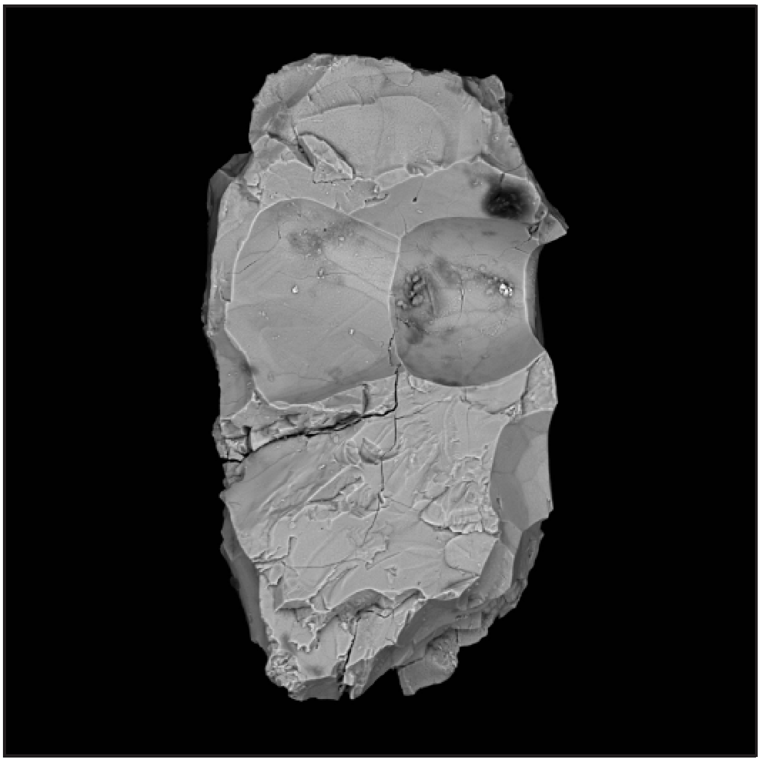
A Russian record of a Middle Ordovician meteorite shower: Extraterrestrial chromite in Volkhovian-Kundan (lower Darriwilian) strata at Lynna River, St. Petersburg region

Anders Lindskog

Dissertations in Geology at Lund University,
Master's thesis, no 287
(45 hp/ECTS credits)



Department of Earth- and Ecosystem Sciences
Division of Geology
Lund University
2011

A Russian record of a Middle Ordovician meteorite shower:

Extraterrestrial chromite in Volkhovian-Kundan (lower Darriwilian) strata at Lynna River, St. Petersburg region

Master Thesis

Anders Lindskog

Department of Earth and Ecosystem Sciences
Division of Geology
Lund University
2011

Contents

Cover picture: ”Murray?” (no, it's just a somewhat piratey chromite grain).

A Russian record of a Middle Ordovician meteorite shower: Extraterrestrial chromite in Volkhovian-Kundan (lower Darriwilian) strata at Lynna River, St. Petersburg region

ANDERS LINDSKOG

Lindskog, A., 2011: A Russian record of a Middle Ordovician meteorite shower: Extraterrestrial chromite in Volkhovian-Kundan (lower Darriwilian) strata at Lynna River, St. Petersburg region. *Examensarbeten i geologi vid Lunds universitet, nr. 287*, 32 pp. 45 ECTS credits.

Abstract: Numerous fossil meteorites and high concentrations of sediment-dispersed extraterrestrial chromite (EC) grains with typical ordinary chondritic composition have previously been documented from 467±1.6 Ma Ma lower Kundan (Middle Ordovician) strata. These finds most likely reflect a temporarily enhanced influx of ordinary chondritic matter, following the disruption of the L chondrite parent body in the asteroid belt 470±6 Ma. In this study, an uppermost Volkhovian-lower Kundan limestone/marl succession at Lynna River, St. Petersburg region, northwestern Russia, has been sampled and its extraterrestrial component determined through chromite grain extraction and analysis. Seven samples, forming two separate sample sets, were collected at the locality. Four samples from strata around the *Lenodus variabilis-Yangtzeplacognathus crassus* conodont zone boundary yielded a total of 397 EC grains in 51.5 kg of rock (average ~7.71 EC grains kg^{-1}). A successive increase in the concentration of EC and other heavy mineral grains upwards in this sample set likely traces sea-level rise. Three stratigraphically lower-lying samples, from strata around the *Baltoniodus norrlandicus-L. variabilis* conodont zone boundary, which corresponds to the Volkhov-Kunda boundary, yielded only two EC grains in 38.2 kg of rock (average ~0.05 EC grains kg^{-1}). This lack of EC enrichment contrasts with preceding studies at other localities, which have consistently identified a notable EC component in the lowermost *L. variabilis* conodont zone. Discrepancies in the timing of the initial EC enrichment between localities, as well as variations in concentration within individual stratigraphies, may be explained by differential deposition, however, the predictable increase in EC abundance in lower Kundan strata is best explained by an enhanced influx of ordinary chondritic matter. A strong similarity in average EC chemical composition between this and other comparable studies indicates that all or most EC grains in these Middle Ordovician strata share a common source – most likely the L chondrite parent body.

Keywords: Lynna River, extraterrestrial chromite, fossil meteorites, Volkhov, Kunda, Darriwilian, heavy minerals, *Lenodus variabilis*.

Anders Lindskog, Department of Earth and Ecosystem Sciences, Division of Geology, Lund University, Sölvegatan 12, SE-223 62 Lund, Sweden. E-mail: anders.lindskog.818@student.lu.se.

Ett ryskt sedimentarkiv över ett mellanordoviciskt meteoritregn: Utomjordisk kromit i volkhov-kundalager (undre Darriwilian) vid floden Lynna, St. Petersburgregionen

ANDERS LINDSKOG

Lindskog, A., 2011: Ett ryskt sedimentarkiv över ett mellanordoviciskt meteoritregn: Utomjordisk kromit i volkhov -kundalager (undre Darriwilian) vid floden Lynna, St. Petersburgregionen. *Examensarbeten i geologi vid Lunds universitet, nr. 287*, 32 sid. 45 hp.

Sammanfattning: Tidigare studier har dokumenterat ett flertal fossila meteoriter samt höga koncentrationer av utomjordisk kromit med typisk kondritisk sammansättning i sedimentlager från undre kunda (mellanordovicium, 467±1.6 Ma). Dessa fynd reflekterar sannolikt ett tillfälligt förhöjt inflöde av kondritiskt material, efter uppbrytningen av L-kondriternas föräldrakropp 470±6 Ma. I den här studien undersöktes innehållet av utomjordisk kromit i prover från en lagerföljd omfattande översta volkhov och undre kunda, vid floden Lynna, i St. Petersburgregionen i nordvästra Ryssland. Sju prover, i två separata provserier, valdes ut vid lokalen. Fyra prover med totalt 51,5 kg sten från lager kring gränsen mellan conodontzonerna *Lenodus variabilis* och *Yangtzeplacognathus crassus* innehöll sammanlagt 397 utomjordiska kromitkorn (medel ~7,71 korn kg^{-1}). En successiv ökning i koncentrationerna av utomjordisk kromit och andra tungmineral uppåt i denna provserie spårar sannolikt en havsnivåhöjning. Tre lägre liggande prover med totalt 38,2 kg sten, från lager kring gränsen för conodontzonerna *Baltoniodus norrlandicus* och *L. variabilis*, motsvarande volkhov-kundagränsen, innehöll endast två utomjordiska kromitkorn (medel ~0,05 korn kg^{-1}). Detta står i kontrast mot tidigare studier vid andra lokaler, vilka alla har påvisat en förhöjd kromitkoncentration i den nedersta delen av *L. variabilis*-zonen. Skillnader i vid vilken nivå den initiala kromitanrikningen inträder i lagerföljderna vid olika lokaler, liksom koncentrationsvariationer inom lagerföljder, kan förklaras med olikformig deposition, men den förutsägbara ökningen av utomjordisk kromit i lager från undre kunda förklaras bäst med att en tid med förhöjt inflöde av kondritiskt material inföll. En god överensstämmelse mellan den kemiska sammansättningen hos kromitkorn från den här studien och kromit från andra liknande studier indikerar att alla (eller de flesta) korn i dessa mellanordoviciska lager har samma ursprungskälla – sannolikt L-kondriternas föräldrakropp.

Nyckelord: Lynna, utomjordisk kromit, fossila meteoriter, volkhov, kunda, tungmineral, *Lenodus variabilis*.

Anders Lindskog, Institutionen för geo- och ekosystemvetenskaper, Enheten för geologi, Lunds universitet, Sölvegatan 12, 223 62 Lund. E-post: anders.lindskog.818@student.lu.se.

1 Introduction

1.1 Background

Several recent studies have documented high concentrations of extraterrestrial matter – most notably, numerous fossil meteorites – in ~467 Ma Middle Ordovician rocks (e.g. Schmitz et al. 1996; Schmitz et al. 2001; Schmitz & Häggström 2006; Schmitz et al. 2008; Cronholm 2009, Korochantsev et al. 2009; Cronholm & Schmitz 2010). Though fossil meteorites are yet to be found outside a select few Swedish localities, an anomalous abundance of sediment-dispersed extraterrestrial chromite (EC) grains has been shown to occur in coeval strata at several localities, both in Sweden and abroad. This apparently rather sudden increase in extraterrestrial matter in the mid-Ordovician strata has been interpreted as the result of a disruption event in the asteroid belt, which produced swarms of variously-sized debris that eventually crossed paths with Earth (e.g. Schmitz et al. 2001; Korochantseva et al. 2007; Schmitz et al. 2008).

Beginning slightly above the base of the *Lenodus variabilis* conodont biozone, which marks the base of the Kunda Baltoscandian Regional Stage (Dronov 2005a), EC grains typically become appreciably more abundant (e.g. Cronholm & Schmitz 2010). Higher in the strata, an EC 'spike' is observed, in turn followed by variably EC-enriched beds throughout the succeeding *Yangtzeplacognathus crassus* and *Eoplacognathus (Lenodus*?) *pseudoplanus* conodont zones before the concentration ebbs out again (throughout this thesis, where applicable, the conodont nomenclature and zonation of Mellgren & Eriksson 2010 is used). The aim of this study is to investigate if a similar chromite signal is present in the Lynna River section – already, Korochantsev et al. (2009) confirmed that EC grains at least occur in the studied rock succession. EC concentration will then be compared to that of other heavy minerals, in order to gain insight into deposition rates and hydrodynamic concentration processes that may have acted at the seafloor. Of particular interest is to investigate if the initiation of the EC enrichment coincides with the Volkhov-Kunda boundary.

1.2 A brief interlude on the basics of meteorites and meteorite classification

In short, a meteorite may be defined as any extraterrestrial object (i.e. meteoroid) that passes through the atmosphere and reaches Earth's surface (or any other planet's surface, for that matter; e.g. Allaby 2008). However, most meteoritic objects are submillimeter-sized, and thus often collectively referred to as cosmic dust (e.g. Love & Brownlee 1993; Peucker-Ehrenbrink 2000). Calculations based on marine isotopic trace elements (Os, Ir) and systematic dust collection both indicate that the annual influx of cosmic dust is around 30,000 to 50,000 tons (Love & Brownlee 1993; Peucker-Ehrenbrink 2000). Larger extraterrestrial objects, more befitting of the term meteorite as generally perceived, are thought to contribute approximately the same mass annually, however, intermittent, unusually large objects may offset averages and influx may vary considerably over long time scales. Most such meteorites likely originate from the asteroid belt, which is situated between Mars and Jupiter, though some have been associated with Earth's moon and Mars (Anders 1964; Gladman et al. 1997; Bischoff 2001).

Chemical and petrographic characteristics provide the main method of meteorite classification, with minerals and their textures having a central role (e.g. Bunch et al. 1967; Van Schmus & Wood 1967; Affiatalab & Wasson 1980; Kallemeyn et al. 1989; Bischoff 2001). Over 250 minerals – many of which are not found on Earth – have been identified in meteorites, and the basic meteorite composition is best described as one consisting of silicates, metals and sulfides (with varying proportions; Anders 1964; Rubin 1997, see this reference for a review of meteorite mineralogies). Meteorites may be divided into three main types; stony, iron and stony-iron meteorites (~96.7%, ~2.7% and ~0.6% of identified meteorites, respectively; Anders 1964; Cronholm 2009 and references therein). The descriptive type names speak for themselves, regarding general characteristics. Each of these meteorite types may be subdivided into several classes, groups and subgroups, though only a specific class of stony meteorites, called ordinary chondrites, are of relevance to describe in further detail herein.

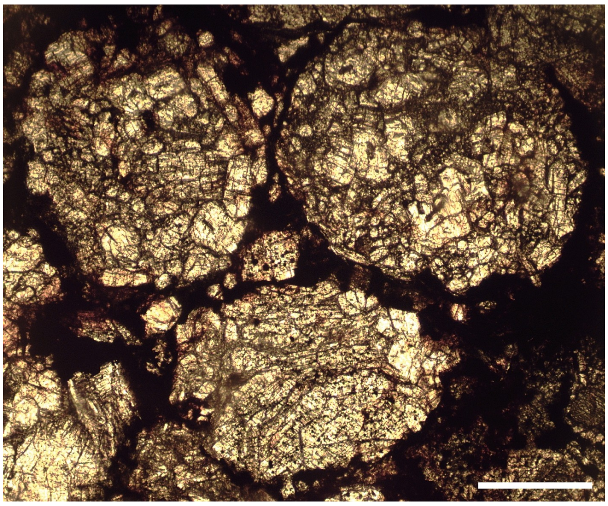


Fig. 1. Chondrules, appearing as small mineral globules throughout the meteorite matrix (thin-section of the recent Hallingeberg L3 meteorite). Scale bar is 250 µm. .

Ordinary chondrites are part of the main stony-meteorite class called chondrites, which lends its name from the characteristic so-called chondrules within such meteorites (Fig. 1; chondrites are one of two groups of stony meteorites, the other being achondrites, which lack chondrules; Anders 1964). Chondrules are submillimeter- to millimeter-sized frozen mineral droplets, formed at the time of our Solar system's birth. Ordinary chondrites dominate among identified meteorites, amassing to some 88% of all finds (Cronholm 2009 and references therein). The meteorite class can be subdivided into three more or less distinct groups, called H, L and LL (in order of relative abundance; e.g. Bunch et al. 1967; Cronholm 2009). H-group ordinary chondrites are characterized by high total-iron and free-metal (Fe, Ni) content, whereas those of the L group contain less, and LL-group members even lesser (i.e. *H*igh total-iron, *L*ow total iron, *L*ow total iron and *L*ow free metal). Silicate iron-oxide content displays a reverse pattern (and is thus closely tied to e.g. olivine fayalite content). Based on petrographic details, such as distinctness of chondrules, silicate homogeneity and presence of igneous glass, chondrite groups may be further subdivided into petrologic types (Bunch et al. 1967; Van Schmus & Wood 1967; Cronholm 2009). The types are termed H3-H6, L3-L6 and LL3-LL6, with numbers indicating increasing metamorphic imprint ('equilibration'), most notable through deteriorating chondrule texture (type 7 also exists, however, it is rare; types numbered 1-2 do not embrace ordinary chondrites). Similarly, ordinary chondrites may be categorized by shock stage, again through numbering from 1 to 6, with 1 being the least shock affected, and 6 being the most (Stöffler et al. 1991).

1.3 Indications of an enhanced influx of extraterrestrial matter in the Middle Ordovician

Following the identification of the first fossil meteorite from mid-Ordovician strata in Jämtland, central Sweden, in 1980, systematic search at Kinnekulle in Västergötland, southern Sweden, has yielded a remarkable amount of meteorites in a rather narrow interval of Kundan (Darriwilian, Arenigian-Llanvirnian) 'orthoceratite limestone' (e.g. Thorslund & Wickman 1981; Nyström et al. 1988; Schmitz et al. 1996; Schmitz et al. 2001; Schmitz et al. 2008). At present, close to a hundred specimens have been found at Kinnekulle, and one specimen has also been found at Mt. Billingen, also in Västergötland (B. Schmitz pers. comm. 2011-09-09; Tassinari et al. 2004).

Though they often retain some relict features, such as recognizable chondrule texture, fossil meteorites contain almost no original mineral constituents – most minerals have long since weathered and become substituted by others (principally calcite, barite and phyllosilicate pseudomorphs; Thorslund & Wickman 1981; Thorslund et al. 1984; Nyström et al. 1988; Nyström & Wickman 1991; Schmitz et al. 1996; Bridges et al. 2007). Chromite, a spinel-group mineral with the ideal formula $FeCr_2O_4$, typically constitutes the sole exception, as it is highly resistant to weathering and, thus, alteration and substitution (Fig. 2). It is the dominant oxide in ordinary chondrites, typically accounting for approximately 0.25% by weight (with chromite grains being both more abundant and larger-sized in higher petrologic types; Keil 1962; Rubin 1997; Bridges et al. 2007; Alwmark et al. 2011). The mineral is dispersed throughout the whole meteorite, and may be substantially concentrated in chondrules (Ramdohr 1967a). Chromite of extraterrestrial, ordinary chondritic origin typically displays distinct chemical composition, with relatively little variation between similar-source grains (this also applies to other minerals; Bunch et al. 1967; Snetsinger et al. 1967; Affiatalab & Wasson 1980; Wlotska 2005; Schmitz & Häggström 2006). As such, H, L and LL ordinary-chondrite groups have individual, relatively narrow compositional ranges for chromite, as do their subgroups, but there is some overlap in-between. Terrestrial chromite grains, which stem from (ultra-)mafic rocks, display a wide range of compositions, including those that are typical for ordinary chondritic grains (e.g. Gu & Wills 1988; Barnes & Roeder 2001). Consequently, chemical composition of chromite grains may indicate their provenance, but other proxies are desired in order to strengthen interpretation (e.g. Korochantsev et al. 2009).

As shown first by Thorslund & Wickman (1981), chromite in fossil ordinary chondrites largely retains its original, distinctly meteoritic chemical composition. Given the arduousness of finding fossil meteorites, extraction and analysis of sediment-dispersed chromite has thus become a relatively easy and efficient method to enable evaluation of the extraterrestrial, ordinary chondritic component in condensed sedimentary rocks (e.g. Schmitz et al. 2001). Such ventures have shown that the Middle Ordovician interval harboring abundant fossil meteorites in Sweden also yields unusually high amounts of chromite with typical ordinary chondritic composition, at localities in Sweden, China and Russia (e.g. Schmitz et al. 1996; Schmitz et al. 2001; Schmitz & Häggström 2006; Häggström & Schmitz 2007; Schmitz et al. 2008; Korochantsev et al. 2009; Cronholm & Schmitz 2010). Subsequently, this chromite has been interpreted as being of extraterrestrial origin. In the previously studied rock sections, extraterrestrial chromite (EC) abundance in the sediments increases from essentially zero to several grains per kilogram of rock; e.g. ~3 grains kg^{-1} in the Schmitz & Häggström (2006) study, ~6 grains kg^{-1} in the Häggström & Schmitz (2007) study, ~4 grains kg^{-1} in the Korochantsev et al. (2009) and Cronholm & Schmitz (2010) studies. This increase typically occurs slightly above the lower boundary of the *Lenodus variabilis conodont* zone and the EC enrichment appears to persist, with varying concentration, throughout the succeeding *Yangtzeplacognathus crassus and Eoplacognathus (Lenodus?) pseudoplanus* conodont zones. Pre-*L. variabilis* EC concentrations are comparable to those of similar condensed strata of much younger age (Cronholm & Schmitz 2007; Schmitz et al. 2010). Calculations indicate that there was a one to two order of magnitude increase in the influx of extraterrestrial matter during this mid-Ordovician interval (Schmitz et al. 1996; Schmitz et al. 2001; Schmitz et al. 2003; Cronholm & Schmitz 2007). As previously studied rock sections show no

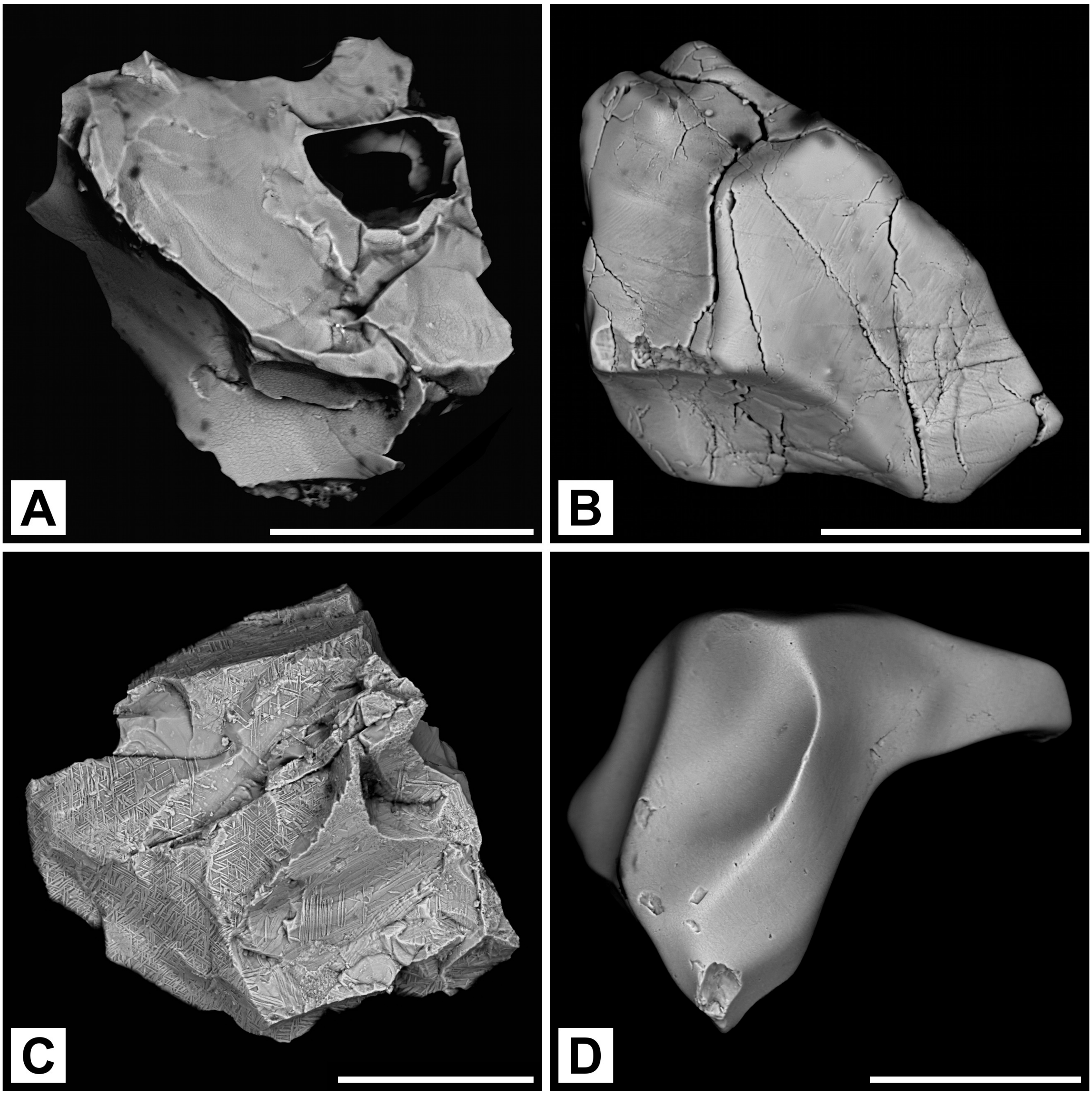


Fig. 2. A selection of chromite grains from this study (SEM, backscattered electron images). All scale bars 50 µm. **A.** Extraterrestrial chromite (EC) grain displaying characteristic angularity and excellent state of preservation (very angular/angular; sample Ly1, EC #72). **B.** EC grain displaying uncharacteristic rounding (sub-rounded/sub-angular; sample Ly5, EC #105). **C.** EC grain displaying characteristic angularity and excellent state of preservation (very angular/angular; sample Ly4, EC #37). Note the Widmanstätten-like pattern on the grain surface. **D.** EC grain displaying uncharacteristic rounding (sub-rounded/sub-angular; sample Ly2Ö, EC #21).

obvious signs of significant change in deposition rate, such attributes cannot easily explain the enrichment in extraterrestrial matter (e.g. Schmitz et al. 2008; Cronholm & Schmitz 2010). The finding of a single fossil meteorite in the *Eoplacognathus suecicus* conodont zone together with slightly enhanced EC values (~0.45 grains kg^{-1}) imply that the influx of extraterrestrial matter was higher than normal for at least five million years, from the lowermost Kundan into the Aseri Regional Stage (the meteorite in question, named 'Brunflo', was actually the first of the mid-Ordovician ordinary chondrites ever found; Thorslund & Wickman 1981; Alwmark & Schmitz 2009b). Most of the sediment-dispersed chromite grains probably stem from weathering and subsequent disintegration of relatively small (subcentimeter- to centimeter-sized) meteorites (Schmitz et al. 2003; Heck et al. 2008; Meier et al. 2010).

In addition to fossil meteorites and related chromite, several other indices of an increased extraterrestrial influx have been investigated in relevant rock intervals. Schmitz et al. (1996) measured various chemical elements, most importantly Ir, throughout the most meteorite-rich interval at Kinnekulle, Sweden, but could not conclusively tie elevated Ir levels to extraterrestrial enrichment (see also Schmitz et al. 1997). Patterson et al. (1998) measured the extraterrestrial ^{3}He component in the meteorite- and chromite-rich strata at Kinnekulle, Sweden, but no conclusive results were attained (meteorite values indicate significant ^{3}He loss through time). Cronholm (2009) investigated the Os and $^{187}Os/^{188}Os$ distribution throughout the strata at Kinnekulle. Anomalous values were recorded in the most meteorite- and chromite-rich rock interval, leading the author to suggest a connection to the increased influx of extraterrestrial matter.

1.4 Possible links between relict meteoritic material and events in the Solar system

Lacking the possibility of conventional, more direct classification due to the majority of primary minerals having been replaced by secondary ones, several features of the fossil meteorites have been investigated in order to shed light onto their classification. Chemistry, size and texture of chromite grains, and silicate inclusions in these, together with density, size and texture of relict chondrules, all indicate that the fossil meteorites are L chondrites of petrologic types 3 to 6 (Schmitz et al. 2001; Bridges et al. 2007; Greenwood et al. 2007; Alwmark & Schmitz 2009a).

Already in the 1960s, it became apparent that many L chondrites have endured some catastrophic event, which typically 'reset their K-Ar clocks' (Anders 1964; Turner et al. 1966; Bogard 1995; Keil et al. 1994; Haack et al. 1996). This event, hypothesized to be some kind of asteroid disruption due to collision in the asteroid belt, was constrained to around 500 Ma. Several authors have thus proposed a relationship between the breakup of the L-chondrite parent body and the increased influx of extraterrestrial matter to Earth in the Middle Ordovician (e.g. Schmitz et al. 1997; Heck et al. 2004). Recent ^{40}Ar-^{39}Ar analyses of L chondrites have dated the breakup event to 470±6 Ma, well in line with calibrated dating of the most meteorite-rich interval in the Swedish Middle Ordovician strata to 467±1.6 Ma (Korochantseva et al. 2007). L chondrites have been tentatively associated with the Gefion family of asteroids, situated in the intermediate main asteroid belt (Nesvorný et al. 2008; cf. Nesvorný et al. 2002).

^{21}Ne concentration, which results from cosmic ray exposure, increases in fossil-meteorite chromite when ascending through the Kinnekulle strata from the *L. variabilis* to the *E. (L.?) pseudoplanus* conodont zone (Heck et al. 2004; see also Heck et al. 2008). This indicates that stratigraphically higher-lying fossil meteorites have endured increasingly longer time in space before encountering Earth, and thus that all (or most) meteorites stem from the same dispersion event, likely the disruption of the L-chondrite parent body. Calculated exposure ages suggest that transport from the asteroid belt to Earth of the stratigraphically lower-most-lying meteorites took only 100-200 kyr, with the uppermost-lying sampled meteorites arriving approximately 1 Myr afterwards. These ages are corroborated by estimates of sedimentation rate and modeled asteroid breakup scenarios (Schmitz et al. 1996; Gladman et al. 1997; Zappalà et al. 1998; Schmitz et al. 2001).

Even today, about two thirds of Earth-crossing L chondrites – equating to ~30% of all identified ordinary chondrites – bear record of the ~470 Ma disruption event, however, their cosmic-ray exposure ages are never more than 70 Myr, indicating that they come from larger bodies that either survived the event or reaccreted in its aftermath (as cosmic rays only penetrate the outermost meter or so of objects; e.g. Keil et al. 1994; Nesvorný et al. 2008).

1.5 Implications of an increased influx of meteoritic matter

Schmitz et al. (2001) noted that there is a relatively large number of known astroblemes (i.e. impact structures) from the Middle to Late Ordovician, and thus suggested a connection to the breakup of the L-chondrite parent body (see also Korochantseva et al. 2007). At present, 178 confirmed impact structures are known globally (Earth Impact Database 2011). Of these, at least nine are Middle to Late Ordovician in age, with individual age estimates ranging from ~470 to ~445 Ma. Five of them are situated in the Baltoscandian region (see Dypvik et al. 2008). One of these, the Lockne crater in central Sweden, which is dated to ~458 Ma, has been successfully associated with an ordinary chondritic impactor (sediment samples yielded more than 75 EC grains kg^{-1}; Alwmark & Schmitz 2007; Schmitz et al. 2011). Culler et al. (2000) dated impact-produced glass spherules from lunar soil samples collected during the Apollo 14 mission, and concluded that there appears to be an enhanced impact rate from ~0.4 Ga and onwards.

In addition to indications of enhanced cratering rates, Middle Ordovician – especially Darriwilian – strata contain numerous megabreccias, typically situated at continental margins (Parnell 2009 and references therein). Some beds in such strata have been interpreted as tsunami deposits. As megabreccias and tsunami deposits may be direct or indirect results of large impacts, Parnell (2009) suggested a causal connection to the heightened influx of meteorites. Such features may also result from other processes, such as those acting in plate tectonics (Spence & Tucker 1997; Meinhold et al. 2010). Alwmark et al. (2010) showed that the so-called Osmussaar breccia in northwestern Estonia, which is dated to ~466 Ma, is very rich in EC grains (~13 grains kg^{-1}). This, together with previously documented shocked quartz, indicates that an ordinary chondritic impactor may be responsible for the brecciation (further references can be found in Alwmark et al. 2010). Schmitz et al. (2008) also noted that the time around the onset of the enhanced meteoritic influx often displays deviant lithologies (e.g. the 'Täljsten' in

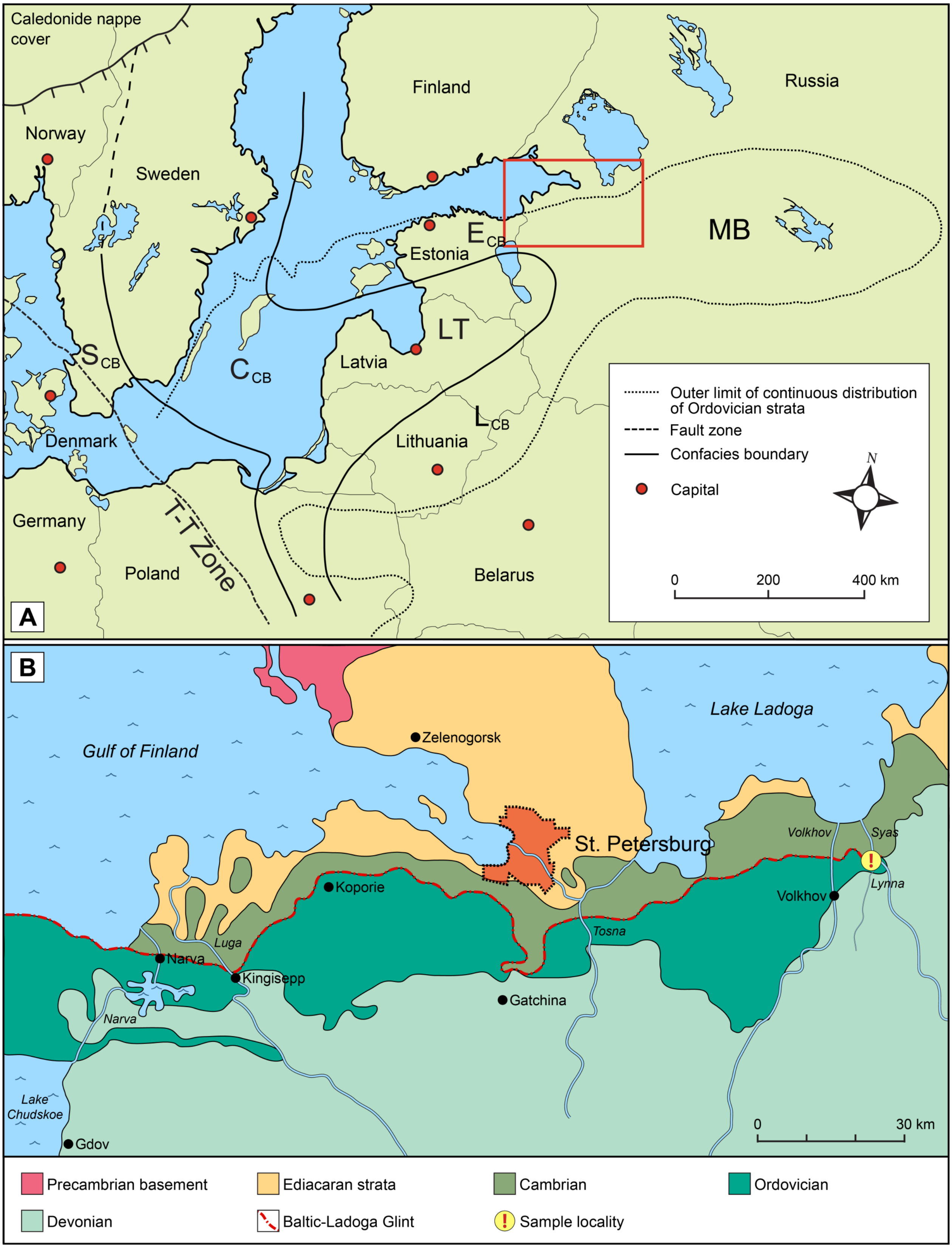


Fig. 3. **A.** Map of the Baltoscandian region, with confacies belts (CB) indicated (modified from Mellgren & Eriksson 2010). C_{CB} = Central CB; E_{CB} = Estonian CB; L_{CB} = Lithuanian CB; LT = Livonian Tongue; MB = Moscow Basin; S_{CB} = Scanian CB. Red rectangle indicates outline of B. **B.** Map of the St. Petersburg region, with general geology and notable geographic features indicated (modified from Dronov & Mikuláš 2010).

Sweden, 'mini-mounds' in China).

The meteorite- and EC-rich Middle Ordovician rock interval encompasses early parts of the Great Ordovician Biodiversification Event (GOBE), which saw the diversification and radiation of the so-called Palaeozoic Evolutionary Fauna (Webby et al. 2004; Schmitz et al. 2008). By comparing brachiopod diversity data, compiled from extensive sampling at several localities in the East Baltic (including the Lynna River section), with EC data from Sweden and China, Schmitz et al. (2008) noted a close temporal correlation between the onset of a remarkable brachiopod diversification and the enhanced influx of extraterrestrial matter (see also Rasmussen et al. 2007). Schmitz et al. (2008) thus proposed that an increase in the influx of kilometer-sized asteroids may have stimulated biodiversification during the GOBE, in line with the so-called Intermediate Disturbance Hypothesis (see further references in Schmitz et al. 2008). Similar views were brought forward by Culler et al. (2000).

2 Geologic setting, stratigraphy, and previous studies

2.1 The Ordovician of Baltoscandia

The Baltoscandian region (here including westernmost Russia) harbors laterally extensive Palaeozoic rocks, formed from the sediments of a vast epeiric sea that covered large parts of the palaeocontinent Baltica at the time (Fig. 3; Lindström 1963; Jaanusson 1972; Nielsen 2004; Dronov 2005b; Dronov & Mikuláš 2010). Longterm tectonic stability has maintained a distinct, time persistent facies zonation in the region, resulting in so-called confacies belts, which record a general deepening of the Baltoscandian palaeobasin roughly along a northeast-southwestern transect. Terrigenous sediment input was limited, and net deposition rates were most often exceedingly slow, typically only a few millimeters (~1-9) per thousand years (e.g. Nielsen 2004). Varyingly long periods of non-deposition were recurrent (e.g. Lindström 1963, 1979; Dronov 2005b). Thus, numerous diastems are present in the rock record, however, the composite Ordovician succession of Baltoscandia is essentially complete. Some individual lithologic units may be correlated over large distances, both within and between countries. Throughout the Ordovician, Baltica drifted from southern subpolar to subtropical-tropical latitudes, while rotating counterclockwise (Fig. 4; Cocks & Torsvik 2006).

Published Baltoscandian sea-level curves for the Ordovician are in part contradictory both at regional and global scales, and thus debated (see e.g. Nielsen 2004; Rasmussen et al. 2009; Dronov et al. 2011). In short, controversy may often be said to result from differing views on relations between sedimentologic properties (i.e. facies) and depth of deposition (a longstanding debate also exists regarding absolute depths in the palaeobasin). Regardless, it is generally assumed that the inferred sea-level changes reflect eustasy.

Fig. 4. A reconstruction of Middle Ordovician palaeogeography (Kundan, circa 466 Ma). Baltica was situated between southern temperate and subtropical realms. Note that large parts of most palaeocontinents were covered by epeiric seas. This paleogeographic reconstruction was made using the software BugPlates (courtesy of StatoilHydro), developed by Trond H. Torsvik (previously available at www.geodynamics.no). See Cocks & Torsvik (2006) for further information about reconstructions of Palaeozoic palaeogeography.

2.2 Geology of the St. Petersburg region

The St. Petersburg region straddles the borderlands between the Baltic igneous shield and the Moscow basin (Dronov 2005c; Dronov & Mikuláš 2010). Overlying Ediacaran (Vendian) deposits, the Lower Palaeozoic strata of the region comprise some 220 to 350 meters of nearly flat-lying rocks, of which 120-150 meters are Cambrian and 100-200 meters are Ordovician beds. Cambrian and lowermost Ordovician (Tremadocian) strata mainly consist of unconsolidated clays and quartz sands. The succeeding Ordovician strata are characterized by carbonate rocks, which record a gradual transition from subpolar via temperate ('cool-water') to tropical ('warm-water') environment through time, entailing a successive increase in carbonate production, as a result of continental drift. Distinctly tropical elements enter the rocks in the Katian (e.g. Dronov & Mikuláš 2010; cf. Zaika 2005). Latest Ordovician (middle Katian-Hirnantian) and Silurian deposits are not preserved in the St. Petersburg region (Fedorov 2003; Dronov 2005a; Dronov & Mikuláš 2010). Ordovician carbonates lie upon an elevated area, called the Ordovician (formerly Silurian) plateau (e.g. Dronov et al. 2002; Dronov & Mikuláš 2010 and references therein). This plateau is bounded to the north by an escarpment called the Baltic-Ladoga Glint (or, simply, the Baltic Glint), resulting in a line of natural Middle Cambrian-Lower Ordovician outcrops. From west to east, the plateau can be subdivided into two parts; the Izhorian and the Volkhovian plateaus, respectively.

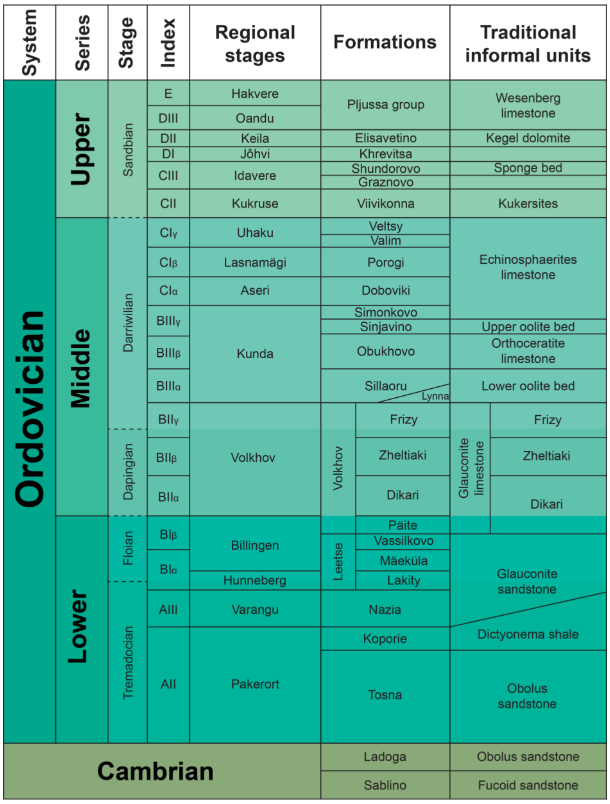


Fig. 5. The Ordovician stratigraphy of the St. Petersburg region (modified from Dronov & Mikuláš 2010; cf. Bergström et al. 2009).

The Ordovician geology of Baltoscandia is subdivided into eighteen regional stages (Fig. 5; Bergström et al. 2009). Most of these are recorded in the St. Petersburg region, but only some aspects of the Volkhov and Kunda stages – the strata of which have been sampled for this study – are relevant to discuss in detail. Both of these stages are considered to represent at least one depositional sequence (e.g. Dronov & Mikuláš 2010; Dronov et al. 2011; cf. Rasmussen et al. 2009). In the St. Petersburg region, Volkhov (BII zone) strata are typified by glauconite-speckled, variably argillaceous bioclastic limestone, ranging from marl to grainstone (Dronov 2005a; Dronov & Mikuláš 2010). The Volkhov Stage in its entirety is included in the Volkhov Formation, which may be subdivided into the informal Dikari (BII$_{\alpha}$), Zheltjaki (BII$_{\beta}$) and Frizy (BII$_{\gamma}$) members. The stage and formation share an upper boundary (the stage's lower boundary is at a conspicuous, regionally traceable hardground, called 'Blommiga bladet' in Sweden, 'Püstakkiht' in Estonia and 'Steklo' in Russia, which is actually situated a bit up in the BII$_{\alpha}$ zone; e.g. Dronov et al. 2002). Biogenic mud mounds occur at several levels in the lower and middle parts (BII$_{\alpha\text{-}\beta}$; Fedorov 2003; Tolmacheva et al. 2003). The succeeding Kunda (BIII) Stage begins with the appearance of assemblages representing the *Asaphus expansus* trilobite and *L. variabilis* conodont biozones, and its base is marked by a conspicuous surface of non-deposition that records a significant sea-level fall (estimated to 30-40 m; e.g. Dronov 2005a, 2005d; Dronov & Mikuláš 2010). Kundan strata comprise variably argillaceous bioclastic limestones, often collectively referred to as 'orthoceratite limestones'. Unlike in subjacent Volkhovian strata, glauconite is rare, likely as a result of a warmer depositional environment. In places, iron ooids, possibly connected to volcanic ashfalls, are abundant and conspicuous, resulting in so-called iron oolites (e.g. Dronov et al. 2005; Sturesson et al. 1999; Sturesson 2003 and references therein). The Kunda stage is subdivided into the Sillaoru (BIII$_{\alpha\text{-}\beta}$, 'lower oolite bed'), Obukhovo (BIII$_{\beta\text{-}\gamma}$, 'orthoceratite limestone' *sensu stricto*), Sinjavino (BIII$_{\gamma}$, 'upper oolite bed') and Simankovo (BIII$_{\gamma}$) formations (Dronov 2005a; Dronov & Mikuláš 2010). In the easternmost St. Petersburg region, the Lynna Formation (BIII$_{\alpha}$) replaces part of the Sillaoru Formation.

The Middle Ordovician deposits in the St. Petersburg region have been interpreted as tempestites formed in a storm-dominated, shallow-marine carbonate ramp environment (e.g. Dronov et al. 2002; Hansen & Nielsen 2003; Dronov & Mikuláš 2010). As such, individual beds may have been laid down in a matter of days, or even hours. The beds were then reworked for long periods – often several thousands of years – before subsequent sediment deposition. Graded beds, rich in coarse-grained shell debris, and various storm-related erosional features are typical. These tempestite beds may have substantial lateral extent and some can be traced for hundreds of kilometers along the Baltic-Ladoga Glint (thus providing very precise regional correlation). A sedimentologic west-to-east proximal-distal trend is clearly discernible in the region.

The geology of the St. Petersburg region has been actively studied since the early 19th century (unfortunately, many older publications are in Russian; e.g. Dronov 2005c; Dronov & Mikuláš 2010). A chronicle of significant geologic ventures undertaken in the St. Petersburg region is provided by Dronov & Mikuláš (2010), and a review of the regional Ordovician (ichno-)fossil fauna is provided by Dronov et al. (2005).

2.2.1 The Lynna River section

Along the Lynna River, a tributary to the larger Syas River, rocks from the mid-Volkhovian (uppermost BII$_{\beta}$) throughout the whole Kundan are exposed (Fig. 6; Hansen & Harper 2003; Hansen & Nielsen 2003; Pushkin & Popov 2005; Dronov & Mikuláš 2010; Hansen 2010). In total, the strata may reach a thickness of approximately ten meters (Volkhovian ~3 m, Kundan ~7 m). Rock color may vary on smaller scales, but gray hues dominate the river valley.

Fig. 6. The sampled strata at Lynna River, St. Petersburg region, northwestern Russia, with the Volkhov-Kunda boundary indicated (photo by B. Schmitz).

Volkhovian strata consist of glauconitic limestones, typically (bioclastic) wackestone and packstone, intercalated with clay/marl (Dronov & Mikuláš 2010; Hansen 2010; cf. regional description above). Glauconite-rich hardgrounds are recurrent. The exposed BII_{β} zone (Zheltjaki Member) is characterized by a yellow stain, whereas the BII_{γ} zone (Frizy Member) is the more typical gray. The latter may be subdivided into seven informal lithostratigraphic units, in stratigraphically ascending order called the 'lower unit of intercalation', 'Sliven', 'middle unit of intercalation', 'Gorelik', 'upper unit of intercalation', 'Podkoroba' and 'Koroba'. The boundary between the Volkhov and Kunda stages is marked by a glauconite-impregnated hardground, situated in a strongly glauconite-enriched limestone interval (Fig. 7).

Kundan strata typically consist of gray, argillaceous limestones, ranging from mudstone to wackestone, intercalated with clay/marl (Dronov & Mikuláš 2010; Hansen 2010). The Sillaoru Formation, however, deviates from this general description. It begins with a conspicuous, decimeter-thick clay interval, which is subdivided into a lower red and an upper gray part. A discontinuous, highly argillaceous limestone layer is found in-between. Gray limestones then resume and continue throughout the overlying strata, in which cephalopod conchs are common (some uncertainty exists regarding the boundaries of the Sillaoru Formation at the locality). Iron ooids are scarce throughout.

Sediments forming the strata at Lynna River were deposited in a mid-carbonate ramp environment, below fairweather wavebase (Hansen 2010). This relatively deep setting resulted in a rather complete stratigraphy, with only minor hiatuses, as compared to coeval, more shallow-water, sections towards the west (Rasmussen et al. 2009).

2.2.2 Previous studies at Lynna River

Most previous studies of the Lynna River section have revolved around paleontologic and sedimentologic aspects of the rocks, typically with little bearing on the subject of this thesis (but see e.g. Hansen & Harper 2003; Hansen 2010; Pushkin & Popov 2005; Rasmussen et al. 2007; Rasmussen & Harper 2008; Rasmussen et al. 2009). Korochantsev et al. (2009) performed a limited investigation of chromite content in the Lynna River strata. Two samples, one from the upper Lynna Formation (~6.5 kg) and another from the Lynna-Sillaoru formational boundary (~4 kg), yielded notable amounts of chromite grains. Chemical analyses showed that a majority of the grains were likely of extraterrestrial, ordinary chondritic origin. The lower sample also contained two Ni-rich grains. Korochantsev et al. (2009) suggested EC concentrations of ~0.6 and ~2.9 grains kg^{-1} for the lower and upper sample, respectively, and noted that an increased EC concentration upwards through the stratigraphy is in contrast with EC patterns previously observed at other localities, which typically display decline upwards, after an initial EC 'spike'. An inverse relationship between chromite and clay content was also observed; as chromite content increased, clay content decreased, however, not at the same rates.

The sample levels studied by Korochantsev et al. (2009) roughly correspond to samples Ly1 and Ly4 of this study, however, due to different sample processing methods, results may not be directly comparable (see below). Recalculations by this author indicate an EC concentration of ~4.2 grains kg^{-1} in the upper sample of Korochantsev et al. (2009).

3 Materials and methods

3.1 Sample collection and processing

Two separate sets of bulk samples were collected in the strata at Lynna River, leaving a ~2 m sample gap in-between (Fig. 7). One sample set is centered around the Volkhov-Kunda boundary, which corresponds to the *Baltoniodus norrlandicus*-*L. variabilis* conodont and *A. lepidurus*-*A. expansus* trilobite zone boundaries, and also the Volkhov-Lynna formational boundary. The other sample set covers the succeeding *L. variabilis*-*Y. crassus* conodont and *A. expansus*-*A. raniceps* trilobite zone boundaries, coinciding with the Lynna-Sillaoru formational boundary, in the lower-middle Kundan. Relative stratigraphic positions of samples are easily inferred from their assigned codes; samples from the lower set are denoted by standalone numbers and samples from the upper set are denoted by the prefix Ly, followed by a number, with individual sample sets in numerically correct order when ascending through the stratigraphy. In total, seven rock samples, with a combined weight of 89.7 kg, were selected for analysis in this study and processed largely according to methods established by Schmitz et al. (2001).

In the laboratory, samples were weighed and thereafter carefully cleaned with regular tap water, in order to eliminate contaminants (e.g. detrital clay/grains;

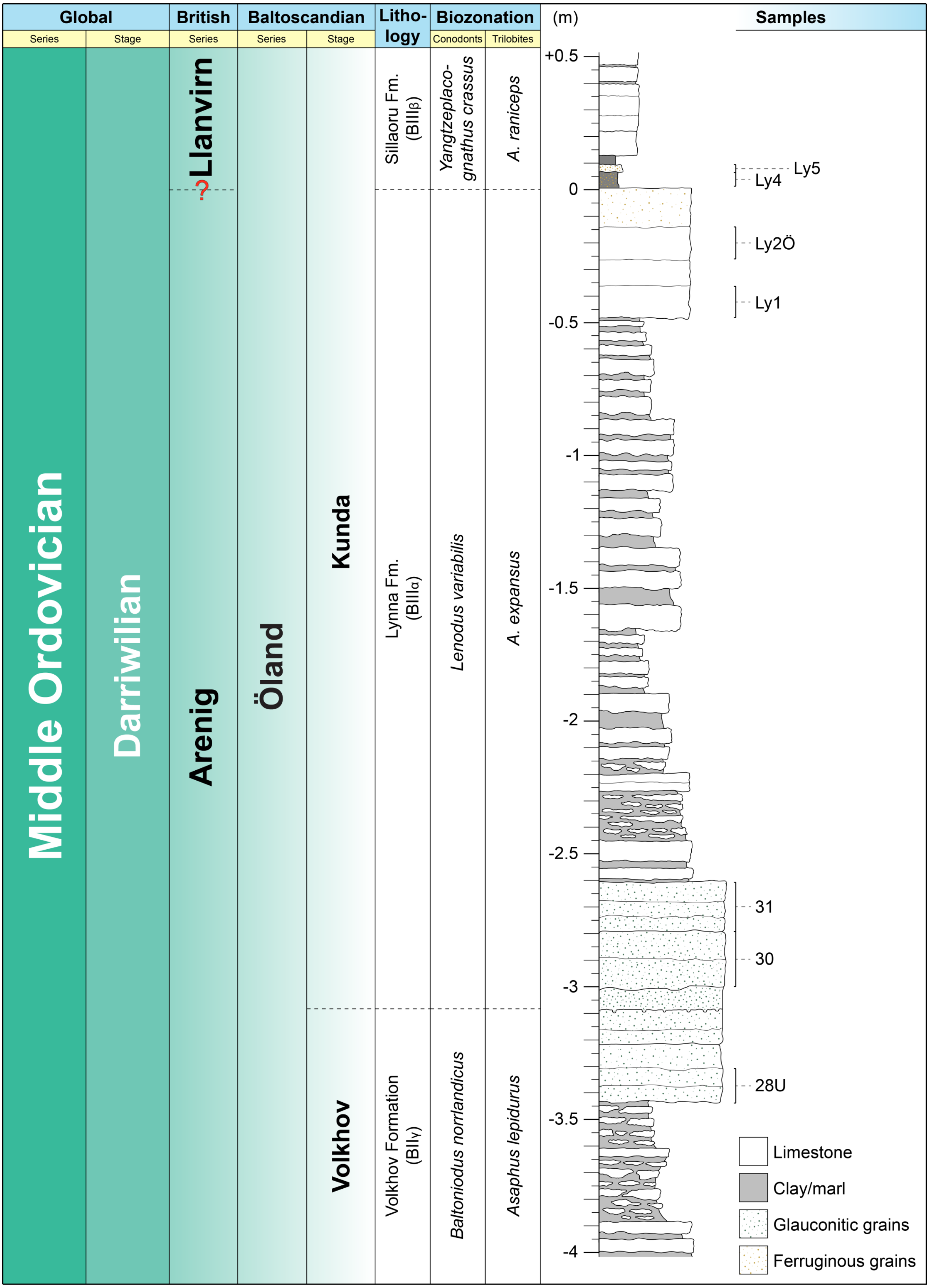


Fig. 7. The sample stratigraphy at the Lynna River locality (after hand-drawn original by A. Dronov).

throughout the following preparation process, utmost care was taken in order to avoid contamination). The samples were then separately dissolved in 6 M hydrochloric acid and their insoluble residues manually wet-sieved through a 32 µm grate. Treatment of the resulting materials in 3.8 M hydrofluoric acid followed, producing residues with only the most resilient constituents remaining. These were again wet-sieved, dividing the material into three size fractions; 32-63 µm, 63-355 µm and >355 µm. Excessive amounts of undissolved (authigenic) glauconitic grains prompted the use of density separation techniques, employing 'LST fastfloat' heavy liquid, for samples 28U, 30 and 31 prior to further processing.

The dried 63-355 µm fraction of each sample was studied under an optical stereo microscope and suspected chromite and ilmenite (*sensu lato*, ~$FeTiO_3$) grains manually extracted. In some sample residues, abundant shiny, opaque iron-oxide and carbon-rich grains – superficially similar to chromite – introduced considerable difficulty to the search for relevant grains (cf. Alwmark & Schmitz 2009b). With the exception of sample Ly4, residues were meticulously scanned for grains at least three times. Due to extended time needed for acid treatment, and the overwhelming size of resulting residues, sample Ly4 was only completely scanned for grains once. After crude homogenization, ~50% (by dry weight) of the sample residues were then scanned a second time. Sample results were extrapolated from these results; the number of grains found in the second scan were multiplied by two, and added to the number of grains found in the first scan, together with a tentative third-scan yield, which was calculated with the assumption of a linear decrease in grain yield between successive scans. Subsequently, in absolute numbers, the results for sample Ly4 may not be comparable to those of the other samples, however, the chromite-ilmenite ratio should be relatively accurate.

All extracted grains were mounted onto carbon tape and chemically analyzed with an Oxford Instruments INCA X-Sight energy-dispersive spectrometer, attached to a Hitachi S-3400N scanning electron microscope (SEM, with 15 kV acceleration voltage, using cobalt as a standard). Mineral types were thus confidently identified. Identified chromite grains were subject to additional (30-second counting live-time) analyses, and individual grain backscatter images and spectra were compiled and stored in a database (as a safety-measure, in case of grain loss during subsequent processing, with pictures permitting later superficial studies of grains). With the exception of sample Ly4, chromite grains were then cast in epoxy, smoothly polished and analyzed again (80-second counting live-time; Ly4 was exempt due to time prioritization). At least three point analyses were performed on each grain, in order to provide information on possible element zonation and ensure reproducibility of results (typically <2% major-element discrepancy between individual point analyses).

The resulting grain data was compiled into a database, and grains kg^{-1} values were calculated for every identified grain type and sample. Samples and reference materials are stored at the Division of Geology, Department of Earth and Ecosystem Sciences, Lund University, Sweden.

In preparation for this project, an 'orthoceratite limestone' (wackestone) sample (11.35 kg) from the *L. variabilis* conodont zone ('Arkeologen' unit; see e.g. Schmitz et al. 2001 for stratigraphic terminology) at the Thorsberg Quarry, Kinnekulle, southern Sweden, was selected for processing, both for educational and scientific purposes. The sample was retrieved in close proximity to a fossil meteorite (Ark-025) and then processed in order to learn the methods of chromite extraction and analysis, and at the same time investigate if proximity to a meteorite would be reflected in the grain data (18 M hydrofluoric acid treatment prevented ilmenite extraction). The sample contained abundant chromite, amassing to a total of 171 grains. 40 of these were interpreted as EC (see below), based on preliminary analyses. This corresponds to an EC concentration of ~3.5 grains kg^{-1}, which is similar to previously documented highest concentrations in roughly coeval beds at the sampling locality (see Schmitz & Häggström 2006).

3.2 Defining characteristics of extraterrestrial chromite grains

As already noted, ordinary chondritic chromite grains display distinct, rather unvaried composition, which is resistant to alteration. However, some chromite elements and compounds appear to be more susceptible to diagenetic influence than others (Barnes 2000; Schmitz et al. 2001; Schmitz & Häggström 2006). FeO, MnO and ZnO appear to be readily interchangeable during diagenesis and thus display varying concentrations, whereas most other identified compounds are rather stable (TiO_2 noteworthily so). ZnO concentration is typically low in recent ordinary chondritic chromite, and its notable presence in many relict chromite grains may thus be explained by introduction during diagenesis (e.g. Bunch et al. 1967; Thorslund et al. 1984; Wlotzka 2005).

In this study, extraterrestrial chromite (EC) grains are identified according to compositional characteristics as defined by Schmitz & Häggström (2006), with a revised TiO_2 range as introduced by Cronholm & Schmitz (2010); MgO ~1.5-4 wt%, Al_2O_3 ~5-8 wt%, TiO_2 ~1.4-3.5 wt%, V_2O_3 ~0.6-0.9 wt%, Cr_2O_3 ~55-60 wt%, and FeO ~25-30 wt%. The notable TiO_2 and V_2O_3 concentrations are considered to be especially important EC indicators (e.g. Bunch et al. 1967; Schmitz & Häggström 2006; Cronholm 2009). Grains that display significant deviation from any of the above ranges, not readily explained by 'simple' (e.g. diagenetic) element interchange, are classified as 'other chromium-rich spinel' (OC). This, however, does not automatically exclude an extraterrestrial origin (cf. Wlotzka 2005).

4 Results

4.1 Characteristics of rock samples, acid-insoluble residues, and extracted heavy mineral grains

Rock-sample characteristics fit well with the general lithologic descriptions provided in section 2.2 above; both sample sets are characterized by mud-, wacke- and packstones, but glauconite is only present in the lower sample set. The Ly4 sample level, which harbors a poorly consolidated, red clay/marl, containing centimeter-sized limestone nodules, constitutes a clear exception to these lithologies. Overall, hand samples display varying redox conditions, as inferred by variegated (grayish-reddish) color. Samples are often noticeably fossiliferous, with trilobites, brachiopods and bryozoans being dominant among macroscopic fossils. Trace fossils (e.g. *Trypanites*, *Bergaueria*) are also quite common (in concerned samples, glauconite grains are clearly concentrated in burrows). All processed samples reacted strongly to hydrochloric acid treatment, indicating considerable $CaCO_3$ content.

Glauconitic grains, often in the form of fossil steinkerns, are ubiquitous in the 63-355 µm residues from the lower sample set, whereas achromatic, transparent siliciclastic grains (e.g. quartz) dominate in samples Ly1 and Ly2Ö. The Ly4 and Ly5 residues are dominated by golden-yellow-colored, iron-rich grains (goethite/limonite?), again often in the form of fossil steinkerns. In all concerned samples, fossil steinkerns are visibly etched by acid yet often easily identifiable at higher taxonomic levels. Biotite grains are typically common, as are iron-oxide and amorphous coal grains (see 3.1). Chromium-bearing non-spinel grains also occur. Apart from the various mineral(-oid) grains, iron-rich spherules are common in most sample residues (Fig. 8). In general, >355 µm and 32-63 µm fractions resemble the 63-355 µm ones, however, rusty-red aggregates (iron ooids?) occur in the >355 µm fractions.

The average size of extracted chromite grains is estimated to approximately 90x70 µm, with individual axis lengths varying between approximately 40 µm and 200 µm. As in preceding studies, most EC grains are anhedral and angular, and display an excellent state of preservation, indicating limited time in the sedimentary system (Fig. 2; cf. e.g. Alwmark et al. 2010; Cronholm & Schmitz 2010. EC grains may typically be classified as very angular to sub-angular, with a select few being classified as sub-rounded (Pettijohn et al. 1987 *sensu* Tucker 2001). OC grains range from being very angular to well-rounded, however, the small number of grains found in this study do not allow any meaningful comparison between grain types. Ilmenite and remaining silicate grains are similar in size to chromite, and display varying levels of roundness, ranging from euhedral to well-rounded. Little can be interpreted from this, however, as most are notably etched by hydrofluoric acid. Many of the better preserved quartz grains display a 'frosted' appearance, typical for aeolian sediment (cf. Tucker 2001).

Silicate inclusions, with diameters of only a few micrometers, occur in chromite grains (cf. Alwmark & Schmitz 2009a). Additionally, some grains harbor cavities which may be dislodged/dissolved inclusions.

No obvious signs of large impact – i.e. shocked quartz, microtectites/-crystites – have been confidently observed in the sample materials, however, many resulting products are unlikely to be preserved in the sedimentary record, let alone survive the acid treatment used in this project. Some iron-rich spherules in the 63-355 µm fractions resemble aerodynamically shaped microtektites, but lack chemical signs indicating an extraterrestrial origin (such as significant Ni content).

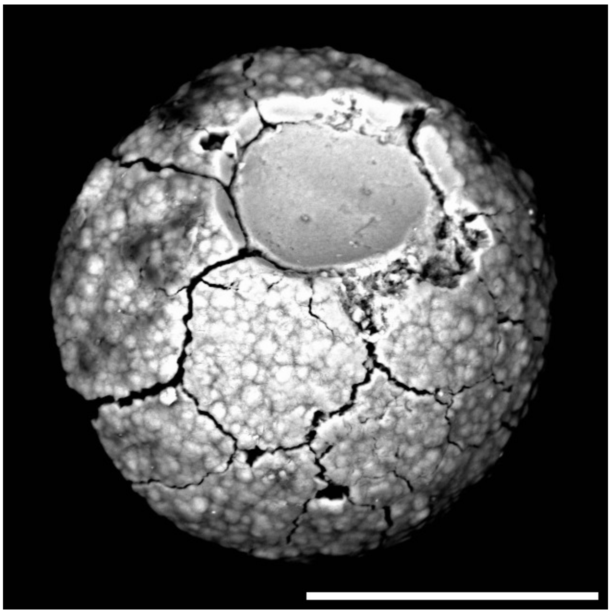


Fig. 8. An iron-rich spherule (SEM, backscattered electron image; sample Ly1). These spherules are abundant in some samples. Scale bar 50 µm.

4.2 Chromite and ilmenite content in samples

Table 1 and Fig. 9 provide an overview of the heavy mineral content in samples.

Sample 28U (14 kg, gray mud/wackestone) yielded three chromite grains, of which only one is interpreted as EC. This corresponds to a concentration of 0.07 EC grains kg^{-1} of rock, and 0.14 OC grains kg^{-1}. Six ilmenite grains were found, corresponding to 0.43 grains kg^{-1}. The EC grain contains a notable, but highly variable, amount of NiO (max. 1.96 wt% in individual analysis points).

Sample 30 (14.4 kg, gray pack/wackestone) yielded only one chromite grain, which was interpreted as EC, corresponding to 0.07 EC grains kg^{-1} (and 0.00 OC grains kg^{-1}). Three ilmenite grains were found, corresponding to 0.21 grains kg^{-1}.

Sample 31 (9.8 kg, gray mud/wackestone) yielded no chromite, nor any ilmenite. Thus, concentration is

Table 1. Extraterrestrial chromite (EC), other chromium-rich spinel (OC) and ilmenite (*sensu lato*) in samples from Lynna River (see Fig. 7 for stratigraphic positions of samples). See also Fig. 9.

Sample	Sample weight (kg)	No. EC grains	EC grains kg^{-1}	No. OC grains	OC grains kg^{-1}	No. ilmenite grains	Ilmenite grains kg^{-1}
28U	14.0	1	0.07	2	0.14	6	0.43
30	14.4	1	0.07	0	0.00	3	0.21
31	9.8	0	0.00	0	0.00	0	0.00
Ly1	14.5	76	5.24	2	0.14	47	3.24
Ly2Ö	14.5	113	7.79	2	0.14	104	7.17
Ly4[a]	10.0	84[b]	8.40	4[c]	0.40	74[d]	7.40
Ly5	12.5	124	9.92	3	0.24	393	31.44
Total	89.7	399		13		627	

[a] Preliminary analysis data.
[b] Extrapolated from 72 grains.
[c] Extrapolated from 3 grains.
[d] Extrapolated from 60 grains.

effectively 0.00 grains kg^{-1} for all identified grain types.

The Ly1 sample (14.5 kg, gray wackestone) yielded 78 chromite grains, of which only two were interpreted as OC. This equates to ~5.24 EC grains kg^{-1} of rock, and ~0.14 OC grains kg^{-1}. 47 ilmenite grains were found, corresponding to ~3.24 grains kg^{-1}. Three EC grains contain notable amounts of NiO (max. 1.04 wt%), two of them in combination with enhanced MgO concentration, at the expense of FeO.

Ly2Ö (14.5 kg, gray-red wacke/mudstone) yielded a total of 115 chromite grains. All but two were interpreted as EC, resulting in a concentration of ~7.79 EC grains kg^{-1}, and ~0.14 OC grains kg^{-1}. 104 ilmenite grains were found, corresponding to ~7.17 grains kg^{-1}. Nine EC grains contain notable amounts of NiO (max. 1.26 wt%). Such grains often display enhanced MgO or FeO concentrations, typically at the expense of one another.

Extrapolated data (see 3.1) for Ly4 (10 kg, red clay/marl) indicate that ~88 chromite grains may be found in the sample (the incomplete residue scan process yielded 72 grains). Extrapolated, preliminary grain analyses indicate that 84 of them are EC, corresponding to ~8.40 EC grains kg^{-1}, and ~0.40 OC grains kg^{-1}. Extrapolation gives 74 ilmenite grains, corresponding to ~7.40 grains kg^{-1} (the incomplete residue scan process yielded 60 grains). Two EC grains contain notable amounts of NiO (max. 1.21 wt%). Regardless of extrapolation, the deviant lithology of this sample hinders direct comparison with data of other samples (moreover, only preliminary analyses were performed on extracted chromite grains).

Ly5 (12.5 kg, gray-red mud/wackestone) yielded a total of 127 chromite grains. 124 were identified as EC grains, equivalent to ~9.92 EC grains kg^{-1} of rock, and ~0.24 OC grains kg^{-1}. 393 ilmenite grains were found, corresponding to ~31.44 grains kg^{-1}. One EC grain contains a notable amount of NiO (max. 0.89 wt%), and also ZnO.

In summary, the lower sample set (three samples, total weight 38.2 kg) yielded a total of only four chromite grains, of which two were interpreted as EC. This corresponds to average concentrations of ~0.05 grains kg^{-1} for both EC and OC grains. Ilmenite grains amassed to nine grains, corresponding to an average concentration of ~0.24 grains kg^{-1}. Excluding sample Ly4, the upper sample set (three samples, total weight 41.5 kg) yielded 320 chromite grains, of which 313 were interpreted as EC. This corresponds to averages of ~7.54 EC grains kg^{-1} and ~0.17 OC grains kg^{-1}. In total, 544 ilmenite grains were found, corresponding to an average concentration of 13.11 grains kg^{-1} (however, about two-thirds of these were found in the Ly5 sample alone). When including Ly4 (giving a total weight of 51.5 kg), total grain yields increase to 408 chromite grains (of which 16 were extrapolated), including 397 EC grains, and 618 ilmenite grains (of which 8 were extrapolated). Average concentrations thus change to ~7.71 EC grains kg^{-1}, ~0.21 OC grains kg^{-1}, and ~12.00 ilmenite grains kg^{-1}. A clear trend of increasing heavy-mineral grain concentration, when ascending stratigraphically, is seen in the upper sample set. Several grains contain notable amounts of NiO.

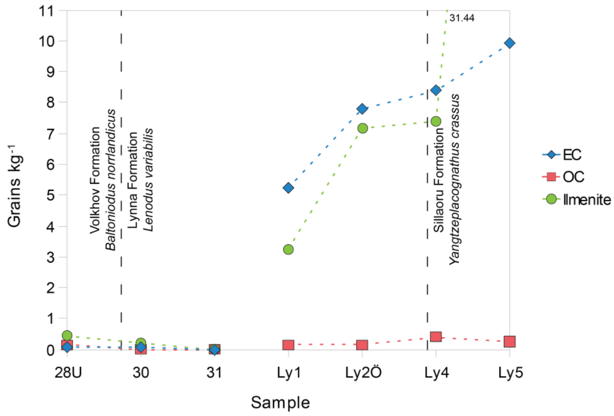


Fig. 9. Heavy mineral content in samples, expressed as grains kg^{-1}. EC = extraterrestrial chromite; OC = other chromium-rich spinel. Formations and conodont zones are indicated. See also Fig. 7 and Table 1.

4.3 EC composition

Data from chemical analyses of EC grains is presented in Table 2 and Fig. 10 (full data set in Appendix Table 1), and a comparison with grain data from various preceding chromite studies is presented in Table 3 and

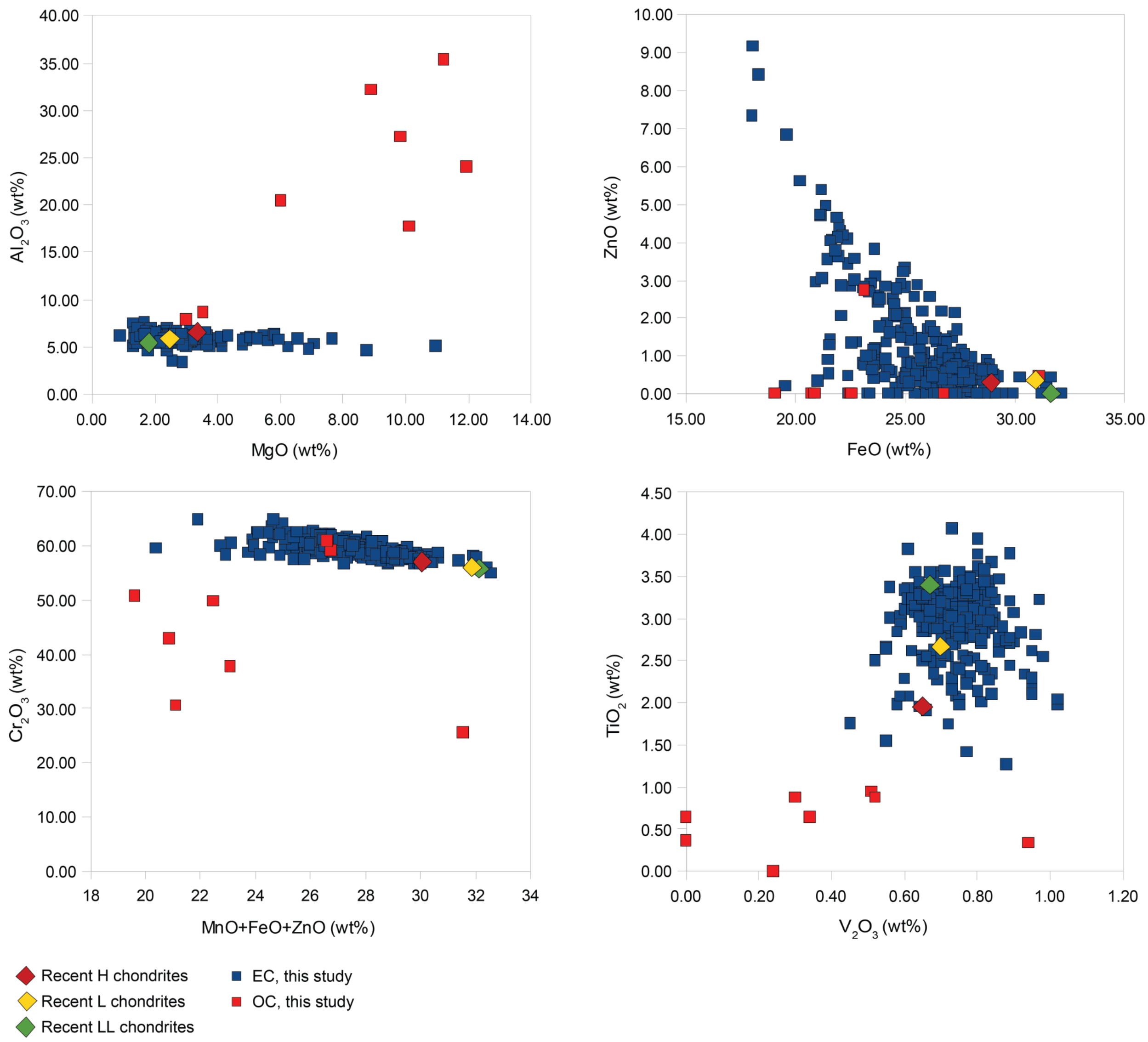


Fig. 10. Chemical composition of sediment-dispersed extraterrestrial chromite (EC) and other chromium-rich spinel (OC) grains from this study (sample Ly4 exempt), plotted together with average chromite compositions of recent ordinary chondrite groups. One unusually FeO-rich OC outlier from sample Ly1 is consistently omitted. See also Table 2, Appendix Table 1 and Appendix Table 2.

Table 2. Average chemical composition (compound wt% ± 1 s.d.) of sediment-dispersed extraterrestrial chromite (EC) grains in samples from Lynna River. n.d. = not detected. See also Fig. 10 and Appendix Table 1.

Sample	No. of grains	MgO	Al_2O_3	TiO_2	V_2O_3	Cr_2O_3	MnO	FeO	NiO	ZnO	Total
28U	1	4.37±0.00	6.25±0.00	2.40±0.00	0.75±0.00	56.79±0.00	0.72±0.00	26.48±0.00	1.39±0.00	n.d.	99.14±0.00
30	1	2.91±0.00	3.49±0.00	2.55±0.00	0.66±0.00	60.87±0.00	0.69±0.00	28.22±0.00	n.d.	n.d.	99.40±0.00
Ly1	76	2.78±1.12	5.99±0.33	3.00±0.42	0.72±0.08	59.15±1.35	0.77±0.20	25.81±2.11	0.02±0.12	1.14±1.2	99.39±0.58
Ly2Ö	113	2.79±1.30	6.08±0.49	2.94±0.42	0.74±0.09	59.33±1.72	0.81±0.20	25.92±2.24	0.04±0.13	0.89±0.88	99.52±0.61
Ly4[a]	88[b]	2.24±1.45	6.84±3.38	2.46±0.64	0.54±0.27	53.83±7.86	0.46±0.46	30.43±8.72	0.01±0.09	1.14±1.87	97.96±1.86
Ly5	124	2.73±0.81	6.06±0.36	3.05±0.42	0.75±0.09	59.52±1.28	0.79±0.21	25.76±2.47	0.00±0.04	1.26±1.73	99.92±0.54

[a] Preliminary analysis data.
[b] Extrapolated from 72 grains.

Fig. 11 (cf. Schmitz & Häggström 2006; Häggström & Schmitz 2007; Cronholm & Schmitz 2010). Overall, EC chemical composition is homogeneous, with little variation within or between grains, nor between samples. Most grains conform within analytical error to the compositional ranges for ordinary chondritic chromite as defined above, however, some deviations, most notably in MgO concentration, have been allowed, as there are clear element-exchange relationships; MgO 0.93-10.98 wt%, Al_2O_3 3.49-7.66 wt%, TiO_2 1.27-4.07 wt%, V_2O_3 0.45-1.02 wt%, Cr_2O_3 55.00-64.89 wt%, and FeO 17.98-32.11 wt%.

Averages from various studies of relict EC grains mostly cluster together tightly in Fig. 11, however,

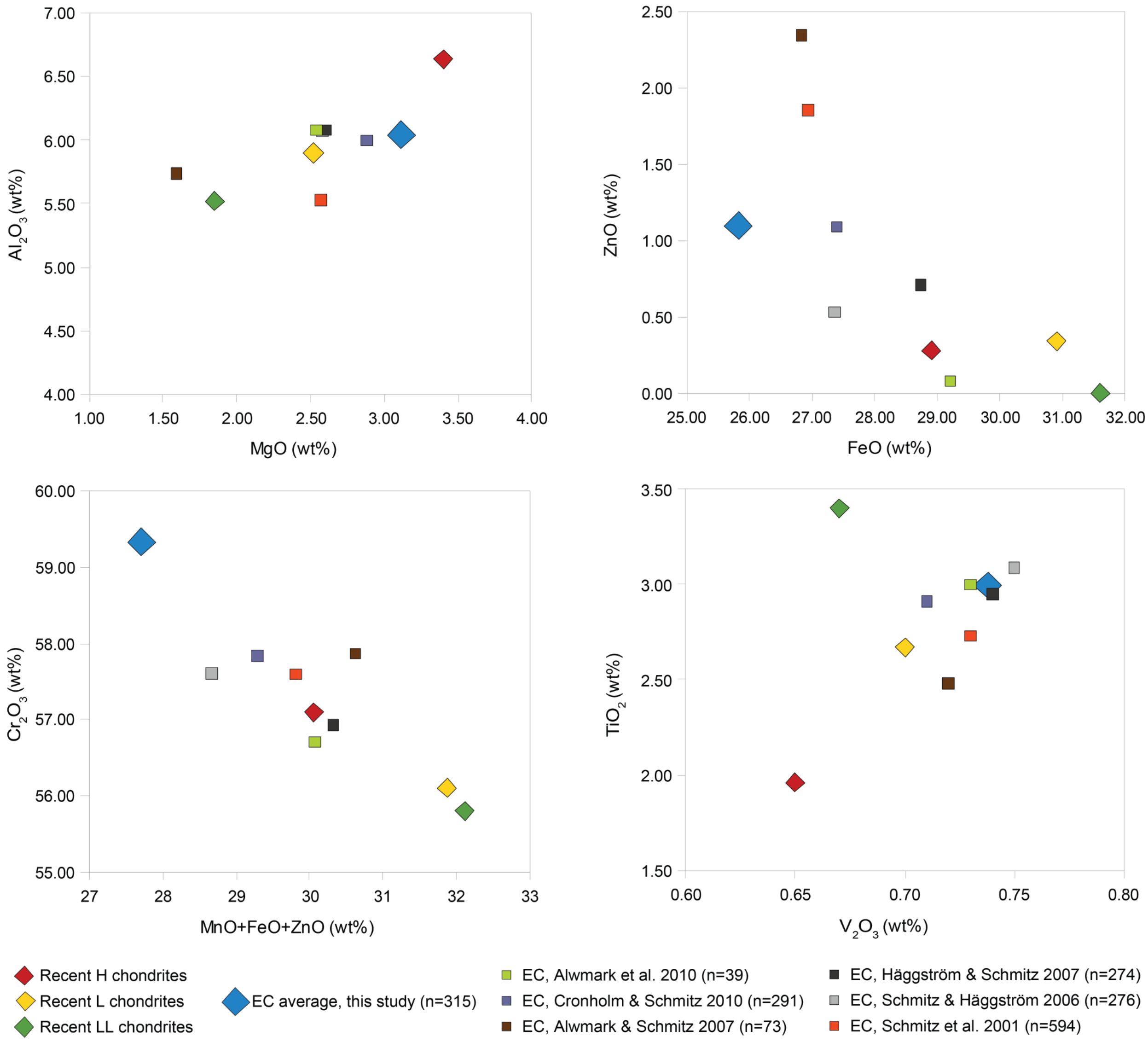


Fig. 11. Average chemical composition of sediment-dispersed extraterrestrial chromite (EC) from this study (sample Ly4 exempt), plotted together with average chromite compositions of recent ordinary chondrite groups and averages compositions of relict EC from other studies. See also Table 2 and Table 3.

compared to average compositions of chromite in recent ordinary chondrite groups, a shift is consistently seen in plots involving FeO and ZnO. Due to diagenetic influence, these compounds display notable variation in concentration, and, in general, FeO appears to be depleted, whereas ZnO is enriched, in relict EC grains (cf. e.g. Schmitz et al. 2001). A 'tail' of increasingly altered grains thus protrudes from the main cluster in the ZnO-FeO plot in Fig. 10. The most striking difference between this study and preceding studies, is that the all-sample average Cr_2O_3 value is relatively high, whereas the average FeO value is relatively low. This indicates significant leaching of FeO throughout time, shifting balance towards a higher Cr_2O_3 concentration. Most relict-EC averages lie close to the average composition of chromite from recent L chondrites in the Al_2O_3-MgO and TiO_2-V_2O_3 plots.

Unlike other compounds, where present, NiO displays highly variable concentration within single grains. In general, NiO-enrichment appears to be confined to the outermost parts of, and cracks in, grains, but exceptions occur. Most of the NiO-rich grains are notably vesicular and contain numerous cracks, and some display a sharply defined, but discontinuous, MgO-/FeO-/NiO-enriched rim.

4.4 OC composition

Data from chemical analyses of OC grains is presented in Fig. 10 (full data set in Appendix Table 2). OC provenance is not investigated in great detail, but it may be noted that many OC grains have compositions that almost completely fulfill the criteria for EC grain identification, though have at least one compound (typically Al_2O_3 and/or TiO_2) well outside its typical ordinary chondritic range (see Fig. 10). These grains may be diagenetically altered EC grains, or, simply, other extraterrestrial chromium-bearing spinel grains (some ilmenite grains may also be extraterrestrial; cf.

Table 3. All-sample average chemical composition (compound wt% ± 1 s.d.) of extraterrestrial chromite (EC) grains from this study (sample Ly4 exempt), compared to average compositions determined in previous studies of relict EC and chromite from recent ordinary chondrites. n.d. = not detected. See also Fig. 11.

Grain source Study	MgO	Al_2O_3	TiO_2	V_2O_3	Cr_2O_3	MnO	FeO	NiO	ZnO
315 sediment-dispersed EC grains This study	2.77±1.08	6.04±0.43	2.99±0.43	0.74±0.09	59.36±1.48	0.79±0.20	25.84±2.30	0.02±0.13	1.09±1.37
Chromite from 13 recent H chondrites Wlotzka (2005)	3.40±0.18	6.64±0.41	1.96±0.29	0.65±0.03	57.10±1.10	0.88±0.07	28.90±0.6	n.d.	0.28±0.14
Chromite from 6 recent L chondrites Wlotzka (2005)	2.52±0.21	5.90±0.19	2.67±0.44	0.70±0.06	56.10±0.80	0.63±0.08	30.90±0.60	n.d.	0.34±0.06
Chromite from 4 recent LL chondrites Wlotzka (2005)	1.85±0.14	5.52±0.17	3.40±0.57	0.67±0.10	55.80±0.56	0.51±0.04	31.60±0.62	n.d.	n.d.
39 sediment-dispersed EC grains Alwmark et al. (2010)	2.54±0.22	6.08±0.25	3.00±0.26	0.73±0.05	56.71±0.48	0.79±0.19	29.20±0.53	n.d.	0.08±0.21
291 sediment-dispersed EC grains Cronholm & Schmitz (2010)	2.88±0.88	6.00±0.36	2.91±0.4	0.71±0.08	57.84±1.14	0.80±0.26	27.40±1.84	n.d.	1.09±1.12
73 sediment-dispersed EC grains Alwmark & Schmitz (2007)	1.59±1.54	5.74±0.75	2.48±0.38	0.72±0.05	57.87±1.09	1.44±0.47	26.83±1.84	0.05±0.14	2.35±2.10
274 sediment-dispersed EC grains Häggström & Schmitz (2007)	2.69±1.10	6.08±0.73	2.95±0.44	0.74±0.07	56.93±1.29	0.87±0.25	28.74±1.72	n.d.	0.71±0.84
276 sediment-dispersed EC grains Schmitz & Häggström (2006)	2.58±0.79	6.07±0.76	3.09±0.33	0.75±0.07	57.61±1.58	0.78±0.20	27.36±2.63	n.d.	0.53±0.50
594 EC grains from fossil meteorites Schmitz et al. (2001)	2.57±0.83	5.53±0.29	2.73±0.40	0.73±0.03	57.60±1.30	1.01±0.33	26.94±3.89	n.d.	1.86±2.43

Wlotzka 2005; Häggström & Schmitz 2007; Cronholm & Schmitz 2010). Regardless, as very few non-EC grains were found in this study, small changes in OC numbers have little effect on overall statistics.

5 Discussion

5.1 The source of the sediment-dispersed EC grains

As in preceding studies of relict EC grains, the all-sample average composition of EC grains from this study does not fit entirely with the average chromite composition of either of the recent ordinary chondrite groups. Relatively stable compounds (e.g. TiO_2, V_2O_3) in EC grains from this study plot close to the average of chromite from recent L chondrites, indicating that the grains may stem from an L-chondritic source, however, as the data spread also encompasses the average chromite composition of other ordinary chondrite groups, one cannot exclude that such grains are at least represented among the many grains found in this study. Regardless, taking the multifaceted approach of preceding studies of relict EC into account, an interpretation that most EC grains in this study stem from L chondrites is reasonable. The overall good match between the average composition of sediment-dispersed EC grains from this study and those of other similar studies, together with the stratigraphic/temporal co-occurrence of an EC 'spike', indicates that the grains share a common source. The remarkable concentration of EC grains in the upper sample set of this study – as of yet surpassed only by impact-related deposits – may thus best be interpreted as a result of a temporarily heightened influx of extraterrestrial matter, following the disruption of the L-chondrite parent body.

The contrastingly low EC concentration in the lower sample set likely represents the background flux of EC grains, preceding the disruption event. The lack of EC enrichment in samples 30 and 31 is at odds with previous studies, which have consistently identified a notable EC component in the lowermost *L. variabilis* conodont (*A. expansus* trilobite) zone. As an increased influx of EC must have been a global event, this aberration may simply be a result of differential deposition, accentuated by the poor time resolution inherent to condensed sections and the somewhat arbitrary boundaries of biozones.

5.1.1 NiO-rich EC grains

Prior to this study, NiO-rich relict EC grains in seemingly undisturbed strata had only been documented by Korochantsev et al. (2009; Alwmark & Schmitz 2007 found NiO-enriched chromite grains in impact resurge deposits). If NiO-enrichment is not a secondary feature that is (as of yet) unique to the Lynna River strata, the reason for a lack of such grains in other studies may be their use of harsher hydrofluoric-acid treatment (18 M; Korochantsev et al. 2009 only used HCl). Three main scenarios come to mind for explaining the NiO, and simultaneous MgO/FeO, enrichment in some EC grains: 1) The enrichment is a primary feature, with such grains reflecting 'unequilibrated' host-meteorite conditions (of e.g. petrologic-type 3 meteorites, which, however, often have chromite grains smaller than the size fraction investigated herein). Grain zonation may thus be present. 2) The grains were originally situated in, or in contact with, the fusion crust of their host meteorite. Sharply defined metal-rich rims may accrete due to melting of surrounding meteorite matrix, as friction heat is produced during descent through Earth's atmosphere, followed by rapid cooling (meteorite bulk composition is typically rich in all concerned elements; cf. Ramdohr 1967b; Genge & Grady 1999; Parashar et al. 2010). 3) The grains have become diagenetically altered. Compounds more typical to be enriched due to diagenetic processes (most notably, ZnO) are not particularly abundant in NiO-rich grains, as compared to other grains, and Ni should be rather stable in the environmental conditions present in the sampled carbonate rocks (see Fujiwara & Domae 2004). Further studies are needed in order to reach any conclusions regarding this matter.

5.2 Chromite and ilmenite concentrations, and their relation to the depositional environment

Close inspection of sample grain data reveals an apparent covariation among identified heavy minerals (however, the small number of samples prevents meaningful statistical analysis; cf. Schmitz & Häggström 2006; Häggström & Schmitz 2007). Such observations are not surprising, as chromite and ilmenite should behave similarly in sedimentary systems, given their similar density (chromite 4.8 g cm^{-3}, ilmenite 4.7 g cm^{-3}; Wenk & Bulakh 2004) and hardness (chromite 5.5, ilmenite 5-6; ibid.). Processes of winnowing and selective transport, entailing hydrodynamic concentration and sorting, are likely to produce patterns of covariation among grains with similar characteristics. On this note, the storm-dominated environment represented by the (tempestite) beds at Lynna River may be an important factor behind the unusually high EC concentrations in the upper sample set, as compared to preceding studies at other localities. Studies have shown that significant natural sorting may occur during storms, producing more or less concentrated lag/placer deposits, which are most likely to be preserved and further concentrated throughout time if they are deposited below fairweather wavebase (Barrie et al. 1988; cf. 2.2). Tidal currents can enhance this process. Sturesson et al. (1999) noted a general increase in heavy mineral content in Middle Ordovician strata along a west-east transect of Baltoscandia.

Although heightened compared to background levels, the EC influx during the time interval represented by the upper sample set is likely to have been rather stable. Thus, the successively increasing EC concentration can only reflect increasing condensation – i.e. time-averaging – towards the top of the sampled strata. This is also indicated by a simultaneous (but not 1:1) increase in ilmenite concentration. The increasing condensation may best be explained by sea-level change and associated changes in sediment deposition. Assigning a direction to this sea-level change, based on heavy-mineral grain data alone, is difficult, however, lithologic change from gray to reddish limestone, with increasingly less argillaceous content (cf. Korochantsev et al. 2009), indicates transgression throughout most of the upper sample set, possibly with the exception of sample Ly4, which may represent a regressive event. This interpretation corroborates the high-resolution sea-level curve presented by Rasmussen et al. (2009), which was based on brachiopod assemblages. The time-averaging that accompanies condensation is likely to have significant impact on biodiversity data and generalized time estimates, based on net-deposition rate.

The consistently low amounts of OC grains, as compared to some studies in Sweden (see e.g. Schmitz & Häggström 2006), indicates considerable distance to sources of such grains.

In summary, rather than being 'seeded' by weathering of large ordinary chondritic objects at the seafloor, the unusually – and increasingly – high amounts of sediment-dispersed EC grains in the upper sample set of this study are best explained by the interplay between an enhanced influx of ordinary chondritic matter and terrestrial-marine processes, such as hydrodynamic sorting and variations in deposition rate.

6 Conclusions

The lower sample set of this study does not record any increase in EC grains in the lowermost *L. variabilis* conodont zone (*A. expansus* trilobite zone), as seen in preceding studies at localities in Sweden and China (average ~0.05 EC grains kg^{-1}). This may simply reflect differential deposition between localities.

In contrast to the lower sample set, the upper sample set, around the *L. variabilis*-*Y. crassus* conodont (*A. expansus*-*A. raniceps* trilobite) zone boundary, yielded remarkably large amounts of EC grains, as of yet outnumbered only by impact-related deposits (average ~7.71 grains kg^{-1}). Though weathering of unusually large meteoritic objects may have contributed substantial amounts of EC grains, the consistently high and partly harmonizing chromite and ilmenite numbers are more likely to reflect the combined effect of an enhanced influx of extraterrestrial matter and effective sediment winnowing in the relatively high-energy depositional environment represented by the Lynna River strata. The concentration of heavy minerals – in particular ilmenite – increases when ascending stratigraphically, probably tracing sea-level rise.

Yet again, it is shown that an enhanced concentration of EC grains may be found in lower Kundan strata. This rather predictable EC presence corroborates the prevailing view that there was an increased influx of extraterrestrial matter, following the breakup of the L-chondrite parent body ~470 Ma. Future studies may determine in which stratigraphic level, and in what manner, this EC enrichment initiates at Lynna River.

7 Acknowledgments

During my three years as a student at Lund university, many people – both students and employees – have contributed to making my studies a joyous experience, and, thus, many people deserve my personal thanks. I will do my best to thank them in some other way than mentioning them in this short concluding text. First and foremost, I would here like to express my gratitude towards my supervisors. Birger Schmitz is thanked for entrusting me with this exciting (and expensive) project, and for always taking time for me from his often superhumanly busy schedule. Anders Cronholm is thanked for showing me the ropes and guiding me through the project, and for always offering a helping hand when needed. Mats Eriksson is thanked for suggesting my participation in this project in the first place, and for stimulating discussions throughout it. All my supervisors are thanked for encouragement and support, and for feedback during the writing process. Andrei Dronov is thanked for indirectly providing me with field notes, Sanna Holm is thanked for LST instructions, Anders Lindh for SEM help, Anna Pettersson for pointing me in this direction and for helping out in the laboratory every now and then, and My Riebe is thanked for taking part in stimulating discussions and also for helping out here and there. A collective thanks to all who have exchanged ideas with me during my thesis work. I hope I did not forget anyone here...

8 References

Affiatalab, F. & Wasson, J.T., 1980: Composition of the metal phases in ordinary chondrites. *Geo chimica et Cosmochimica Acta 44*, pp. 431-446.

Allaby, M. (ed.), 2008: *Oxford dictionary of earth sciences*. Oxford University Press, Oxford. 672 pp.

Alwmark, C. & Schmitz, B., 2007: Extraterrestrial chromite in the resurge deposits of the early Late Ordovician Lockne crater, central Sweden. *Earth and Planetary Science Letters 253*, pp. 291-303.

Alwmark, C. & Schmitz, B., 2009a: Relict silicate inclusions in extraterrestrial chromite and their use in the classification of fossil chondritic material. *Geochimica et Cosmochimica Acta 73*, pp. 1472-1486.

Alwmark, C. & Schmitz, B., 2009b: The origin of the Brunflo fossil meteorite and extraterrestrial chromite in mid-Ordovician limestone from the Gärde quarry (Jämtland, central Sweden). *Meteoritics & Planetary Science 44*, pp. 95-106.

Alwmark, C., Schmitz, B. & Kirsimäe, K., 2010: The mid-Ordovician Osmussaar breccia in Estonia linked to the disruption of the L-chondrite parent body in the asteroid belt. *Geological Society of America Bulletin 122*, pp. 1039-1046.

Alwmark, C., Schmitz, B., Holm, S., Maroni, F. & Stampanoni, M., 2011: A 3-D study of mineral inclusions in chromite from ordinary chondrites using synchrotron radiation X-ray tomographic microscopy – Method and applications. *Meteoritics and Planetary Science 46*, pp. 1071-1081.

Anders, E., 1964: Origin, age, and composition of meteorites. *Space Science Reviews 3*, pp. 583-714.

Barnes, S.J, 2000: Chromite in komatiites, II. Modification during greenschist to mid-amphibolite facies metamorphism. *Journal of Petrology 41*, pp. 387-409.

Barrie, J.V., Emory-Moore, M., Luternauer, J.L. & Bornhold, B.D., 1988: Origin of modern heavy mineral deposits, Northern British Columbia continental shelf. *Marine Geology 84*, pp. 43-51.

Barnes, S.J. & Roeder, P.L., 2001: The range of spinel compositions in terrestrial mafic and ultramafic rocks. *Journal of Petrology 42*, pp. 2279-2302.

Bergström, S.M., Chen, X., Guitierrez-Marco, J.C. & Dronov, A., 2009: The new chronostratigraphic classification of the Ordovician System and its relations to major regional series and stages and to $\delta^{13}C$ chemostratigraphy. *Lethaia 42*, pp. 97-107.

Bischoff, A., 2001: Meteorite classification and the definition of new chondrite classes as a result of successful meteorite search in hot and cold deserts. *Planetary and Space Science 49*, pp. 769-776.

Bogard, D.D., 1995: Impact ages of meteorites: A synthesis. *Meteoritics 30*, pp. 244-268.

Bridges, J.C., Schmitz, B., Hutchison, R., Greenwood, R.C., Tassinari, M. & Franchi, I.A., 2007: Petrographic classification of Middle Ordovician fossil meteorites from Sweden. *Meteoritics & Planetary Science 42*, pp. 1781-1789.

Bunch, T.E., Keil, K. & Snetsinger, K.G., 1967: Chromite composition in relation to chemistry and texture of ordinary chondrites. *Geochimica et Cosmochimica Acta 31*, pp. 1569-1582.

Cocks, L.R.M. & Torsvik, T.H., 2006: European geography in a global context from the Vendian to the end of the Palaeozoic. *In* Gee, D.G. & Stephenson, R.A. (eds.): *European Lithosphere Dynamics. Geological Society, London, Memoirs, 32*, pp. 83-95.

Cronholm, A., 2009: The flux of extraterrestrial matter to Earth as recorded in Paleogene and Middle Ordovician marine sediments. *Litholund theses 17*. 104 pp.

Cronholm, A. & Schmitz, B., 2007: Extraterrestrial chromite in latest Maastrichtian and Paleocene pelagic limestone at Gubbio, Italy: The flux of -unmelted ordinary chondrites. *Meteoritics & Plane tary Science 42*, pp. 2099-2109.

Cronholm, A. & Schmitz, B., 2010: Extraterrestrial chromite distribution across the mid-Ordovician Puxi River section, central China: Evidence for a global major spike in flux of L-chondritic matter. *Icarus 208*, pp. 36-48.

Culler, T.S., Becker, T.A., Muller, R.A. & Renne, P.R., 2000. Lunar impact history from 40Ar/39Ar dating of glass spherules. *Science 287*, pp. 1785-1788.

Dronov, A., 2005a: Ordovician the St. Petersburg region. *In* Dronov, A., Tolmacheva, T., Raevskaya, E. & Nestell, M. (eds.), 2005: *Cambrian and Ordovician of St. Petersburg region*, pp. 5-9.

Dronov, A., 2005b: Aspects of sedimentation. *In* Dronov, A., Tolmacheva, T., Raevskaya, E. & Nestell, M. (eds.), 2005: *Cambrian and Ordovician of St. Petersburg region*, pp. 9-11.

Dronov, A., 2005c: An introduction to the geology of the St. Petersburg region. *In* Dronov, A., Tolmacheva, T., Raevskaya, E. & Nestell, M. (eds.), 2005: *Cambrian and Ordovician of St. Petersburg region*, pp. 2-4.

Dronov, A., 2005d: Sequence stratigraphy and sea-level changes. *In* Dronov, A., Tolmacheva, T., Raevskaya, E. & Nestell, M. (eds.), 2005: *Cambrian and Ordovician of St. Petersburg region*, pp. 12-15.

Dronov, A.V., Mikuláš, R. & Logvinova, M., 2002: Trace fossils and ichnofabrics across the Volkhov depositional sequence (Ordovician, Arenigian of St. Petersburg region, Russia). *Journal of the Czech Geological Society 47*, pp. 133-146.

Dronov, A., Tolmacheva, T., Raevskaya, E. & Nestell, M. (eds.), 2005: *Cambrian and Ordovician of St. Petersburg region*. 62 pp.

Dronov, A. & Mikuláš, R., 2010: Paleozoic ichnology of St. Petersburg region – excursion guidebook. *Transactions of the Geological Institute vol. 596*. Moscow. 70 pp.

Dronov, A., Ainsaar, L., Kaljo, D., Meidla, T., Saadre, T. & Einasto, R., 2011: Ordovician of Baltoscandia: Facies, sequences and sea-level changes. *In* Gutiérrez-Marco, J.C., Rábano, I. & García-Bellido, D. (eds.): *Ordovician of the world (Cuadernos del Museo Geominero 14),* pp. 143-150. Intituto Geológico y Minero de España, Madrid.

Dypvik, H., Plado, J., Heinberg, C., Håkansson, E., Pesonen, L.J., Schmitz, B. & Raiskila, S., 2008: Impact structures and events – a Nordic perspective. *Episodes 31*, pp. 107-114.

Earth Impact Database (Planetary and Space Science Centre, University of New Brunswick, Canada.), 2011: http://www.passc.net/EarthImpactDatabase (accessed 2011-09-30).

Fedorov, P.V., 2003: Lower Ordovician mud mounds from the St. Petersburg region, northwestern Russia. *Bulletin of the Geological Society of Denmark 50*, pp. 125-137.

Fujiwara, K. & Domae, M., 2004: Thermodynamic Evaluation of Nickel Solubility Depending on Redox Environment during Shutdown in PWR Primary Systems. *14th International Conference on the Properties of Water and Steam in Kyoto*, pp. 581-586.

Genge, M.J. & Grady, M.M., 1999: The fusion crusts of stony meteorites: Implications for the atmospheric reprocessing of extraterrestrial materials. *Meteoritics & Planetary Science 34*, pp. 341-356.

Gladman, B.J., Migliorini, F., Morbidelli, A., Zappalà, V., Michel, P., Cellino, A., Froeschlé, C., Levison, H.F., Bailey, M. & Duncan, M., 1997: Dynamical lifetimes of objects injected into asteroid belt resonances. *Science 277*, pp. 197-201.

Greenwood, R.C., Schmitz, B., Bridges, J.C., Hutchison, R. & Franchi, I.A., 2007: Disruption of the L chondrite parent body: New oxygen isotope evidence from Ordovician relict chromite grains. *Earth and Planetary Science Letters 262*, pp. 204-213.

Gu, F. & Wills, B.A., 1988: Chromite – mineralogy and processing. *Minerals Engineering 1*, pp. 235-240.

Haack, H., Farinella, P., Scott, E.R.D. & Keil, K., 1996: Meteoritic, asteroidal, and theoretical constraints on the 500 Ma disruption of the L chondrite parent body. *Icarus 119*, pp. 182-191.

Hansen, J. & Harper, D.A.T., 2003: Brachiopod macrofaunal distribution through the upper Volkhov-lower Kunda (Lower Ordovician) rocks, Lynna River, St. Petersburg region. *Bulletin of the Geological Society of Denmark 50*, pp. 45-53.

Hansen, T., 2010: Cyrtometopinid trilobites from the upper Volkhov and lower Lynna formations (lower Darriwilian) of NW Russia. *Bulletin of the Geological Society of Denmark 58*, pp. 1-13.

Hansen, T. & Nielsen, A.T., 2003: Upper Arenig trilobite biostratigraphy and sea-level changes at Lynna River near Volkhov, Russia. *Bulletin of the Geological Society of Denmark 50*, pp. 105-114.

Heck, P.R., Schmitz, B., Baur, H., Halliday, A.N. & Wieler, R., 2004: Fast delivery of meteorites to Earth after a major asteroid collision. *Nature 430*, pp. 323-325.

Heck, P.R., Schmitz, B., Baur, H. & Wieler, R., 2008: Noble gases in fossil micrometeorites and meteorites from 470 Myr old sediments from southern Sweden, and new evidence for the L-chondrite parent body breakup event. *Meteoritics & Planetary Science 43*, pp. 517-528.

Häggström, T. & Schmitz, B., 2007: Distribution of extraterrestrial chromite in Middle Ordovician Komstad Limestone in the Killeröd quarry, Scania, Sweden. *Bulletin of the Geological Society of Denmark 55*, pp. 37-58.

Jaanusson, V., 1972: Aspects of carbonate sedimentation in the Ordovician of Baltoscandia. *Lethaia 6*, pp. 11-34.

Kallemeyn, G.W., Rubin, A.E., Wang, D. & Wasson, J.T., 1989: Ordinary chondrites: Bulk compositions, classification, lithophile-element fractionations, and composition-petrographic type relationships. *Geochimica et Cosmochimica Acta 53*, pp. 2747- 2767.

Keil, K., 1962: On the phase composition of meteorites. *Journal of Geophysical Research 67*, p. 4055-4061.

Keil, K., Haack, H. & Scott, E.R., 1994: Catastrophic fragmentation of asteroids: Evidence from meteorites. *Planetary and Space Science 42*, pp. 1109-1122.

Korochantsev, A.V., Lorenz, C.A., Ivanova, M.A., Zaytsev, A.V., Kononkova, N.N., Roshchina, I.A., Korochantseva, D.A., Sadilenko, D.A. & Skripnik, A.Y., 2009: Sediment-dispersed extraterrestrial chromite in Ordovician limestone from Russia. *Abstracts of papers submitted to the lunar and planetary science conference XL*. 2 pp.

Korochantseva, E.V., Trieloff, M., Lorenz, C.A., Buykin, A.I., Ivanonva, M.A., Schwarz, W.H., Hopp, J. & Jessberger, E.K., 2007: L-chondrite

asteroid breakup tied to Ordovician meteorite shower by multiple isochron 40Ar-39Ar dating. *Meteoritics & Planetary Science 42*, pp. 113-130.
Lindström, M., 1963: Sedimentary folds and the development of limestone in an Early Ordovician sea. *Sedimentology 2*, pp. 243-292.
Lindström, M., 1979: Diagenesis of Lower Ordovician hardgrounds in Sweden. *Geologica et Palaeontologica 13*, pp. 9-30.
Love, S.G. & Brownlee, D.E., 1993: A direct measurement of the terrestrial mass accretion rate of cosmic dust. *Science 262*, pp. 550-553.
Meier, M.M.M., Schmitz, B., Baur, H. & Wieler, R., 2010: Noble gases in individual L chondritic micrometeorites preserved in an Ordovician limestone. *Earth and Planetary Science Letters 290*, pp. 54-63.
Meinhold, G., Arslan, A., Lehnert, O. & Stampfli, G.M., 2010: Global mass wasting during the Middle Ordovician: Meteoritic trigger or plate-tectonic environment?. *Gondwana Research 19*, pp. 535-541.
Mellgren, J.I.S. & Eriksson, M.E., 2010: Untangling a Darriwilian (Middle Ordovician) palaeoecological event in Baltoscandia: conodont faunal changes across the 'Täljsten' interval. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh 100*, pp. 353-370.
Nesvorný, D., Morbidelli, A., Vokrouhlický, D., Bottke, W.F. & Brož, M., 2002: The Flora family: A case of the dynamically dispersed collisional swarm?. *Icarus 157*, pp. 155-172.
Nesvorný, D., Vokrouhlický, D., Morbidelli, A., Bottke, W.F., 2008: Asteroidal source of L chondrite meteorites. *Icarus 200*, pp. 698-701.
Nielsen, A.T., 2004: Ordovician sea level changes: A Baltoscandian perspective. In Webby, B.D., Paris, F., Droser, M.L. & Percival, I.G. (eds.): *The Great Ordovician Biodiversification Event*, pp. 84-93. Columbia University Press, New York.
Nyström, J.O., Lindström, M. & Wickman, F.E., 1988: Discovery of a second Ordovician meteorite using chromite as a tracer. *Nature 336*, pp. 572-574.
Nyström, J.O. & Wickman, F.E., 1991: The Ordovician chondrite from Brunflo, central Sweden, II. Secondary minerals. *Lithos 27*, pp. 167-185.
Parashar, K., Prasad, M.S. & Chauhan, S.S.S., 2010: Investigations on a large collection of cosmic dust from the central Indian Ocean. *Earth, Moon, and Planets 107*, pp. 197-217.
Parnell, J., 2009: Global mass wasting at continental margins during Ordovician high meteorite influx. *Nature Geoscience 2*, pp. 57-61.
Patterson, D.B., Farley, K.A. & Schmitz, B., 1998: Preservation of extraterrestrial ^{3}He in 480-Ma-old marine limestones. *Earth and Planetary Science Letters 163*, pp. 315-325.
Pettijohn, F.J., Potter, P.E. & Siever, R., 1987: *Sand and sandstone (second edition)*. Springer-Verlag, New York. 553 pp.
Peucker-Ehrenbrink, B. & Ravizza, G., 2000: The effects of sampling artifacts on cosmic dust flux estimates: A reevaluation of nonvolatile tracers (Os, Ir). *Geochimica et Cosmochimica Acta 64*, pp. 1965-1970.
Pushkin, V.I. & Popov, L.E., 2005: Two enigmatic bryozoans from the Middle Ordovician of the East Baltic. *Palaeontology 48*, pp. 1065-1074.
Ramdohr, P, 1967a: Chromite and chromite chondrules in meteorites – I. *Geochimica et Cosmochimica Acta 31*, pp. 1961-1967.
Ramdohr, P., 1967b: Die schmelzkruste der meteoriten. *Earth and Planetary Science Letters 2*, pp. 197-209.
Rasmussen, C.M.Ø., Hansen, J. & Harper, D.A.T., 2007: Baltica: A mid Ordovician diversity hotspot. *Historical Biology 19*, pp. 255-261.
Rasmussen, C.M.Ø. & Harper, D.A.T., 2009: Resolving early mid-Ordovician bioevents in the East Baltic based on brachiopods. *Geobios 41*, pp. 533-542.
Rasmussen, C.M.Ø., Nielsen, A.T. & Harper, D.A.T., 2009: Ecostratigraphical interpretation of lower Middle Ordovician East Baltic sections based on brachiopods. *Geological Magazine 146*, pp. 717-731.
Rubin, A.E., 1997: Mineralogy of meteorite groups. *Meteoritics & Planetary Science 32*, pp. 231-247.
Schmitz, B., Lindström, M., Asaro, F. & Tassinari, M., 1996: Geochemistry of meteorite-rich marine limestone strata and fossil meteorites from the lower Ordovician at Kinnekulle, Sweden. *Earth and Planetary Science Letters 145*, pp. 31-48.
Schmitz, B., Peucker-Ehrenbrink, B., Lindström, M. & Tassinari, M., 1997: Accretion rates of meteorites and cosmic dust in the Early Ordovician. *Science 278*, pp. 88-90.
Schmitz, B., Tassinari, M. & Peucker-Ehrenbrink, B., 2001: A rain of ordinary chondritic meteorites in the early Ordovician. *Earth and Planetary Science Letters 194*, pp. 1-15.
Schmitz, B., Häggström, T. & Tassinari, M., 2003: Sediment-dispersed extraterrestrial chromite traces a major asteroid disruption event. *Science 300*, pp. 961-964.
Schmitz, B. & Häggström, T., 2006: Extraterrestrial chromite in Middle Ordovician marine limestone at Kinnekulle, southern Sweden – traces of a major asteroid breakup event. Meteoritics & Planetary *Science 41*, pp. 455-466.
Schmitz, B., Harper, D.A.T., Peucker-Ehrenbrink, B., Stouge, S., Alwmark, C., Cronholm, A., Bergström, S.M., Tassinari, M. & Xiaofeng, W., 2008: Asteroid breakup linked to the Great Ordovician Biodiversification Event. *Nature Geoscience 1*, pp. 49-53.
Schmitz, B., Cronholm, A. & Montanari, A., 2010: A search for extraterrestrial chromite in the late Eocene Massignano section, central Italy. *Special Paper of the Geological Society of America 452*,

pp. 71-82.
Schmitz, B. Heck, P.R., Alwmark, C., Kita, N.T., Meier, M.M.M., Peucker-Ehrenbrink, B., Ushikubo, T. & Valley, J.W., 2011: Determining the impactor of the Ordovician Lockne crater: Oxygen and neon isotopes in chromite versus sedimentary PGE signatures. *Earth and Planetary Science Letters 306*, pp. 149-155.
Snetsinger, K.G., Keil. K. & Bunch, T.E., 1967: Chromite from "equilibrated" chondrites. *The American Mineralogist 52*, pp. 1322-1331.
Spence, G.H. & Tucker, M.E., 1997: Genesis of limestone megabreccias and their significance in carbonate sequence stratigraphic models: A review. *Sedimentary Geology 112*, pp. 163-193.
Sturesson, U., 2003: Lower Palaeozoic iron oolites and volcanism from a Baltoscandian perspective. *Sedimentary Geology 159*, pp. 241-256.
Sturesson, U., Dronov, A. & Saadre, T. 1999: Lower Ordovician iron ooids and associated oolitic clays in Russia and Estonia: a clue to the origin of iron oolites?. *Sedimentary Geology 123*, pp. 63-80.
Stöffler, D., Keil, K. & Scott, E.R.D., 1991: Shock metamorphism of ordinary chondrites. *Geochimica et Cosmochimica Acta 55*, pp. 3845-3867.
Tassinari, M., Schmitz, B. & Löfgren, A., 2004: The first fossil meteorite from the mid-Ordovician of the Gullhögen quarry, Billingen, southern Sweden. *GFF 126*, pp. 321-324.
Thorslund, P. & Wickman, F.E., 1981: Middle Ordovician chondrite in fossiliferous limestone from Brunflo, central Sweden. *Nature 289*, pp. 285-286.
Thorslund, P., Wickman, F.E. & Nyström, J.O., 1984: The Ordovician chondrite from Brunflo, central Sweden, I. General description and primary minerals. *Lithos 17*, pp. 87-100.
Tolmacheva, T., Fedorov, P. & Egerquist, E., 2003: Conodonts and brachiopods from the Volkhov Stage (Lower Ordovician) microbial mud mound at Putilovo Quarry, north-western Russia. *Bulletin of the Geological Society of Denmark 50*, pp. 63-74.
Tucker, M.E., 2001: *Sedimentary petrology: An introduction to the origin of sedimentary rocks (third edition).* Blackwell Publishing, Oxford. 262 pp.
Turner, G., Miller, J.A. & Grasty, L.R., 1966: The thermal history of the Bruderheim meteorite. *Earth and Planetary Science Letters 1*, pp. 155-157.
Van Schmus, W.R. & Wood, J.A., 1967: A chemical-petrologic classification for the chondritic meteorites. *Geochimica et Cosmochimica Acta 31*, pp. 747-765.
Webby, B.D., Paris, F., Droser, M.L. & Percival, I.G. (eds.), 2004: *The Great Ordovician Biodiversification Event*. Columbia University Press, New York. 484 pp.
Wenk, H.-R. & Bulakh, A., 2004: *Minerals: Their constitution and origin*. Cambridge University Press, Cambridge. 646 pp.
Wlotzka, F., 2005: Cr spinel and chromite as petrogenetic indicators in ordinary chondrites: Equilibration temperatures of petrologic types 3.7 to 6. *Meteoritics & Planetary Science 40*, pp. 1673-1702.
Zaika, J., 2005: Corals. *In* Dronov, A., Tolmacheva, T., Raevskaya, E. & Nestell, M. (eds.), 2005: *Cambrian and Ordovician of St. Petersburg region*, p. 29.
Zappalà, V., Cellino, A., Gladman, B.J., Manley, S. & Migliorini, F., 1998: Asteroid showers on Earth after family breakup events. *Icarus 134*, pp. 176-179.

Appendix

Appendix Table 1. Chemical composition (compound wt% ± 1 s.d.) of sediment-dispersed extraterrestrial chromite (EC) grains in samples from Lynna River. n.d. = not detected.

Sample Grain #	MgO	Al_2O_3	TiO_2	V_2O_3	Cr_2O_3	MnO	FeO	NiO	ZnO	Total
28U										
#1	4.37	6.25	2.40	0.75	56.79	0.72	26.48	1.39	n.d.	99.14
30										
#1	2.91	3.49	2.55	0.66	60.87	0.69	28.22	n.d.	n.d.	99.40
Ly1										
#1	2.19	6.02	3.40	0.65	59.65	0.77	26.78	n.d.	0.42	99.88
#2	2.47	5.85	2.91	0.75	57.08	1.06	28.49	n.d.	0.36	98.97
#3	2.57	6.47	2.42	0.74	59.17	0.87	24.79	n.d.	2.90	99.93
#4	2.35	6.03	2.83	0.82	58.28	0.81	27.32	n.d.	1.67	100.10
#5	2.79	5.93	3.16	0.68	58.32	0.96	26.99	n.d.	0.89	99.70
#6	2.72	5.67	3.24	0.71	57.62	0.90	25.53	n.d.	2.86	99.25
#7	3.05	5.88	3.18	0.71	58.18	0.84	27.99	n.d.	0.36	100.19
#8	2.65	5.85	3.13	0.76	57.74	1.05	24.49	n.d.	2.36	98.03
#9	2.13	6.17	3.27	0.68	57.38	0.79	26.66	n.d.	1.10	98.18
#10	2.67	5.75	3.13	0.62	58.88	0.68	25.21	n.d.	1.41	98.35
#11	2.06	5.81	3.44	0.82	59.96	0.55	26.70	n.d.	0.50	99.84
#12	7.69	5.98	3.23	0.67	58.45	0.50	22.40	n.d.	n.d.	98.93
#13	2.78	5.77	3.11	0.69	58.13	0.89	29.01	n.d.	n.d.	100.39
#14	6.94	4.86	1.99	0.58	57.70	0.77	24.09	0.74	0.90	98.56
#15	2.46	5.78	3.42	0.69	57.85	0.92	26.94	n.d.	0.93	98.98
#16	2.52	6.31	2.84	0.81	57.98	1.01	28.16	n.d.	0.51	100.13
#17	2.62	6.01	3.44	0.64	58.96	0.72	25.82	n.d.	1.06	99.27
#18	2.85	5.88	3.25	0.67	57.38	0.83	28.36	n.d.	n.d.	99.22
#19	2.35	6.01	3.08	0.68	57.09	0.89	28.38	n.d.	0.64	99.11
#20	2.46	5.86	3.11	0.62	57.89	0.80	26.64	n.d.	2.17	99.56
#21	3.68	5.25	3.07	0.63	57.61	0.78	26.99	n.d.	0.42	98.43
#22	2.84	6.03	3.29	0.76	58.94	0.83	25.11	n.d.	1.68	99.49
#23	3.10	6.08	2.80	0.79	59.04	0.84	27.29	n.d.	n.d.	99.94
#24	2.70	6.07	3.09	0.76	60.10	0.82	22.66	n.d.	2.99	99.19
#25	2.02	5.77	2.75	0.81	61.21	0.59	26.24	n.d.	n.d.	99.39
#26	2.01	6.24	2.91	0.66	59.90	0.74	26.97	n.d.	0.66	100.10
#27	2.63	5.92	3.13	0.69	59.34	0.79	23.28	n.d.	2.71	98.49
#28	2.65	6.08	3.01	0.77	58.60	0.84	27.55	n.d.	0.31	99.82
#29	2.32	6.04	3.48	0.78	60.80	n.d.	23.33	n.d.	2.67	99.42
#30	5.31	6.01	3.31	0.77	60.01	1.13	21.52	n.d.	1.28	99.35
#31	2.46	5.69	3.18	0.67	59.12	0.95	27.09	n.d.	0.34	99.50
#32	2.76	6.00	3.31	0.73	57.86	0.85	27.18	n.d.	0.72	99.40
#33	2.21	6.00	3.16	0.83	59.39	0.78	25.67	n.d.	1.09	99.13
#34	1.92	6.47	3.08	0.82	60.11	0.74	25.27	n.d.	0.79	99.22
#35	2.54	5.90	3.33	0.77	59.22	0.74	27.14	n.d.	n.d.	99.63
#36	3.21	5.85	2.99	0.81	59.29	0.90	26.41	n.d.	0.42	99.88
#37	2.34	6.50	3.02	0.67	60.07	0.78	24.59	n.d.	2.06	100.05
#38	1.47	5.42	2.65	0.55	57.86	n.d.	31.59	n.d.	0.42	99.97
#39	2.15	6.31	1.75	0.72	61.25	0.86	21.79	n.d.	3.77	98.60
#40	3.09	6.19	3.50	0.68	59.43	0.88	25.91	n.d.	0.28	99.96
#41	2.92	6.13	3.23	0.85	60.24	0.77	24.56	n.d.	n.d.	98.70

#42	2.40	6.41	2.88	0.68	57.74	0.85	29.04	n.d.	n.d.	100.01
#43	2.54	6.03	3.24	0.62	58.44	0.64	26.83	n.d.	0.57	98.92
#44	2.09	5.99	3.02	0.64	58.64	0.76	28.60	n.d.	n.d.	99.74
#45	2.30	6.29	3.16	0.63	59.17	0.87	24.59	n.d.	2.77	99.77
#46	2.43	6.01	3.17	0.66	58.25	0.88	25.37	n.d.	2.54	99.31
#47	1.65	6.31	3.47	0.86	61.24	0.61	24.03	n.d.	0.43	98.60
#48	1.43	5.94	3.24	0.65	60.34	0.56	26.58	n.d.	n.d.	98.75
#49	4.14	6.10	2.08	0.59	61.70	n.d.	24.98	n.d.	0.41	100.00[a]
#50	2.41	5.18	2.32	0.78	61.95	0.81	25.45	n.d.	0.49	99.38
#51	2.13	6.35	3.07	0.84	60.72	0.62	25.55	n.d.	0.78	100.05
#52	2.48	6.20	2.98	0.75	59.47	0.88	23.80	n.d.	2.48	99.06
#53	2.46	5.99	2.78	0.70	56.79	0.90	28.49	n.d.	0.60	98.71
#54	2.41	6.19	3.32	0.73	59.34	0.75	24.89	0.59	1.08	99.31
#55	2.12	5.93	2.98	0.83	59.06	0.73	27.62	n.d.	0.37	99.64
#56	1.86	6.24	3.59	0.82	62.62	0.59	22.05	n.d.	2.84	100.60
#57	3.63	6.69	2.50	0.77	58.77	0.99	25.61	n.d.	1.15	100.11
#58	6.58	5.96	2.35	0.68	58.47	0.80	23.36	0.53	n.d.	98.73
#59	2.67	6.24	3.34	0.77	58.83	0.61	25.73	n.d.	0.86	99.06
#60	5.97	5.87	3.10	0.67	58.26	0.66	24.21	n.d.	n.d.	98.74
#61	1.59	6.18	2.88	0.69	60.66	0.56	26.67	n.d.	0.36	99.58
#62	2.66	6.43	3.32	0.84	57.96	0.75	25.65	n.d.	0.93	98.53
#63	2.93	5.72	3.25	0.65	57.88	0.87	27.29	n.d.	0.78	99.37
#64	2.32	5.70	3.29	0.64	61.19	0.77	24.79	n.d.	1.47	100.17
#65	3.72	5.86	2.29	0.60	57.61	0.79	27.90	n.d.	0.36	99.13
#66	3.22	5.94	2.59	0.70	59.33	0.72	26.20	n.d.	0.52	99.22
#67	2.05	6.60	1.42	0.77	61.32	0.80	19.59	n.d.	6.82	99.37
#68	2.33	6.08	3.05	0.72	56.92	0.83	28.93	n.d.	0.62	99.48
#69	2.94	5.37	3.31	0.72	58.44	0.60	27.08	n.d.	0.68	99.14
#70	2.95	6.33	2.23	0.77	62.23	0.77	22.06	n.d.	2.05	99.39
#71	2.11	5.54	3.28	0.66	58.69	0.89	27.65	n.d.	0.54	99.36
#72	2.42	5.48	3.03	0.73	58.91	0.92	24.88	n.d.	3.21	99.59
#73	1.73	6.46	3.55	0.67	60.33	0.49	25.16	n.d.	0.29	98.69
#74	2.81	5.94	2.30	0.95	61.02	0.92	24.79	n.d.	1.47	100.20
#75	2.89	6.50	2.55	0.98	60.38	0.89	21.15	n.d.	5.37	100.71
#76	2.22	5.66	3.20	0.70	60.01	0.87	26.21	n.d.	0.44	99.31
Ly2Ö										
#1	2.96	5.96	2.97	0.68	57.92	1.02	27.56	n.d.	0.50	99.57
#2	2.91	5.88	3.24	0.67	59.09	0.91	26.41	n.d.	0.38	99.48
#3	2.79	6.35	2.78	0.78	57.40	1.01	25.74	n.d.	2.17	99.02
#4	2.81	6.11	3.63	0.80	59.69	0.77	25.00	n.d.	0.52	99.33
#5	3.36	5.95	3.11	0.68	58.52	0.88	25.86	n.d.	0.24	98.60
#6	1.63	5.96	3.34	0.83	62.57	0.96	21.43	n.d.	3.53	100.25
#7	2.60	3.61	2.08	0.61	58.29	0.72	31.18	n.d.	n.d.	99.09
#8	2.17	6.33	2.85	0.79	58.40	0.78	27.90	n.d.	0.53	99.75
#9	2.84	6.25	3.16	0.71	59.04	0.80	26.76	n.d.	0.22	99.77
#10	2.04	6.59	3.07	0.78	60.38	0.80	25.08	n.d.	0.42	99.16
#11	3.10	6.00	3.34	0.60	56.77	0.95	27.31	n.d.	0.53	98.60
#12	2.51	6.17	3.07	0.66	57.53	0.89	27.78	n.d.	0.18	98.78
#13	1.70	7.66	2.27	0.83	55.00	0.42	32.11	n.d.	n.d.	100.00[b]
#14	2.89	5.90	2.99	0.73	57.75	0.80	26.76	n.d.	1.42	99.23
#15	2.26	5.95	2.85	0.58	57.45	0.91	28.29	n.d.	0.41	98.70
#16	2.85	6.54	2.27	0.77	57.69	0.96	27.26	n.d.	0.55	98.90
#17	2.03	6.66	3.23	0.75	60.06	0.64	22.47	n.d.	2.81	98.64
#18	2.43	4.76	3.00	0.72	61.77	0.95	27.08	n.d.	n.d.	100.71

#19	2.90	5.92	2.91	0.65	58.77	0.81	26.70	n.d.	0.43	99.08
#20	3.17	5.76	3.09	0.77	57.74	0.74	27.66	n.d.	1.03	99.98
#21	2.43	7.13	3.15	0.82	59.07	0.86	25.07	n.d.	0.82	99.35
#22	2.95	6.24	3.35	0.73	56.98	0.97	27.41	n.d.	0.46	99.09
#23	3.85	5.64	3.08	0.80	61.70	0.76	22.52	n.d.	1.33	99.68
#24	3.85	6.08	3.02	0.64	59.18	0.82	25.06	n.d.	0.27	98.92
#25	2.19	5.96	3.28	0.83	59.33	0.68	27.03	n.d.	0.22	99.53
#26	2.60	5.89	3.22	0.71	58.93	0.83	26.87	n.d.	0.45	99.50
#27	3.65	6.12	2.97	0.83	59.47	0.92	24.34	n.d.	0.55	98.84
#28	2.89	5.71	3.12	0.60	57.98	0.81	27.07	n.d.	0.55	98.72
#29	1.59	6.27	2.91	0.87	62.98	0.67	25.02	n.d.	0.38	100.69
#30	1.41	6.70	3.22	0.80	63.54	0.63	23.54	n.d.	0.40	100.24
#31	1.93	5.68	1.98	1.02	64.10	1.15	20.89	n.d.	2.93	99.66
#32	2.10	6.64	3.19	0.74	62.66	0.92	21.19	n.d.	3.03	100.48
#33	1.79	6.11	3.28	0.67	62.31	0.73	25.11	n.d.	0.32	100.32
#34	1.88	6.38	3.34	0.71	61.28	0.71	22.36	n.d.	3.41	100.07
#35	1.41	5.44	2.05	1.02	64.89	0.75	23.14	n.d.	0.74	99.44
#36	1.98	5.90	3.39	0.74	60.30	0.66	26.95	n.d.	0.38	100.29
#37	2.22	6.27	2.85	0.75	59.26	0.91	27.05	n.d.	0.64	99.94
#38	2.46	6.04	3.40	0.82	61.33	0.74	23.52	n.d.	1.16	99.47
#39	2.94	6.10	1.55	0.55	61.00	0.96	27.01	0.26	0.63	101.01
#40	2.73	6.75	2.27	0.69	61.13	1.03	24.10	n.d.	1.36	100.06
#41	2.74	6.44	3.77	0.80	61.35	0.90	21.56	n.d.	1.43	99.00
#42	2.10	6.21	3.25	0.70	59.48	0.72	26.97	n.d.	0.61	100.03
#43	1.69	6.39	3.24	0.64	61.02	0.49	26.24	n.d.	0.28	99.97
#44	2.38	6.34	2.97	0.74	60.21	0.79	26.91	n.d.	0.17	100.52
#45	2.40	6.29	3.01	0.82	58.57	0.98	24.06	n.d.	2.82	98.94
#46	6.29	5.14	2.56	0.65	60.06	0.53	24.93	n.d.	0.41	100.57
#47	2.39	6.20	2.98	0.71	58.08	0.97	26.07	n.d.	2.55	99.94
#48	3.72	6.27	3.38	0.76	59.66	0.66	24.12	n.d.	0.64	99.22
#49	2.58	6.08	3.24	0.61	58.73	0.97	25.85	n.d.	1.09	99.14
#50	3.08	6.00	2.63	0.68	59.25	0.75	26.37	0.37	0.62	99.75
#51	2.32	6.28	2.96	0.74	59.69	0.84	26.10	n.d.	0.64	99.57
#52	2.34	6.75	2.14	0.80	60.48	0.94	21.56	n.d.	4.02	99.04
#53	2.31	6.04	3.17	0.69	59.46	0.88	25.53	n.d.	0.33	98.41
#54	1.49	7.03	2.93	0.82	62.53	n.d.	23.44	n.d.	0.98	99.21
#55	2.41	5.91	3.45	0.76	59.55	0.77	25.98	n.d.	0.23	99.06
#56	2.42	5.99	3.03	0.80	58.12	0.84	26.11	n.d.	1.75	99.06
#57	2.60	5.86	3.23	0.69	58.32	0.87	27.67	n.d.	0.48	99.71
#58	2.13	6.13	2.11	0.95	60.13	0.97	26.40	n.d.	0.72	99.54
#59	1.67	5.61	2.75	0.71	59.96	0.76	28.57	n.d.	0.16	100.19
#60	2.52	6.01	3.02	0.67	57.18	1.04	28.03	n.d.	0.66	99.12
#61	2.97	6.00	3.17	0.79	58.73	0.76	25.09	n.d.	0.53	98.05
#62	2.60	5.98	3.08	0.71	57.04	0.72	28.75	n.d.	0.45	99.32
#63	1.81	6.76	2.70	0.73	61.92	0.84	21.92	n.d.	3.60	100.28
#64	2.73	6.02	2.49	0.68	58.00	0.91	27.87	n.d.	0.50	99.20
#65	2.74	6.08	3.24	0.61	58.03	1.00	25.22	n.d.	1.61	98.53
#66	3.78	5.24	2.55	0.72	59.72	0.73	25.92	n.d.	n.d.	98.65
#67	2.67	6.17	3.31	0.72	58.92	0.74	25.57	n.d.	0.48	98.59
#68	2.23	6.28	3.22	0.80	58.18	0.85	26.67	n.d.	0.89	99.12
#69	2.41	5.89	3.37	0.79	58.82	0.82	25.78	n.d.	0.75	98.63
#70	2.32	6.47	2.18	0.73	60.28	0.91	24.13	n.d.	1.85	98.86
#71	2.35	5.91	3.05	0.73	58.68	0.78	26.85	n.d.	0.44	98.79
#72	2.32	6.06	3.26	0.70	57.97	0.77	27.95	n.d.	0.35	99.39
#73	2.15	5.87	2.92	0.72	57.13	0.72	29.20	n.d.	0.45	99.15
#74	2.83	6.01	2.76	0.76	57.66	1.08	27.06	n.d.	1.08	99.24

#75	3.27	6.23	2.86	0.74	57.54	0.74	28.10	n.d.	0.34	99.82
#76	2.48	6.06	3.05	0.72	58.45	1.04	24.94	n.d.	2.79	99.53
#77	2.71	6.10	2.91	0.78	58.26	0.89	26.30	n.d.	1.62	99.56
#78	2.56	5.90	3.25	0.62	58.02	0.91	27.57	n.d.	0.70	99.53
#79	2.63	6.39	2.30	0.73	58.15	1.15	27.20	n.d.	0.64	99.18
#80	2.88	5.78	3.24	0.74	58.50	0.96	26.81	n.d.	0.44	99.35
#81	5.87	6.33	2.96	0.68	60.07	0.71	21.50	0.36	0.52	99.00
#82	4.84	5.83	2.48	0.70	59.55	0.78	23.54	0.39	0.74	98.85
#83	2.98	5.76	2.51	0.65	58.12	0.73	27.49	0.45	0.36	99.05
#84	10.98	5.19	1.92	0.66	59.69	0.69	19.49	0.77	0.20	99.57
#85	7.09	5.45	2.67	0.55	58.84	0.92	22.36	0.52	0.46	98.86
#86	8.78	4.70	1.96	0.64	57.57	0.54	24.23	0.70	0.61	99.72
#87	3.09	6.12	2.16	0.73	57.50	0.95	28.49	n.d.	0.66	99.70
#88	3.04	5.17	2.57	0.71	59.53	1.02	27.27	n.d.	0.67	99.99
#89	2.93	5.74	2.96	0.82	57.73	1.01	27.15	n.d.	0.75	99.10
#90	2.55	6.48	2.44	0.81	57.74	1.14	27.25	n.d.	0.93	99.34
#91	2.17	6.26	3.27	0.78	59.41	0.77	26.89	n.d.	0.53	100.08
#92	3.22	6.30	3.14	0.74	59.37	1.27	22.66	n.d.	3.55	100.24
#93	2.01	6.22	3.78	0.89	61.24	0.49	25.08	n.d.	0.22	99.93
#94	2.48	6.10	3.13	0.71	57.15	0.77	28.58	n.d.	0.65	99.58
#95	2.41	6.46	2.80	0.75	58.74	0.70	27.76	n.d.	0.29	99.90
#96	2.72	5.90	3.11	0.77	56.82	0.99	28.26	n.d.	0.48	99.05
#97	2.72	5.58	2.96	0.76	56.94	0.93	29.01	n.d.	0.49	99.38
#98	2.98	6.19	3.12	0.79	57.74	0.98	26.87	n.d.	1.33	99.99
#99	2.53	6.22	3.07	0.75	59.86	0.79	26.19	n.d.	0.54	99.95
#100	2.62	5.87	3.21	0.71	59.00	0.74	27.98	n.d.	0.56	100.70
#101	1.40	6.06	2.51	0.52	58.88	0.74	29.89	n.d.	n.d.	100.00[c]
#102	2.63	6.34	3.46	0.82	58.89	0.77	26.85	n.d.	0.62	100.38
#103	5.07	6.08	3.14	0.71	59.57	0.79	24.85	n.d.	0.29	100.52
#104	2.29	5.93	3.55	0.63	60.10	0.64	26.14	n.d.	0.26	99.53
#105	2.32	6.34	2.97	0.65	59.95	0.73	26.09	n.d.	0.53	99.58
#106	2.74	5.82	3.18	0.76	59.70	0.89	24.48	n.d.	2.07	99.64
#107	2.79	6.33	3.11	0.71	59.82	0.85	26.28	n.d.	0.40	100.29
#108	2.53	6.06	3.09	0.73	59.10	0.77	28.16	n.d.	0.37	100.83
#109	2.60	6.28	2.78	0.89	62.53	n.d.	23.48	0.32	0.61	99.48
#110	1.91	7.09	3.23	0.97	62.17	0.64	23.21	n.d.	0.99	100.21
#111	2.18	5.86	2.84	0.92	57.33	0.74	30.19	n.d.	0.43	100.48
#112	1.89	6.57	3.28	0.79	60.79	n.d.	23.79	n.d.	1.75	98.87
#113	1.77	6.83	2.34	0.93	61.46	0.54	24.26	n.d.	1.60	99.73
Ly4 (preliminary analyses)										
#1	1.47	8.24	3.63	0.81	65.53	n.d.	18.82	n.d.	n.d.	98.49
#2	1.38	6.47	2.54	0.82	51.23	n.d.	37.14	n.d.	n.d.	99.58
#3	2.64	6.00	2.46	0.95	61.96	n.d.	23.08	n.d.	0.21	97.31
#4	2.44	6.49	3.49	0.89	62.78	n.d.	20.03	n.d.	1.03	97.15
#5	1.59	7.88	2.78	0.88	63.57	n.d.	21.33	n.d.	1.96	99.99
#6	2.91	5.40	1.97	0.46	48.95	n.d.	38.30	n.d.	n.d.	98.00
#7	1.01	4.98	1.56	0.44	33.50	n.d.	52.77	n.d.	0.93	95.20
#8	2.42	7.89	3.17	0.82	58.46	1.13	23.45	n.d.	1.78	99.13
#9	2.86	8.31	2.12	0.84	60.64	n.d.	19.03	n.d.	5.51	99.31
#10	1.01	5.93	2.29	0.71	46.37	0.74	38.78	n.d.	n.d.	95.83
#11	2.94	5.86	1.11	0.92	61.64	1.36	18.22	n.d.	8.89	100.94
#12	1.25	7.58	3.46	0.87	63.49	n.d.	21.46	n.d.	n.d.	97.94
#13	1.92	4.72	2.06	n.d.	48.87	n.d.	38.57	n.d.	0.05	96.19
#14	4.07	9.75	2.30	n.d.	58.64	1.02	21.56	n.d.	1.13	98.47

#15	1.17	4.58	3.47	n.d.	62.98	n.d.	21.29	n.d.	1.66	95.14
#16	1.58	6.47	2.34	0.61	51.21	n.d.	35.04	n.d.	0.84	98.10
#17	1.90	8.63	3.16	0.64	57.68	n.d.	25.43	n.d.	n.d.	97.43
#18	1.49	7.35	1.94	n.d.	43.52	n.d.	44.54	n.d.	0.32	99.18
#19	1.39	4.96	1.93	n.d.	47.24	n.d.	40.68	n.d.	n.d.	96.20
#20	1.52	5.68	1.97	0.48	47.17	n.d.	39.32	n.d.	0.60	96.73
#21	3.68	5.61	2.57	0.69	59.99	n.d.	25.89	n.d.	0.96	99.39
#22	3.73	7.69	2.84	0.64	54.35	n.d.	28.69	n.d.	0.62	98.57
#23	1.88	5.15	1.66	0.57	51.43	n.d.	37.48	n.d.	0.78	98.94
#24	4.74	5.32	2.33	0.78	57.77	0.87	29.18	n.d.	n.d.	100.99
#25	2.67	7.73	2.21	n.d.	54.01	n.d.	32.82	n.d.	n.d.	99.44
#26	2.48	6.78	2.87	0.66	58.62	n.d.	18.00	n.d.	7.13	96.54
#27	1.36	5.39	2.32	0.63	57.88	n.d.	21.70	n.d.	7.24	96.52
#28	1.93	4.70	2.05	0.64	59.01	0.82	28.47	n.d.	n.d.	97.61
#29	1.56	7.06	2.63	0.80	60.05	1.00	21.73	n.d.	2.18	97.01
#30	1.63	6.81	1.54	0.56	53.01	0.89	34.60	n.d.	0.33	99.36
#31	2.22	5.20	1.87	0.55	53.60	0.86	30.34	0.42	1.38	96.45
#32	2.06	7.03	3.47	0.76	61.59	0.82	25.53	n.d.	0.42	101.68
#33	1.45	5.55	2.14	0.61	49.32	n.d.	39.36	n.d.	0.30	98.73
#34	2.04	5.23	2.05	0.40	51.23	0.80	35.72	n.d.	0.65	98.12
#35	1.13	4.83	2.59	0.57	56.92	n.d.	32.20	n.d.	0.66	98.90
#36	3.29	5.54	2.53	0.44	52.78	0.68	35.20	n.d.	0.37	100.83
#37	1.37	5.13	2.89	0.56	57.16	0.63	27.19	n.d.	0.64	95.56
#38	1.79	4.98	1.90	0.36	47.55	0.97	38.09	n.d.	0.39	96.04
#39	2.60	5.39	1.75	0.57	57.04	0.76	30.48	n.d.	0.25	98.86
#40	1.44	5.60	2.95	0.69	60.95	0.84	24.27	n.d.	0.98	97.73
#41	1.20	5.71	2.15	0.51	45.38	0.90	40.02	n.d.	0.37	96.25
#42	2.59	6.52	2.19	0.84	58.11	0.43	27.78	n.d.	n.d.	98.45
#43	2.39	8.12	2.60	0.68	58.88	0.62	20.15	n.d.	2.41	95.85
#44	6.10	32.24	0.62	0.26	23.94	n.d.	35.38	n.d.	0.31	98.84
#45	1.43	6.30	3.27	0.69	57.78	0.65	27.32	n.d.	0.52	97.95
#46	2.59	7.55	3.12	0.84	59.61	0.78	19.22	n.d.	5.04	98.75
#47	2.68	8.32	2.91	0.59	58.99	1.23	20.12	n.d.	3.92	98.78
#48	1.45	5.94	2.39	0.48	40.05	n.d.	45.78	n.d.	0.48	96.57
#49	2.34	7.26	2.79	0.51	47.09	0.83	35.61	n.d.	n.d.	96.43
#50	1.38	5.52	1.89	0.40	51.96	0.81	36.65	n.d.	0.73	99.34
#51	1.80	6.01	3.50	0.71	61.69	1.04	21.95	n.d.	1.55	98.25
#52	3.56	5.58	2.82	0.65	60.30	0.80	24.38	n.d.	0.15	98.24
#53	1.70	7.04	3.24	0.70	58.84	n.d.	26.05	n.d.	0.29	97.86
#54	2.30	8.29	1.72	0.69	55.01	1.19	17.44	n.d.	6.66	93.30
#55	1.88	7.03	2.97	0.45	46.24	0.97	39.83	n.d.	0.17	99.54
#56	11.59	3.72	1.49	0.47	63.77	0.89	17.62	n.d.	1.13	100.69
#57	2.13	5.37	2.14	0.33	54.03	0.72	28.16	n.d.	0.34	93.20
#58	2.26	6.83	3.77	0.68	62.76	0.80	20.49	n.d.	1.74	99.33
#59	2.85	8.30	1.79	0.46	60.42	1.14	24.44	n.d.	0.93	100.33
#60	1.42	5.31	2.18	0.46	43.49	0.68	41.28	n.d.	0.42	95.23
#61	1.69	5.24	2.26	0.51	52.07	0.75	33.85	n.d.	0.17	96.55
#62	1.58	6.04	3.76	0.83	57.55	n.d.	27.21	n.d.	2.20	99.17
#63	1.87	5.14	3.25	0.60	50.00	n.d.	38.15	0.64	0.33	99.98
#64	1.15	6.77	3.07	0.96	58.51	0.62	27.83	n.d.	0.08	98.98
#65	1.48	6.33	2.46	n.d.	52.26	n.d.	36.89	n.d.	0.04	99.46
#66	1.75	7.79	1.78	n.d.	39.20	0.72	46.36	n.d.	0.37	97.97
#67	1.68	6.11	2.29	0.64	54.71	n.d.	31.64	n.d.	0.44	97.49
#68	1.89	6.29	2.26	n.d.	49.78	1.46	37.51	n.d.	0.37	99.57
#69	0.49	4.41	2.18	0.52	46.00	n.d.	37.01	n.d.	1.08	91.71

Ly5

#1	2.66	5.94	3.24	0.68	59.43	0.78	26.04	n.d.	0.85	99.62
#2	4.18	5.09	1.76	0.45	59.77	0.77	26.51	n.d.	0.28	98.80
#3	2.18	5.98	3.48	0.76	58.75	0.78	27.84	n.d.	0.41	100.16
#4	3.19	6.26	3.17	0.77	59.19	0.99	24.94	n.d.	2.12	100.62
#5	4.16	5.80	3.38	0.56	58.53	0.76	27.12	n.d.	n.d.	100.31
#6	2.72	6.31	3.11	0.67	59.87	0.78	22.00	n.d.	4.29	99.77
#7	3.31	6.63	2.01	0.81	58.62	0.77	27.54	n.d.	0.77	100.47
#8	2.75	6.38	3.25	0.72	60.03	1.08	21.63	0.48	4.03	100.35
#9	2.53	6.39	3.83	0.61	60.81	0.67	24.98	n.d.	0.46	100.28
#10	2.51	6.21	2.08	0.74	61.22	0.78	23.61	n.d.	3.08	100.22
#11	2.46	5.77	3.35	0.77	59.63	0.82	27.55	n.d.	n.d.	100.35
#12	2.02	6.64	3.50	0.78	60.69	n.d.	25.96	n.d.	0.66	100.25
#13	2.01	5.65	3.05	0.68	59.44	0.85	27.39	n.d.	0.99	100.08
#14	3.47	5.79	3.45	0.83	60.96	0.71	23.53	n.d.	0.88	99.61
#15	2.19	6.14	3.16	0.72	59.75	0.61	27.27	n.d.	n.d.	99.84
#16	3.35	5.33	3.19	0.75	59.90	0.63	26.83	n.d.	n.d.	99.98
#17	1.91	6.43	3.05	0.73	60.00	0.74	26.72	n.d.	0.32	99.87
#18	2.27	6.06	3.01	0.56	56.13	0.70	31.40	n.d.	0.27	100.41
#19	1.97	6.54	3.57	0.80	62.49	0.82	23.24	n.d.	n.d.	99.44
#20	2.74	6.18	3.33	0.77	59.46	0.68	26.60	n.d.	0.49	100.25
#21	1.92	5.85	3.34	0.68	59.51	0.72	27.63	n.d.	0.52	100.17
#22	3.71	6.08	3.20	0.83	59.78	0.66	25.13	n.d.	0.23	99.62
#23	3.57	6.03	3.31	0.71	58.32	0.88	27.31	n.d.	0.15	100.29
#24	2.03	6.28	3.27	0.81	60.26	0.68	25.57	n.d.	0.56	99.45
#25	2.51	6.30	2.94	0.76	59.76	0.76	23.75	n.d.	2.59	99.38
#26	2.06	5.89	3.01	0.70	59.77	0.56	26.95	n.d.	0.33	99.27
#27	2.66	6.37	3.42	0.75	59.81	0.82	21.95	n.d.	4.42	100.21
#28	2.92	6.02	3.29	0.75	58.67	0.96	27.64	n.d.	0.54	100.80
#29	2.79	6.30	3.05	0.81	59.18	0.87	23.75	n.d.	2.41	99.16
#30	2.49	5.90	3.07	0.73	58.74	0.65	28.64	n.d.	n.d.	100.22
#31	2.56	6.16	3.10	0.75	58.17	0.99	28.92	n.d.	0.35	101.00
#32	1.81	4.73	2.67	0.86	61.82	1.00	21.36	n.d.	4.94	99.19
#33	2.85	6.29	3.47	0.77	60.43	0.67	25.09	n.d.	0.31	99.88
#34	2.94	5.91	3.01	0.78	59.00	0.83	28.06	n.d.	n.d.	100.54
#35	2.72	6.02	2.05	0.75	61.55	1.18	21.11	n.d.	4.69	100.06
#36	2.74	6.01	3.30	0.73	59.28	0.88	25.06	n.d.	1.82	99.82
#37	2.58	5.88	3.27	0.71	59.92	0.59	27.24	n.d.	0.47	100.67
#38	3.72	5.67	3.19	0.75	58.43	0.86	26.03	n.d.	0.51	99.16
#39	5.48	6.34	2.89	0.67	59.83	0.61	23.07	n.d.	0.80	99.68
#40	3.01	6.21	3.26	0.69	58.38	0.95	26.39	n.d.	1.35	100.24
#41	2.58	6.53	2.11	0.84	58.82	0.82	27.47	n.d.	0.30	99.47
#42	2.63	6.03	3.17	0.62	59.34	0.84	26.84	n.d.	0.46	99.95
#43	3.36	6.19	3.21	0.70	58.67	0.69	27.11	n.d.	n.d.	99.93
#44	2.44	6.22	3.40	0.76	60.67	0.75	23.60	n.d.	1.19	99.04
#45	3.34	5.86	2.35	0.84	61.53	0.94	20.16	n.d.	5.60	100.62
#46	2.77	6.04	3.30	0.83	58.60	0.93	24.99	n.d.	2.06	99.52
#47	2.93	6.17	3.22	0.76	58.12	1.17	24.93	n.d.	3.30	100.60
#48	2.76	6.33	3.02	0.85	59.32	0.84	23.56	n.d.	3.80	100.48
#49	2.75	6.06	3.37	0.77	59.07	0.83	22.31	n.d.	4.07	99.23
#50	2.53	6.30	3.50	0.77	60.81	0.71	25.67	n.d.	n.d.	100.29
#51	2.18	6.46	2.93	0.85	60.55	0.79	25.38	n.d.	0.48	99.63
#52	2.81	6.39	2.88	0.83	59.93	0.85	21.86	n.d.	4.63	100.16
#53	2.30	5.87	3.56	0.68	60.08	0.77	24.64	n.d.	2.02	99.92
#54	2.15	5.89	3.04	0.68	60.50	0.93	26.57	n.d.	0.46	100.22
#55	2.66	6.18	2.60	0.86	59.31	0.86	27.13	n.d.	0.53	100.13

#56	3.20	5.83	2.83	0.76	58.22	0.88	26.91	n.d.	0.85	99.47
#57	3.14	6.10	3.31	0.75	58.65	0.78	26.83	n.d.	0.47	100.02
#58	3.00	5.93	2.96	0.65	57.61	0.81	28.24	n.d.	n.d.	99.20
#59	5.65	5.72	2.91	0.71	58.86	0.87	24.82	n.d.	0.25	99.80
#60	4.94	6.01	3.95	0.80	57.95	0.77	24.81	n.d.	0.22	99.44
#61	2.02	6.05	3.30	0.82	59.67	0.57	27.56	n.d.	n.d.	100.00
#62	2.84	6.08	3.26	0.67	59.66	0.82	24.81	n.d.	1.65	99.79
#63	2.53	6.25	3.21	0.89	59.69	1.23	21.07	n.d.	4.71	99.57
#64	2.90	6.22	2.73	0.90	59.07	0.85	26.53	n.d.	0.77	99.96
#65	2.42	6.11	3.08	0.67	58.92	1.12	18.28	n.d.	8.40	99.01
#66	2.70	5.67	3.30	0.63	57.95	0.79	28.61	n.d.	0.65	100.30
#67	0.93	6.29	2.45	0.89	62.38	n.d.	26.68	n.d.	n.d.	99.61
#68	1.34	5.19	2.85	0.66	60.57	0.67	27.64	n.d.	n.d.	98.93
#69	2.23	6.50	2.92	0.69	59.59	0.80	27.73	n.d.	0.36	100.82
#70	2.16	6.11	3.13	0.81	59.82	0.68	25.76	n.d.	1.44	99.90
#71	1.49	5.50	2.16	0.95	61.05	0.83	27.22	n.d.	0.30	99.50
#72	2.30	5.73	2.62	0.95	61.16	1.04	25.92	n.d.	0.66	100.39
#73	1.68	7.19	2.77	0.86	62.24	0.62	24.60	n.d.	n.d.	99.96
#74	2.66	6.47	2.94	0.84	60.48	0.91	23.41	n.d.	2.89	100.60
#75	2.24	6.11	3.46	0.75	61.96	0.78	23.82	n.d.	0.80	99.91
#76	2.37	6.41	3.34	0.78	61.95	0.96	22.74	n.d.	1.35	99.90
#77	2.15	5.91	3.01	0.67	58.81	0.88	28.94	n.d.	n.d.	100.38
#78	1.36	7.63	4.07	0.73	64.93	0.60	20.98	n.d.	0.32	100.63
#79	1.54	6.40	3.30	0.73	62.20	n.d.	24.55	n.d.	0.16	98.88
#80	4.98	5.78	2.86	0.65	58.07	0.81	25.64	n.d.	n.d.	98.80
#81	3.11	5.89	3.21	0.78	58.66	0.96	27.26	n.d.	0.67	100.54
#82	3.05	6.02	3.26	0.66	59.88	1.01	23.08	n.d.	2.80	99.77
#83	2.54	5.92	2.98	0.68	58.39	0.80	28.83	n.d.	0.62	100.76
#84	2.70	5.88	3.56	0.75	59.25	0.72	26.90	n.d.	n.d.	99.75
#85	2.26	5.97	2.72	0.81	59.26	0.79	27.97	n.d.	0.67	100.45
#86	3.36	5.88	3.57	0.71	59.96	0.69	26.80	n.d.	n.d.	100.98
#87	2.12	6.32	3.01	0.78	58.77	0.63	27.97	n.d.	0.05	99.65
#88	2.23	5.74	3.27	0.75	59.86	0.76	27.30	n.d.	n.d.	99.91
#89	3.27	5.87	2.71	0.74	58.23	1.01	26.52	n.d.	0.37	98.72
#90	3.20	5.70	3.04	0.59	58.11	0.92	26.55	n.d.	1.02	99.12
#91	2.27	5.81	3.36	0.61	57.65	0.95	27.80	n.d.	0.52	98.97
#92	2.46	5.84	3.20	0.68	58.57	n.d.	28.17	n.d.	0.36	99.29
#93	2.22	6.22	3.12	0.74	59.45	0.77	26.81	n.d.	0.69	100.02
#94	2.44	6.15	2.93	0.78	57.53	0.85	27.22	n.d.	2.12	100.02
#95	2.17	6.48	2.40	0.82	60.01	0.69	25.00	n.d.	1.85	99.41
#96	2.81	5.78	3.18	0.67	57.69	0.83	28.48	n.d.	n.d.	99.45
#97	1.88	5.94	3.42	0.77	60.71	n.d.	25.74	n.d.	0.49	98.94
#98	2.73	6.21	2.55	0.77	57.85	1.12	28.67	n.d.	0.86	100.76
#99	2.77	5.77	2.92	0.79	57.58	0.94	27.52	n.d.	1.16	99.45
#100	2.43	5.94	3.07	0.79	58.98	0.77	27.13	n.d.	1.49	100.60
#101	2.80	5.54	3.31	0.64	59.20	0.80	24.42	n.d.	2.48	99.18
#102	2.71	6.21	2.81	0.96	59.96	0.77	22.11	n.d.	4.17	99.71
#103	2.46	5.89	3.07	0.90	59.01	0.72	27.19	n.d.	0.61	99.85
#104	2.48	5.95	3.02	0.72	57.62	0.88	28.88	n.d.	0.47	100.03
#105	3.33	6.37	2.98	0.84	58.90	0.60	25.66	n.d.	0.33	99.01
#106	2.90	5.90	3.23	0.69	58.94	0.64	28.03	n.d.	0.51	100.84
#107	2.29	5.73	2.71	0.89	58.25	0.95	27.96	n.d.	0.94	99.73
#108	2.09	6.37	2.74	0.88	59.52	1.02	27.28	n.d.	0.43	100.33
#109	2.69	6.40	1.98	0.75	59.61	1.07	18.04	n.d.	9.15	99.69
#110	2.50	6.01	3.13	0.77	59.50	0.75	26.27	n.d.	0.65	99.58
#111	2.30	5.92	3.22	0.71	59.47	0.81	26.34	n.d.	1.45	100.22

#112	2.77	6.21	2.57	0.76	59.73	1.06	26.56	n.d.	0.83	100.49
#113	2.58	5.88	3.19	0.65	59.43	0.92	25.99	n.d.	1.70	100.33
#114	2.38	6.26	1.27	0.88	62.23	1.11	17.98	n.d.	7.31	99.42
#115	3.15	6.72	2.53	0.79	57.93	0.83	27.86	n.d.	0.19	99.99
#116	2.29	6.14	3.41	0.79	60.27	0.66	27.25	n.d.	0.20	101.00
#117	3.07	5.61	2.62	0.62	58.76	0.70	28.76	n.d.	0.29	100.43
#118	2.84	5.93	2.93	0.59	57.95	0.75	29.40	n.d.	n.d.	100.40
#119	4.83	5.26	3.67	0.84	58.47	0.80	26.13	n.d.	0.56	100.56
#120	2.24	5.68	3.08	0.69	58.00	0.82	28.80	n.d.	0.78	100.08
#121	5.06	6.16	3.05	0.73	58.71	0.70	25.40	n.d.	n.d.	99.80
#122	2.04	6.05	3.58	0.82	59.84	0.64	26.80	n.d.	0.40	100.17
#123	2.74	6.12	3.43	0.78	59.89	0.86	21.89	n.d.	4.12	99.83
#124	5.84	6.47	2.79	0.73	60.69	0.74	21.46	n.d.	0.88	99.61

[a] Grain lost during sample handling. Normalized to 100.00% from preliminary analysis result of 97.04%.
[b] Grain lost during polishing. Normalized to 100.00% from preliminary analysis result of 96.97%.
[c] Grain lost during polishing. Normalized to 100.00% from preliminary analysis result of 97.55%.

Appendix Table 2. Chemical composition (compound wt% ± 1 s.d.) of sediment-dispersed other chromium-rich spinel (OC) grains in samples from Lynna River. n.d. = not detected.

Sample Grain #	MgO	Al_2O_3	TiO_2	V_2O_3	Cr_2O_3	MnO	FeO	NiO	ZnO	Total
28U										
#1	10.13	17.84	0.95	0.51	50.93	0.56	19.04	n.d.	n.d.	99.96
#2	3.58	8.78	0.88	0.52	59.28	n.d.	26.72	n.d.	n.d.	99.76
Ly1										
#1	2.13	3.89	3.88	0.23	10.31	n.d.	76.1	n.d.	n.d.	96.53
#2	8.92	32.24	0.65	0.34	25.66	n.d.	31.06	n.d.	0.47	99.32
Ly2Ö										
#1	6.04	20.53	n.d.	0.24	49.96	n.d.	22.46	n.d.	n.d.	99.22
#2	11.24	35.42	0.37	n.d.	30.61	0.41	20.68	n.d.	n.d.	98.74
Ly4 (preliminary analyses)										
#1	4.09	12.87	2.86	n.d.	53.73	0.66	23.40	n.d.	n.d.	97.61
#2	2.03	7.19	2.29	0.78	33.13	n.d.	54.39	n.d.	n.d.	99.75
#3	1.98	11.25	2.47	n.d.	50.75	n.d.	31.59	n.d.	n.d.	98.04
Ly5										
#1	11.95	24.12	0.65	n.d.	42.96	n.d.	20.84	n.d.	n.d.	100.54
#2	3.03	7.96	0.34	0.94	61.06	0.77	23.10	n.d.	2.73	99.92
#3	9.86	27.25	0.88	0.30	37.87	0.52	22.54	n.d.	n.d.	99.23

Tidigare skrifter i serien "Examensarbeten i Geologi vid Lunds Universitet":

237. Brodén, Olof, 2008: Primär och sekundär migration av hydrokarboner. (15 hskp)
238. Bergman, Bo, 2009: Geofysiska analyser (stångslingram, CVES och IP) av lagerföljd och lakvattenrörelser vid Albäcksdeponin, Trelleborg. (30 hskp)
239. Mehlqvist, Kristina, 2009: The spore record of early land plants from upper Silurian strata in Klinta 1 well, Skåne, Sweden. (45 hskp)
240. Bjärnborg, Karolina, 2009: The copper sulphide mineralization of the Zinkgruvan deposit, Bergslagen, Sweden. (45 hskp)
241. Stenberg, Li, 2009: Historiska kartor som hjälp vid jordartsgeologisk kartering – en pilotstudie från Vångs by i Blekinge. (15 hskp)
242. Nilsson, Mimmi, 2009: Robust U-Pb baddeleyite ages of mafic dykes and intrusions in southern West Greenland: constraints on the coherency of crustal blocks of the North Atlantic Craton. (30 hskp)
243. Hult, Elin, 2009: Oligocene to middle Miocene sediments from ODP leg 159, site 959 offshore Ivory Coast, equatorial West Africa. (15 hskp)
244. Olsson, Håkan, 2009: Climate archives and the Late Ordovician Boda Event. (15 hskp)
245. Wollein Waldetoft, Kristofer, 2009: Svekofennisk granit från olika metamorfa miljöer. (15 hskp)
246. Månsby, Urban, 2009: Late Cretaceous coprolites from the Kristianstad Basin, southern Sweden. (15 hskp)
247. MacGimpsey, I., 2008: Petroleum Geology of the Barents Sea. (15 hskp)
248. Jäckel, O., 2009: Comparison between two sediment X-ray Fluorescence records of the Late Holocene from Disko Bugt, West Greenland; Paleoclimatic and methodological implications. (45 hskp)
249. Andersen, Christine, 2009: The mineral composition of the Burkland Cu-sulphide deposit at Zinkgruvan, Sweden – a supplementary study. (15 hskp)
250. Riebe, My, 2009: Spinel group minerals in carbonaceous and ordinary chondrites. (15 hskp)
251. Nilsson, Filip, 2009: Föroreningsspridning och geologi vid Filborna i Helsingborg. (30 hskp)
252. Peetz, Romina, 2009: A geochemical characterization of the lower part of the Miocene shield-building lavas on Gran Canaria. (45 hskp)
253. Åkesson, Maria, 2010: Mass movements as contamination carriers in surface water systems – Swedish experiences and risks.
254. Löfroth, Elin, 2010: A Greenland ice core perspective on the dating of the Late Bronze Age Santorini eruption. (45 hskp)
255. Ellingsgaard, Óluva, 2009: Formation Evaluation of Interlava Volcaniclastic Rocks from the Faroe Islands and the Faroe-Shetland Basin. (45 hskp)
256. Arvidsson, Kristina, 2010: Geophysical and hydrogeological survey in a part of the Nhandugue River valley, Gorongosa National Park, Mozambique. (45 hskp)
257. Gren, Johan, 2010: Osteo-histology of Mesozoic marine tetrapods – implications for longevity, growth strategies and growth rates. (15 hskp)
258. Syversen, Fredrikke, 2010: Late Jurassic deposits in the Troll field. (15 hskp)
259. Andersson, Pontus, 2010: Hydrogeological investigation for the PEGASUS project, southern Skåne, Sweden. (30 hskp)
260. Noor, Amir, 2010: Upper Ordovician through lowermost Silurian stratigraphy and facies of the Borenshult-1 core, Östergötland, Sweden. (45 hskp)
261. Lewerentz, Alexander, 2010: On the occurrence of baddeleyite in zircon in silica-saturated rocks. (15 hskp)
262. Eriksson, Magnus, 2010: The Ordovician Orthoceratite Limestone and the Blommiga Bladet hardground complex at Horns Udde, Öland. (15 hskp)
263. Lindskog, Anders, 2010: From red to grey and back again: A detailed study of the lower Kundan (Middle Ordovician) 'Täljsten' interval and its enclosing strata in Västergötland, Sweden. (15 hskp)
264. Rääf, Rebecka, 2010: Changes in beyrichiid ostracode faunas during the Late Silurian Lau Event on Gotland, Sweden. (30 hskp)
265. Petersson, Andreas, 2010: Zircon U-Pb, Hf and O isotope constraints on the growth versus recycling of continental crust in

the Grenville orogen, Ohio, USA. (45 hskp)

266. Stenberg, Li, 2010: Geophysical and hydrogeological survey in a part of the Nhandugue River valley, Gorongosa National Park, Mozambique – Area 1 and 2. (45 hskp)

267. Andersen, Christine, 2010: Controls of seafloor depth on hydrothermal vent temperatures - prediction, observation & 2D finite element modeling. (45 hskp)

268. März, Nadine, 2010: When did the Kalahari craton form? Constraints from baddeleyite U-Pb geochronology and geo-chemistry of mafic intrusions in the Kaapvaal and Zimbabwe cratons. (45 hskp)

269. Dyck, Brendan, 2010: Metamorphic rocks in a section across a Svecnorwegian eclogite-bearing deformation zone in Halland: characteristics and regional context. (15 hskp)

270. McGimpsey, Ian, 2010: Petrology and lithogeochemistry of the host rocks to the Nautanen Cu-Au deposit, Gällivare area, northern Sweden. (45 hskp)

271. Ulmius, Jan, 2010: Microspherules from the lowermost Ordovician in Scania, Sweden – affinity and taphonomy. (15 hskp)

272. Andersson, Josefin, Hybertsen, Frida, 2010: Geologi i Helsingborgs kommun – en geoturistkarta med beskrivning. (15 hskp)

273. Barth, Kilian, 2011: Late Weichselian glacial and geomorphological reconstruction of South-Western Scania, Sweden. (45 hskp)

274. Mashramah, Yaser, 2011: Maturity of kerogen, petroleum generation and the application of fossils and organic matter for paleotemperature measurements. (45 hskp)

275. Vang, Ina, 2011: Amphibolites, structures and metamorphism on Flekkerøy, south Norway. (45 hskp)

276. Lindvall, Hanna, 2011: A multi-proxy study of a peat sequence on Nightingale Island, South Atlantic. (45 hskp)

277. Bjerg, Benjamin, 2011: Metodik för att förhindra metanemissioner från avfalls-deponier, tillämpad vid Albäcksdeponin, Trelleborg. (30 hskp)

278. Pettersson, Hanna, 2011: El Hicha – en studie av saltstäppssediment. (15 hskp)

279. Dyck, Brendan, 2011: A key fold structure within a Sveconorwegian eclogite-bearing deformation zone in Halland, south-western Sweden: geometry and tectonic implications. (45 hskp)

280. Hansson, Anton, 2011: Torvstratigrafisk studie av en trädstamshorisont i Viss mosse, centrala Skåne kring 4 000 - 3 000 cal BP med avseende på klimat- och vattenståndsförändringar. (15 hskp)

281. Åkesson, Christine, 2011: Vegetations-utvecklingen i nordvästra Europa under Eem och Weichsel, samt en fallstudie av en submorän, organisk avlagring i Bellinga stenbrott, Skåne. (15 hskp)

282. Silveira, Eduardo M., 2011: First precise U-Pb ages of mafic dykes from the São Francisco Craton. (45 hskp)

283. Holm, Johanna, 2011: Geofysisk utvärdering av grundvattenskydd mellan väg 11 och Vombs vattenverk. (15 hskp)

284. Löfgren, Anneli, 2011: Undersökning av geofysiska metoders användbarhet vid kontroll av den omättade zonen i en infiltrationsdamm vid Vombverket. (15 hskp)

285. Grenholm, Mikael, 2011: Petrology of Birimian granitoids in southern Ghana - petrography and petrogenesis. (15 hskp)

286. Thorbergsson, Gunnlaugur, 2011: A sedimentological study on the formation of a hummocky moraine at Törnåkra in Småland, southern Sweden. (45 hskp)

287. Lindskog, Anders, 2011: A Russian record of a Middle Ordovician meteorite shower: Extraterrestrial chromite in Volkhovian-Kundan (lower Darriwilian) strata at Lynna River, St. Petersburg region. (45 hp)

LUNDS UNIVERSITET

Geologiska enheten
Institutionen för geo- och ekosystemvetenskaper
Sölvegatan 12, 223 62 Lund