) of individual Swedish datasets: (a) topsoils; (b) subsoils; (c) stream sediments. For explanations of colored dots, see Fig. 1.

melting, crystal fractionation, etc.), alteration/mineralization, and weathering (Grunsky, 2010). The first and second PCs usually reveal relationships between observations and variables that reflect underlying lithological variation. In Sweden, where a significant percentage of the surface is covered with overburden such as glacial till, alluvium, or colluvium, the combination of variables and plots of PC loadings reflect a mixture of several surficial processes.

The first two PCs of each of the topsoil and subsoil REE soil datasets account for 95.37% and 95.84%, respectively, of the total variance in each of those datasets. The projections of the 14 REEs on the bi-dimensional space (Figs. 5–7) show the degree of association among the variables. Both LREEs and HREEs form well-defined groups. The Ce plots away from the other REEs due to its anomalous nature. The Eu also plots away from the LREE group due to its distinct behavior among the REEs. Of all the REEs, Ce and Eu show different distribution patterns,

possibly due to the sensitivity of the REEs to redox conditions as shown by Henderson (1984) and Wilde et al. (1996).

The color composite maps of PCs 1, 2 and 3 of the topsoil and subsoil data (Fig. 10) clearly reflect the Archean rocks in northern Sweden and the outline of the second phase of the Svecokarelian orogen, as well as the clay belt along the coast in eastern Sweden and young granites in the southwest. Some mineralizations in northern Sweden are clearly marked on the PCs maps. It is also interesting that different types of REE mineralization are associated with different PC scores (i.e., different colors in the PC color composites). In Fig. 11, which is a color composite map of PC 1, 3 and 4, more details on the variation of PCs related to mineralization can be observed. In this work, color composites of the first three to fourth PCs of each dataset are effective for interpretation of the geochemical data in terms of geological processes.

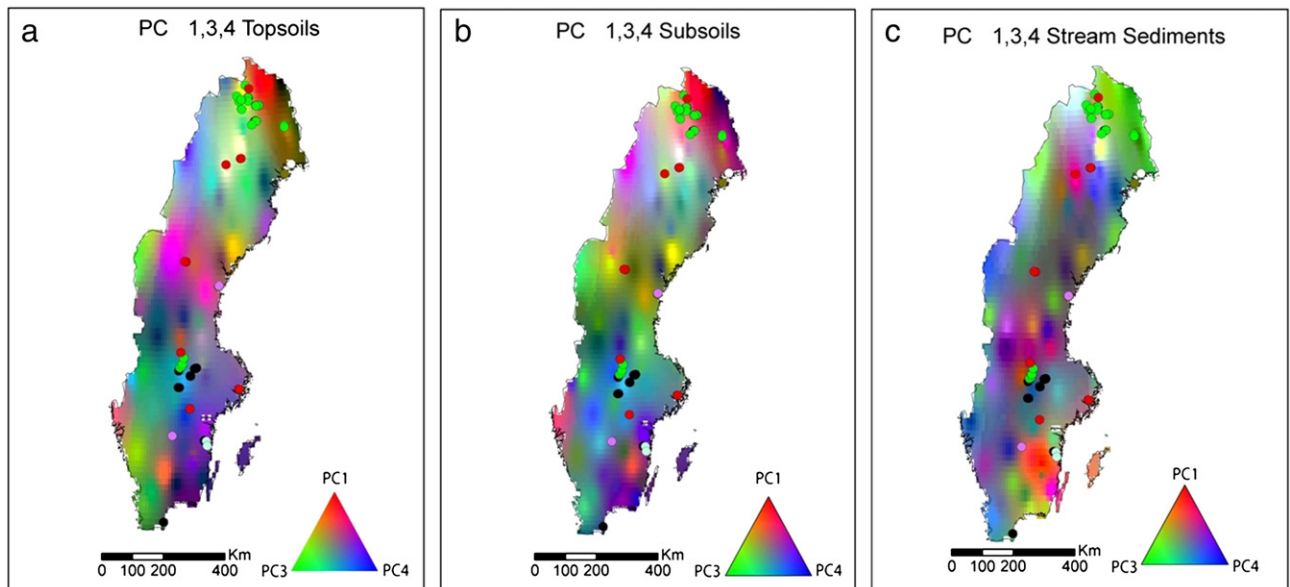


Fig. 11. Color composite images of PC1 (red), PC3 (green) and PC4 (blue) of individual Swedish datasets: (a) topsoils; (b) subsoils; (c) stream sediments. For explanations of colored dots, see Fig. 1.

6. Conclusion

Principal component analyses of rare earth element concentration data in the FOREGS datasets for subsoils, topsoil and stream sediments in Sweden show that each of these datasets comprises three main components from which meaningful interpretations regarding REE distribution in Swedish soils can be drawn. There are strong correlations among REEs in soils and in the underlying bedrock. In topsoils, the highest REE concentrations develop over Archean granites and along the boundary of Archean and Palaeoproterozoic rocks whereas the lowest REE concentrations pertain to soils derived from Sveconorwegian orogen rocks. Subsoils shows slightly different REE distributions, with the highest concentrations developed on Caledonian and Svecokarelian orogen (phase 2) rocks. The highest REE concentrations in stream sediments are generally similar to those in subsoils, but the anomalies also show the boundary of Archean and Palaeoproterozoic rocks in northern Sweden. The lowest REE concentrations occur in soils overlying siliciclastic and carbonate rocks of various ages. LREEs show strong enrichment over HREEs in soils overlying the Archean rocks in northern Sweden, Archean and Palaeoproterozoic basement rocks in Jämtland and Västerbotten, and younger granites in Bohuslan. In contrast, the HREEs show strong enrichment in soils overlying high-grade metamorphic rocks of the Sveconorwegian Orogen in southern Sweden. REE data for stream sediments show various subtle distribution patterns compared to those for subsoils and topsoils. This is attributed to different styles of sediment re-working as well as weathering and biogeochemical processes that the sediments have undergone.

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