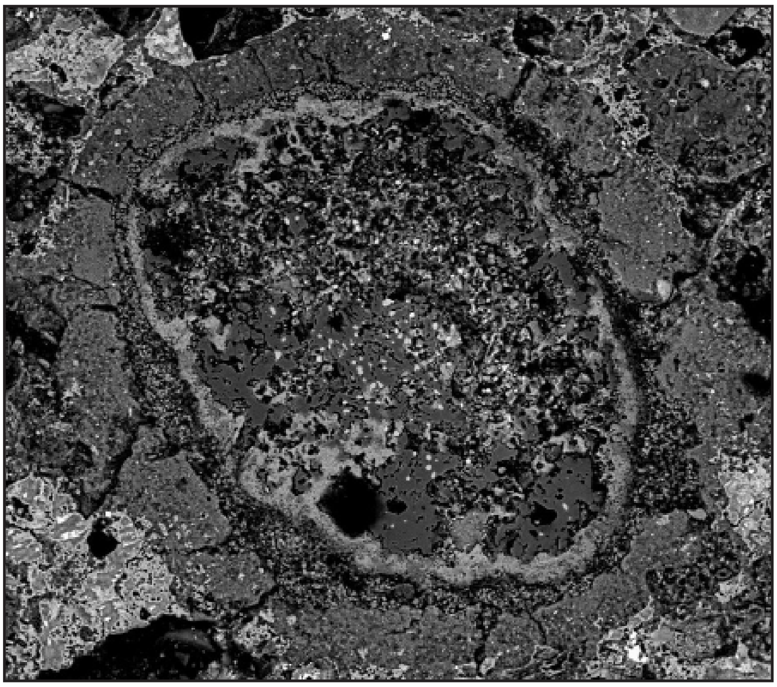
Spinel group minerals in carbonaceous and ordinary chondrites

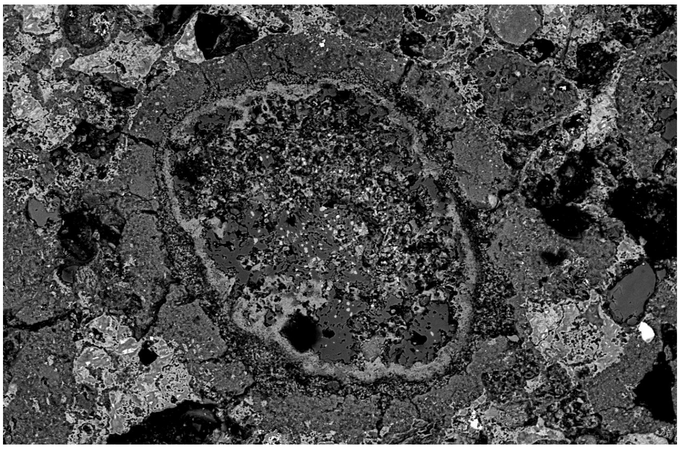
My Riebe

**Examensarbete i geologi vid Lunds Universitet - Berggrundsgeologi, no. 250
(15 hskp/ECTS)**



**Geologiska institutionen
Centrum för GeoBiosfärsvetenskap
Lunds universitet
2009**

Spinel group minerals in carbonaceous and ordinary chondrites



Bachelor Thesis
My Riebe

Department of Geology
Lund University
2009

Contents

Cover Picture: Backscattered image of spinel-rich CAI in NWA 4428 (CM2)

Spinel group minerals in carbonaceous and ordinary chondrites

MY RIEBE

Riebe, M., 2009: Spinel group minerals in carbonaceous and ordinary chondrites. *Examensarbeten i geologi vid Lunds universitet*, Nr. 250, 29pp. 15 ECTS.

Abstract: Meteorites are easily altered in the oxygen-rich environment on the Earth surface. Fossil meteorites are thus uncommon and in the ones, which are found, almost all minerals are secondary. However, the spinel group mineral chromite is resistant to alteration and has successfully been used as a proxy for ordinary chondrites in sediment. The frequency and composition range of spinel group minerals in carbonaceous chondrites are not known well enough to be used as proxies for carbonaceous chondrites. Two carbonaceous chondrites NWA 4428 (CM2) and Allende (CV3) have been systematically investigated in order to determine the frequencies of the spinel group minerals in each chondrite, where in the chondrites the spinel group minerals are located and size and composition of the minerals. The long term aim of this project is to establish a method for detecting spinel group minerals from carbonaceous chondrites in sediment, thus being able to constrain the flux of carbonaceous chondrites further. For references and to compare with previous studies two ordinary chondrites, Jilin (H5) and Mbale (L5/6) were studied in the same way.

Spinel is the most common spinel group mineral in the two carbonaceous chondrites investigated here, whereas chromite is the most common spinel group mineral in the two ordinary chondrites. Spinel is not present in the ordinary chondrites. Chromite is present in the carbonaceous chondrites but is considerably smaller than chromite in the ordinary chondrites (~25 µm compared to ~270 µm). Carbonaceous chondritic chromite also has a larger variety in composition than ordinary chondritic chromite, which is due to the higher amount of thermal metamorphism on the ordinary chondrite parent bodies than the carbonaceous chondrite parent bodies. Spinel in NWA 4428 is essentially pure $MgAl_2O_4$ whereas spinel in Allende varies from pure $MgAl_2O_4$ to FeO contents as high as 24.0 wt%. Magnetite is present in Allende and in Mbale; in Allende, both as spherule and as poorly defined grains with a secondary nature. In Mbale, magnetite only occurs as grains with a secondary nature. In Jilin (H5) Cr-spinel occurs in one aggregate.

To detect extraterrestrial spinel group minerals in sediment, these have to differ from their terrestrial equivalents. To distinguish the CM2 and CV3 spinel analysed here from terrestrial spinel on compositional bases is probably not possible. The carbonaceous chondritic chromite displays a larger variety of compositions than chromite in ordinary chondrites and is therefore probably less suitable as a proxy than chromite in ordinary chondrites. Magnetite spherules in Allende (CV3) appear to have a composition distinct from terrestrial magnetite. Magnetite might however be unsuitable as a proxy due to oxidation on the Earth surface. Further studies are needed in order to get a clear picture of the compositions of spinel group minerals in carbonaceous chondrites.

Keywords: spinel group minerals, carbonaceous chondrites, ordinary chondrites

My Riebe, Department of Geology, GeoBiosphere Science Centre, Lund University, Sölvegatan 12, SE-223 62 Lund, Sweden. E-mail: m_y_r@hotmail.com

Spinellgruppmineral i kolkondriter och ordinära kondriter

MY RIEBE

Riebe, M., 2009: Spinel group minerals in carbonaceous and ordinary chondrites. *Examensarbeten i geologi vid Lunds universitet*, Nr. 250, 29 sid. 15 högskolepoäng.

Sammanfattning: Meteoriter omvandlas lätt i den syrerika miljö som råder på Jorden. Fossila meteoriter är därför ovanliga och de fossila meteoriter som hittats består nästan uteslutande av sekundära mineral. Det finns dock ett spinellgruppmineral, kromit, som är resistent mot omvandling och som med framgång använts som indikator för ordinära kondriter i sediment. Spinellgruppmineral i kolkondriter är inte tillräckligt väldokumenterade när det gäller hur stor andel av meteoriter de utgör och vilka sammansättningar de har, för att kunna användas som indikatorer. Två kolkondriter, NWA 4428 (CM2) och Allende (CV3) har undersökts systematiskt för att avgöra frekvensen av spinellgruppmineral i respektive kondrit, var i kondriterna spinellgruppmineralen finns samt storlek och sammansättning på mineralen. Det långsiktiga målet med det här projektet är att upprätta en metod för att hitta spinellgruppmineral från kolkondriter i sediment och använda dem för att detektera förändringar i inflödet av kolkondriter till jorden. Som referens och för att kunna göra jämförelser med tidigare kvantitativa studier studerades två ordinära kondriter (Jilin H5 och Mbale L5/6) på samma vis som kolkondriterna.

Spinell är det vanligaste spinellgruppmineralet i de två kolkondriter som studerades medan kromit är det vanligaste spinellgruppmineralet i de ordinära kondriter som studerades. Spinell återfanns inte i de ordinära kondriterna. Kromit finns i kolkondriterna, men har betydligt mindre diameter än kromiten i de ordinära kondriterna (25 µm jämfört med ~270 µm). Kromit i kolkondriterna har även en mer varierad sammansättning än kromit i ordinära kondriter, vilket beror på att de ordinära kondriterna är mer termalt omvandlade än kolkondriterna. Spinell i NWA 4428 är i princip ren $MgAl_2O_4$ medan spinell i Allende varierar från nästan helt ren $MgAl_2O_4$ till FeO koncentrationer på 24,0 vikt%. Magnetit finns i Allende och i Mbale. I Allende förekommer magnetit både som sfäruler och som dåligt definierade korn som ser ut att vara sekundära. I Mbale återfinns magnetit enbart som korn som ser ut att vara sekundära. Cr-spinell hittades i ett aggregat i Jilin (H5).

För att ett mineral ska kunna användas som indikator för kolkondriter i sediment måste det gå att skilja från dess terrestriska motsvarigheter. Den spinell i kolkondriter som analyserats här har en sammansättning som också påträffas på jorden. Dessa spineller är således förmodligen olämpliga som indikatorer för kolkondriter. Kromit i kolkondriter har en varierande sammansättning och är därför troligtvis svårare att skilja från terrestrisk kromit än kromit i ordinära kondriter. Magnetit i spheruler i Allende (CV3) har en sammansättning som inte ser ut att förekomma på jorden. Magnetit oxideras dock på jordytan och det är möjligt att magnetit därför inte går att använda. Ytterligare studier behövs för att få fram en tydlig bild av sammansättningen på spinellgruppmineral i kolkondriter och för att med säkerhet avgöra om dessa går att använda för att göra antaganden om förändringar i inflödet av kolkondriter till jorden eller ej.

Nyckelord: spinellgruppmineral, kolkondriter, ordinära kondriter

My Riebe, Geologiska Institutionen, Centrum för GeoBiosfärsvetenskap, Lunds Universitet, Sölvegatan 12, 223 62 Lund, Sverige. E-post: m_y_r@hotmail.com

1 Introduction

The input of cosmic material to Earth today is estimated to 30,000 ± 15,000 tons per year (Peucker-Ehrenbrink & Ravizza 2000). The cosmic material can be divided into two major groups; dust particles (0.05-0.5 mm) and meteorites. Both are important contributors to the influx of cosmic material (Zanda & Rotaru 2001), but only meteorites are considered here. Most common of the recent meteorites are chondrites which comprise over 80 % of the modern falls (Bevan et al. 1998, and references therein). Chondrites are built up by spherical to subspherical objects known as chondrules. Chondrules are believed to have formed directly from the solar nebula. Chondrites have not been differentiated, in contrast to rocks on Earth and differentiated meteorites e.g. iron meteorites.

Most common of the chondrites are the ordinary chondrites, they comprise ~94 % of the modern chondrite falls and finds (Bevan et al. 1998, and references therein). Previous studies have shown that the flux of cosmic material has not been constant through Earth´s history (e.g. Schmitz et al. 1997, Farley et al. 1998, Schmitz & Häggström 2006). However, changes in the rate of cosmic input are hard to determine due to the fact that meteorites alter easily on the Earth surface. Even though most cosmic material is altered on the Earth surface, some minerals in meteorites are resistant to alteration, one such mineral is the spinel group mineral chromite. In ordinary chondrites, chromite has a composition, which differs from that of chromite crystallised on Earth. This makes it possible to distinguish ordinary chondritic chromite from terrestrial chromite based on chemistry. Chromite has successfully been used to determined changes in the flux of ordinary chondrites to the Earth (e.g. Schmitz & Häggström 2006).

Carbonaceous chondrites comprise ~1% of the recent meteorites (Bevan et al. 1998, and references therein), but might have been more common earlier in Earth´s history. Isotopic studies of W and Cr (Shukolyukov & Lugmair 1998, Quitté et al. 2007) and the nature of Ir host-phases (Schurayatz et al. 1997) at the K/T-boundary indicate that the projectile which resulted in the extinction of the dinosaurs probably was a carbonaceous chondrite. The composition and size distribution of spinels, primarily chromite, in ordinary chondrites is well known (e.g. Snetsinger et al. 1967, Wlotzka 2005, Bridges et al. 2007) but no quantitative studies on spinel group minerals in carbonaceous chondrites have been published.

Three spinel group minerals are known from carbonaceous chondrites; magnetite, spinel and chromite. Most of the spinel in carbonaceous chondrites is situated in Calcium-Aluminium-rich inclusions (CAIs). The amount of CAIs varies widely in between carbonaceous chondrite groups (Brearley & Jones 1998). Chromite is situated in olivine chondrules and differs in composition from chromite in ordinary chondrites (Bunch et al. 1967, Fuchs et al. 1973). The abundance of magnetite varies widely within the carbonaceous chondrite class (Brearley & Jones 1998).

Today, no mineral, which survives on the Earth surface and has a composition distinct from terrestrial compositions is known from carbonaceous chondrites. Some of the spinel group minerals might however hold the desirable characteristics; spinels are known to be resistant to alteration and have a structure which allows a wide variety of compositions. In this study spinel group minerals in two carbonaceous chondrites, one belonging to the CM2 group (NWA 4428) and one belonging to the CV3 group (Allende), are investigated. Spinel group minerals in two ordinary chondrites (Jilin H5 and Mbale L5/6) are also studied; the results are used as a reference and are compared with results from earlier quantitative studies of spinel group minerals in ordinary chondrites.

This study aims to answer four questions:

- Which spinel group minerals are found in carbonaceous and ordinary chondrites?
- How frequent are the different spinel group minerals in the chondrites?
- Where in the chondrites are the spinel group minerals located?
- What are the characteristics of the spinel group minerals in the form of composition and size?

The long term aim of this project is to establish a method for detecting spinels from carbonaceous chondrites in sedimentary rocks, thus being able to constrain the flux of carbonaceous chondrites further.

2 Background

2.1 Classification of chondrites

There are two major types of meteorites; chondrites and differentiated meteorites. The differentiated meteorites originate from bodies which, like the Earth, have been melted and differentiated into a high density core and lower density outer parts. Chondrites on the other hand have not been melted after the accretion but retained a pristine chemical composition and morphology. Chondrites are divided into three main classes; carbonaceous chondrites, ordinary chondrites and enstatite chondrites, see Fig. 1. The chondrite classes are further divided into groups based on mineralogy, bulk chemistry, oxidation state and isotopic compositions (Perron & Zanda 2005). Van Schmus & Wood (1967) developed a classification system based on the degree and nature of secondary alteration of chondrites which is used together with the classes and groups. In the Van Schmus & Wood classification, chondrites are organised into different petrologic types (1-6), were type 3 is the least altered chondrites. Types 1 and 2 have been subjected to aqueous alteration, type 1 more than type 2. Type 4-6 represent increasing thermal metamorphism. The chondrite classification system is visualised in Fig. 1.

Carbonaceous chondrites are the chemically most pristine of all meteorites. They resemble the sun in their chemical composition and are high in refractory lithophile elements (Perron & Zanda 2005). Carbonaceous chondrites consist of chondrules, calcium-aluminium-rich inclusions (CAIs), metal and matrix in different proportions. Most carbonaceous chondrites are aqueously altered or weakly thermally altered (Hutchison 2004); aqueously altered chondrites have a phyllosilicate-rich matrix; thermally altered chondrites contain a matrix rich in olivine (Brearley & Jones 1998). The carbonaceous chondrite class is divided into seven groups; CI, CM, CR, CO, CV, CK and CH. The groups are named after one type meteorite fall within each group e.g. CV chondrites are named after the Vigarano meteorite (Hutchison 2004). Each carbonaceous chondrite group has its own characteristics; CI chondrites consist of 99 % phyllosilicates-rich matrix, CM chondrites have small chondrules in a phyllosilicate-rich matrix, CR chondrites also have a phyllosilicate-rich matrix but contain larger chondrules than CM chondrites. CO chondrites and CV chondrites have an olivine-rich matrix; CO chondrites have small chondrules whereas CV chondrites have larger chondrules. CH chondrites are richer in metal than the other chondrite groups. In CK chondrites, metal is almost absent (Hutchison 2004).

Ordinary chondrites consist of chondrules, matrix, variable amounts of metal and rarely of CAIs, they are unmetamorphosed to thermally metamorphosed (Hutchison 2004). The ordinary chondrite class is divided into three groups; H, L and LL chondrites (Brearley & Jones 1998). H chondrites are the most reduced of the ordinary chondrites and LL chondrites are the most oxidised. From H to L to LL ordinary chondrite groups there is a decrease in metal content, an increase in nickel-content in the metal, an increase in FeO content in olivine and an increase in olivine relative to Ca-poor pyroxene (Hutchison 2004).

Enstatite chondrites consist of chondrules, metal, sulphide and little or no low-temperature matrix. Enstatite chondrites are highly reduced and may be unmetamorphosed or thermally metamorphosed. Enstatite chondrites are divided into two groups based on their iron content, EH, which is high in iron and EL, which is low in iron. EH chondrites are more depleted in refractory lithophile elements and have smaller chondrules than EL chondrites (Hutchison 2004).

2.2 Chondrite components

2.2.1 Chondrules

Chondrules are spherical to subspherical objects, 50 µm to several mm in diameter, which were once molten droplets in a low gravitational field (Perron & Zanda 2005). Chondrules are important components of chondrites. They comprise 60-80 vol% of ordinary chondrites and between 15 and 70 vol% of carbonaceous chondrites, with the exception of CI chondrites, which do not contain chondrules (Brearley & Jones 1998). Chondrule nomenclature is primarily based on mineral content and grain size. The most common types of chondrules are: porphyritic pyroxene chondrules, porphyritic olivine-pyroxene chondrules, granular olivine chondrules, barred olivine chondrules, radial pyroxene chondrules, and cryptocrystalline chondrules (Brearley & Jones 1998). Chondrules often consist of larger grains set in a fine-grained or glassy matrix, which is referred to as mesostasis. However, some chondrules e.g. cryptocrystalline chondrules do not contain any larger grains.

2.2.2 Calcium-aluminium-rich inclusions (CAIs)

CAIs have a size range from <1 mm to 2 cm and are in contrast to chondrules often irregular in shape (Grossman 1980). The variation in size is partly due to different amounts of fragmentation and many CAIs are fragments of once larger objects (Greenwood et al. 1994). CAIs are much more common in the carbonaceous chondrite class than in the ordinary and enstatite chondrite classes (Brearley & Jones 1998), but are present in all groups except CI chondrites (Hutchison 2004). CAIs are rich in refractory elements and are believed to be the first solids formed in the solar system, by condensation and/or evaporation that occurred before, or right after, the formation of the sun (Perron & Zanda 2005). Many different kinds of CAIs have been described, primarily from CV carbonaceous chondrites in which the CAIs are most abundant and

Class	Carbonaceous chondrites							Ordinary chondrites			Enstatite chondrites	
Group	CI	CM	CR	CO	CV	CK	CH	H	L	LL	EH	EL
Petrologic type	1	1-2	1-3	3	2-3	3-6	2	3-6	3-6	3-6	3-6	3-6

Fig. 1. Chondrites organised into classes and groups. At the bottom the petrological types in which the groups have representatives (after Brearley & Jones 1998, Hutchison 2004)

also most diverse of all chondrite groups (Brearley & Jones 1998). The main minerals found in CAIs are *melilite* (solid solution series between *gehlenite* ($Ca_2Al(Si,Al)_2O_7$) and *åkermanite* ($Ca_2MgSi_2O_7$)), *spinel*, ($MgAl_2O_4$), *plagioclase* ($(Ca,Na,)(Al,Si)_4O_8$,) *olivine* ($(Mg,Fe)_2SiO_4$), *hibonite* ($CaAl_{12}O_{19}$), *perovskite* ($CaTiO_3$) and *fassaite* ($CaMgSi_2O_6$ enriched in Al and Ti, which mainly replace Si).

2.2.3 Matrix

The matrix of the chondrites is the material between chondrules, CAIs and isolated larger grains. The composition of the matrix varies between chondrite groups. Clastic matrix is composed of fragments of coarse-grained objects, such as chondrules. Non-clastic matrix is composed of low-temperature minerals such as iron-rich olivine and phyllosilicates (Hutchison 2004).

2.3 Spinel group minerals in carbonaceous and ordinary chondrites

2.3.1 Spinel group minerals

The spinel group minerals are built up by unit cells with 32 oxygen ions and 24 cations. Eight of the cations are situated in tetrahedral coordination and sixteen are in octahedral coordination (Deer et al. 1992). The general formula for a spinel unit cell is $X_8^{2+}Y_{16}^{3+}O_{32}$. Depending on the distribution of cations among the tetrahedral and octahedral positions, the spinel group minerals are divided into two subgroups; normal spinels and inverse spinels (Deer et al. 1992). In normal spinels the eight tetrahedral sites are occupied by the eight X^{2+} cations and the sixteen octahedral sites are occupied by the sixteen Y^{3+} cations. This gives the normal spinels the formula $X_8^{2+}Y_{16}^{3+}O_{32}$, or $X^{2+}Y_2^{3+}O_4$. In the inverse spinels the eight tetrahedral positions are occupied by eight of the Y^{3+} cations, and the remaining eight of the Y^{3+} cations together with the eight X^{2+} cations occupy the sixteen octahedral positions. The inverse spinels have the formula $Y_8^{3+}(Y_8^{3+}X_8^{2+})O_{32}$ or $Y^{3+}(Y^{3+}X^{2+})O_4$. Even though the spinel group minerals are divided into normal and inverse structure types, most spinel group minerals occurring in nature have a cations distribution which is somewhere in between normal and inverse (Klein & Hurlbut 1993).

The spinel group consists of 13 end-members among which solid solutions are common. Four of the spinel group minerals occur in carbonaceous and ordinary chondrites; *spinel* ($MgAl_2O_4$), *hercynite* ($Fe^{2+}Al_2O_4$), *chromite* ($Fe^{2+}Cr_2O_4$) and *magnetite* ($Fe^{2+}Fe_2^{3+}O_4$). They are summarised in Table 1 and described below. A continuous series between spinel and hercynite make spinels with variable amounts of Fe^{2+} substituting for Mg common. Also Zn may substitute for Mg, due to a solid solution series between spinel and *gahnite* ($ZnAl_2O_4$). Cr may replace Al in spinel going towards *magnesiochromite* ($MgCr_2O_4$). In hercynite it is possible to get some Fe^{3+} in the Al-position. There is a complete solid solution between hercynite and chromite (Deer et al. 1992), and it is common for chromite to contain some Al. Solid solution series between chromite and spinel is also complete, and chromite often contains considerable amounts of Mg, substituting for Fe^{2+}(Krot et al. 1993). Chromite may also contain some Fe^{3+} and Zn. In magnetite, small amounts of Al, Cr and V may substitute for Fe^{3+} and small amounts of Ca, Mn, Mg, Ni, Co and Zn may replace Fe^{2+}. There is a continuous series between magnetite and *ulvöspinel* (Fe_2TiO_4) and magnetite with considerable proportions of Ti exists (Deer et al. 1992). The end members and possible solid solutions are illustrated with the spinel prism, Fig. 2.

Due to the solid solution series within the spinel group the terminology is not always clear and tends to differ between authors, especially for the spinel group minerals which contain considerable amounts of Cr. Here chrome-rich spinels with a #Cr ((Cr/(Cr+Al) in mol%) $\geq$ 59 are referred to as chromite, whereas chrome-rich spinels with a #Cr <59 are referred to as Cr-spinel. This nomenclature makes it possible to distinguish between Cr-spinel and chromite in ordinary chondrites, but allows the wide range of chrome-rich spinels in carbonaceous chondrites to be processed together as chromite.

Table 1. The spinel group minerals that occur in ordinary and carbonaceous chondrites and the elements that are most likely to enter each mineral

Mineral	Cation	Most common substituting elements
Spinel $MgAl_2O_4$	Mg^{2+}	Fe^{2+}, Zn, V
	Al^{2+}	Cr
Hercynite $Fe^{2+}Al_2O_4$	Fe^{2+}	Mg
	Al^{3+}	Cr, Fe^{3+}
Chromite $Fe^{2+}Cr_2O_4$	Fe^{2+}	Mg, Zn
	Cr^{3+}	Al, Fe^{3+}
Magnetite $Fe^{2+}Fe_2^{3+}O_4$	Fe^{2+}	Ca, Mn, Mg, Ni, Co, Zn
	Fe^{3+}	Al, Cr, V, Ti

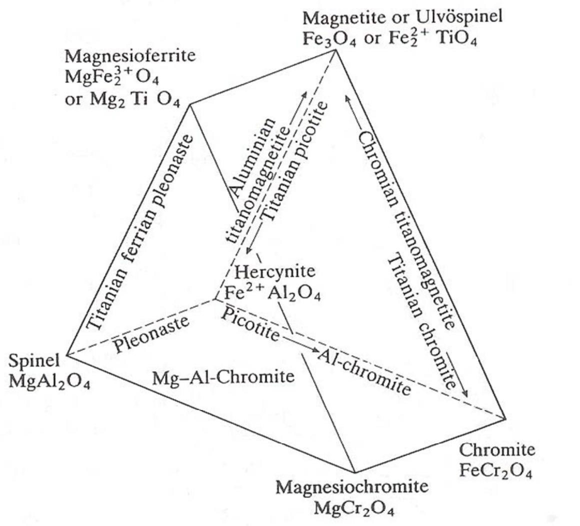


Fig. 2. Spinel prism shows the end members and possible solid solutions in the spinel group (Deer et al.1992)

2.3.2 Spinel group minerals in carbonaceous chondrites

The following is a general review over what is known about the spinel group minerals that occur in carbonaceous chondrites. For two reasons, focus is on CM and CV chondrites; first, because these are the two carbonaceous chondrite groups that have been studied here, see below. Second, because a large part of the research on spinel group minerals in carbonaceous chondrites have been performed on CM (mainly Murchison) and CV (mainly Allende).

Chromite

In carbonaceous chondrites, chromite is present in the matrix and in porphyritic olivine chondrules. Chromite grains in the matrix are small and angular (e.g. Fuchs et al. 1973, Brearley & Jones 1998). The porphyritic olivine chondrules, in which chromite occurs, are typically iron-rich, olivine has a large fayalitic component and is often zoned (McSween 1977a). The chromite grains in these chondrules are euhedral and have a size range from a few µm to tens of µm (Johnson & Prinz 1991). The olivine grains in the porphyritic olivine chondrules are considerably larger than the chromite grains. Chromite is often situated at the margins of, or partly included in, larger olivine crystals. The composition of chromite within the same chondrule and between chondrules varies (Johnson & Prinz 1991).

Johnson & Prinz (1991) studied compositions of chromite and olivine in porphyritic olivine chondrules from chondrites of different groups. They found that the composition of chromite in porphyritic olivine chondrules is dependent on the initial composition of the melt, from which the porphyritic olivine chondrule crystallised, and on the amount of thermal metamorphism experienced by the chondrite. CM chondrites and some CO and CV chondrites have not experienced thermal metamorphism. In these chondrites, chromite has maintained its primary composition. However, some CO and CV chondrites are thermally metamorphosed and have a chromite composition partly determined by the melt composition and partly by metamorphism (Johnson & Prinz 1991).

Analyses of chromite in Murchison (CM) and in Allende (CV3) show some variability from grain to grain and some common, prominent differences from chromite in ordinary chondrites (Fuchs et al. 1973, Brearley & Jones 1998 and references therein). Compared to the chromite in ordinary chondrites analysed by Bunch et al. (1967) and by Wlotzka (2005) the

Table 2. Range of element concentration of chromite in CM2 (Murchison), CV3 chondrites and, average element concentrations of chromite in H, L and LL chondrites

Class	MgO	Al_2O_3	TiO_2	V_2O_3	Cr_2O_3	MnO	FeO	ZnO
CM2*	1.3-8.1	3.2-22.3	0.5-1.7	0.4-0.8	41.9-60.2	0.2-0.3	25.4-32.9	n.d.
CV3¨	1.4-6.70	6.87-15.40	0.85-4.00	0-0.51	45.70-54.70	0-0.20	27.30-31.70	0-0.07
H**	2.66	5.9	2.33	0.68	56.9	0.94	31.2	n.d.
H˘	3.40	6.64	1.96	0.65	57.1	0.88	28.9	0.28
L**	1.99	5.3	2.81	0.72	56.1	0.74	33.0	n.d.
L˘	2.52	5.90	2.67	0.70	56.1	0.63	30.9	0.34
LL**	1.62	5.7	3.23	0.73	54.4	0.63	34.5	n.d.
LL˘	1.85	5.52	3.40	0.67	55.8	0.51	31.6	n.d.

*Data from Fuchs et al. (1973)
¨Data from Brearley & Jones (1998) and references therein
**Data from Bunch et al. (1967)
˘Data from Wlotzka (2005)
n.d.: not detected

chromite in Murchison and Allende are higher in Al_2O_3, and MgO and lower in Cr_2O_3, TiO_2 and FeO (Fuchs et al 1973, Brearley & Jones 1998 and references therein) , see Table 2.

Spinel

Most of the spinel in carbonaceous chondrites is situated in CAIs and is relatively small (10-30 µm; Simon et al. 1994). The amount of CAIs and the relative abundance of different kinds of CAIs vary widely with carbonaceous chondrite group. Most abundant and also most diverse are CAIs in the CV chondrites (Brearley & Jones 1998), but CAIs are also common in CO chondrites, a bit less frequent in CM and CK chondrites, rarely occurring in CR and CH chondrites and not present in CI chondrites (Brearley & Jones 1998). An orange-red, V-rich spinel with up to 5% V_2O_3 and 20% FeO is sometimes present in CV3 chondrites, in a type of CAIs referred to as "fluffy type A inclusions", based on their irregular shape due to heavy alteration of the unstable mineral melilite (Grossman 1980).

Fuchs et al. (1973) analysed spinels in Murchison (CM2), which display a relatively large variation in composition, from almost pure $MgAl_2O_4$ to Cr_2O_3 contents as high as 25.4 wt% and FeO contents as high as 10.9 wt%. Brearley & Jones (1998) published analyses of spinels in CAIs from CM and CV chondrites performed by various authors. These analyses are summarised in Table 3. All analyses of spinel from CAIs in CM chondrites published in Brearley & Jones (1998) are almost pure $MgAl_2O_4$. The majority of the spinels in CAIs in CV chondrites are also fairly pure $MgAl_2O_4$, but some spinels have FeO concentrations as high as 20.7 wt%. Small amounts of SiO_2, CaO and TiO_2 are present in most of the spinels. The majority of the spinels analysed contain small amounts of Cr_2O_3 (0-0.58 wt%). V_2O_3 is mostly low, with the exception of one grain, which contains 4.9 wt%.

In addition to the relatively small spinel grains that are present in CAIs, Murchison (CM2) also contains pale pink, larger spinel grains (60-325 µm), which do not appear to originate from CAIs (Simon et al. 1994). The larger spinel grains differ from the smaller ones in that they hold high amounts of chromium and iron (up to 35 wt% Cr_2O_3 and 17 wt% FeO).

In Murchison (CM2), spinel is present as an accessory phase in olivine chondrules (Fuchs et al. 1973). One example is Cr-spinel (20-50 µm) in Fe-poor porphyritic olivine chondrules with Al-diopside rich matrix. These chondrules are Al_2O_3-rich and FeO-poor compared to the average chondrule composition in CM2 chondrites, which promotes crystallisation of spinel instead of chromite (Simon et al. 1994). Spinel has also been reported associated with isolated forsterite-rich olivine in the matrix of a CM2 chondrite (Cold Bokkeveld). This spinel is magnesium-rich and resembles the composition of spinel in CAIs (Greenwood et al. 1994).

Magnetite

The abundance of magnetite varies widely within the carbonaceous chondrite class. Magnetite is the second most abundant phase in CI chondrites (~ 10 wt%; Hymen & Rowe 1983) and occurs in a wide variety of morphologies (Brearley & Jones 1998). The magnetite in CI chondrites is almost pure Fe_3O_4 (Brearley & Jones 1998). Magnetite is heterogeneously distributed in the Murchison (CM2) chondrite, but in contrast to CI chondrites, the general abundance is low (Fuchs et al. 1973). The amount of magnetite varies widely within the CM group, from 0.4 wt% to 16 wt% (Hymen & Rowe 1983). Spherules of magnetite have been described from the matrix and as inclusions within troilite (FeS) in Murchison (CM2). The magnetite within troilite has a nickel content of 0.8 wt% whereas the magnetite found in the matrix does not contain any nickel (Fuchs et al. 1973).

CV chondrites are divided into oxidised and reduced subgroups based partly on their relative abundances of metal and magnetite (McSween 1977b). The reduced subgroup contains metal and troilite as dominant opaque phases; magnetite is only present in minor amounts. The oxidised subgroup, to which Allende belongs, has magnetite as the dominant oxide phase and contains no or little metal (McSween 1977b). Allende is anomalously low in magnetite for an oxidised CV chondrite and contains ≤1.03 wt% magnetite, other CV chondrites contain as much as 13 wt% magnetite (Hyman & Rowe 1983). Even though reduced CV chondrites only contain small amounts of magnetite compared to oxidised CV chondrites (McSween 1977b), magnetite is the dominant oxide phase in all CV chondrites (Rubin 1997). CV chondrites belonging to the oxidised subgroup have modal proportions of magnetite about five times higher than that of the reduced subgroup (Rubin 1997).

Table 3. Range of element concentration of spinel in CAI in CM and CV chondrites.

Class	MgO	Al_2O_3	TiO_2	V_2O_3	Cr_2O_3	FeO	ZnO	CaO	SiO_2
CM	27.11-28.40	68.32-71.90	0.13-0.33	n.d.	0-2.34	0-0.58	n.d.	0-0.59	0-0.67
CV	12.00-28.63	61.32-71.21	0-0.76	0-4.91	0-0.58	0-20.67	0-0.45	0-1.20	0-0.77

Data from Brearley & Jones (1998) and references therein
n.d.: not detected

2.3.3 Spinel group minerals in ordinary chondrites

Chromite

H chondrites contain ~0.22 wt% chromite and L chondrites contain about ~0.27 wt% chromite (Keil 1962). Bridges et al. (2007) showed that the size of chromite grains in L chondrites varies with petrological type; diameter increases with petrological type. The maximum diameter of chromite in L3 chondrites is 34-50 µm, in L4 84-150 µm, in L5 76-158 µm and in L6 253-638 µm (Bridges et al. 2007).

Chromite is the most common spinel group mineral in ordinary chondrites (Rubin 1997). Chromite is more common in type 4-6 ordinary chondrites than in type 3 ordinary chondrites (Wlotzka 2005). It was found by Snetsinger et al. (1967) that the composition of chromite in equilibrated ordinary chondrites (petrological types 4-6) varies with classes (H, L and LL). This relationship was further substantiated by Bunch et al. (1967) who concluded that FeO, TiO_2 and calculated Fe_3O_2 increase, while Cr_2O_3, MgO and MnO decrease from H to L to LL groups, see Table 2. Al_2O_3 does not show any trend in the Bunch et al. (1967) study but V_2O_3 appears to increase from H to L to LL.

Ramdohr (1973) classified chromite in ordinary chondrites into four main types; 1) *coarse chromite*, 2) *aggregate chromite,* which consists of well developed and rounded crystals in completely random orientation; the outlines of the aggregates are irregular, 3) *decomposition chromite* which forms loose aggregates of small crystals and 4) *exsolution chromite* which occurs as fine grains in pyroxene and olivine.

As in carbonaceous chondrites, chromite occurs within iron-rich porphyritic olivine chondrules in ordinary chondrites of petrological type 3. However, in contrast to carbonaceous chondrites, chromite in porphyritic olivine chondrules in ordinary chondrites are always equilibrated due to thermal metamorphism, thus do not differ significantly in composition neither within the same chondrule nor between chondrules in the same chondrite (Johnson & Prinz 1991).

Spinel

In addition to chromite, some spinel has been reported from ordinary chondrites. In chondrules from chondrites classified as H3.7 and H4, spinel with #Cr ~0.2 has been described (Krot et al. 1993). Wlotzka (2005) refers to all spinels with #Cr between 81 and 0.2 as Cr-spinels and found that these spinels are more widespread in H than in L chondrites and least frequent in LL chondrites. Most common is Cr-spinel in ordinary chondrites of type 3, where it mostly is present as small grains inside chondrules. In type 4-6 ordinary chondrites, Cr-spinel grains are larger than in type 3 ordinary chondrites (Wlotzka 2005). In types 5-6 ordinary chondrites Wlotzka (2005) only found Cr-spinel in large chondrules rich in mesostasis.

CAIs, which are the primary hosts for spinel in carbonaceous chondrites, are rare in ordinary chondrites but are somewhat more common in type 3 ordinary chondrites than in the ordinary chondrites of higher petrological types (Bischoff & Keil 1983). CAIs in H3 chondrites contain hercynian spinel. In type 3 LL, L and H chondrites, hercynian and hercynian-chromian spinel are present in calcium-aluminium-rich chondrules (Bischoff & Keil 1983). Spinel-bearing Al-rich chondrules have also been described from L4 and L5 chondrites (McCoy et al. 1991). The spinels in L4 and L5 Al-rich chondrules range between 30 and 100 µm, are asymmetrically zoned and chromian-hercynitic in composition, with up to 1.1 wt% ZnO (McCoy at al. 1991).

Magnetite

Magnetite is not a common phase in ordinary chondrites, but occurs together with carbides in the matrix, chondrules and chondrule rims in ordinary chondrites of petrological type 3 (Krot et al. 1997). It has been suggested that the magnetite in ordinary chondrites is formed by hydrothermal alteration of metallic iron (Krot et al. 1997).

3 Material and Methods

Four meteorites were investigated within the scope of this study; two ordinary chondrites Jilin (H5) and Mbale (L5/6), and two carbonaceous chondrites; Allende (CV3) and NWA 4428 (CM2). Jilin, Mbale and Allende were available as polished thin sections, whereas NWA 4428 was in cm sized fragments which were mounted in epoxy resin and polished using a 1 µm diamond slurry. The samples were coated with carbon and systematically investigated using a Hitachi S-3400N scanning electron microscope fitted with an energy dispersive spectrometer (INCA x-sight, Oxford Instruments). Each sample was systematically investigated using ~300 times magnification. Suspected spinel group minerals were confirmed using the energy dispersive spectrometer. Only grains above 10 µm are included in this study. It is not reasonable to separate and identify grains smaller than 10 µm from sediments with the methods available at the time being. Quantitative analyses were performed with a 15 kV acceleration voltage, counting time was set to 80 seconds and cobalt was used for calibration. Diameters and areas of spinel grains were measured in the Quartz PCI program. Mean diameters were calculated for each mineral in each chondrite and maximum diameters (D_{max}) were determined. Volume percentage were supposed to be equivalent to area percentage and calculated from the areas obtained from measuring the grains in PCI Quartz and the total area investigated. Weight percentages were calculated from the volume percentage and specific gravities of the minerals and meteorites in question.

4 Results

The occurrence of spinel group minerals in the four meteorites studied is summarised in Table 4 and Fig. 3. Mean compositions and compositional ranges of the spinel group minerals are summarised in Table 5. A more detailed description of the spinels in each meteorite is given below.

4.1 NWA 4428 (CM2)

The NWA 4428 has not been officially classified (Meteoritical Bulletin Database 2009) but has been suggested to belong to the CM2 group, possibly paired with NWA 3340 (Fectay & Bidaut 2009). The observations made here do not contradict that NWA 4428 is a CM2 chondrite and so it is here supposed to be a CM2 chondrite. NWA 4428 has not previously been described, thus a short description of its major components will be given here.

More than 50 vol% of the NWA 4428 is comprised of a phyllosilicate-rich matrix. There are three types of components set in the matrix: chondrules, CAIs and isolated grains. All chondrules, CAIs and some of the isolated grains are rimmed by extremely fine-grained dust-mantles (Figs. 4 & 5). Dust mantles on CAIs are believed to have formed from dust deposited on the surface before the accretion of the parent body (Greenwood et al. 1994). The most common chondrule types are porphyritic olivine chondrules and cryptocrystalline chondrules. Porphyritic olivine chondrules are present both as iron-rich and iron-poor varieties, the iron-poor varieties being the most common. Porphyritic pyroxene chondrules and barred olivine chondrules also occur. The CAIs are between 100 and 250 µm, fine-grained and mostly irregularly shaped.

Largest and most abundant of the isolated mineral grains in the matrix is olivine, which sometimes reaches a diameter of several hundred µm. The isolated olivine grains are mostly forsteritic in their composition, but both crystals with a larger fayalitic component and zoned crystals are present. Besides olivine, relatively large grains (up to 100 µm) of carbonates, spinel (see part 4.1.1 for details) and Ca-pyroxene are present in the matrix. Almost all carbonates are calcium-rich, but magnesium-rich varieties occur occasionally. Smaller grains (up to 20 µm) of corundum, SiO_2, calcium-phosphates and iron-nickel sulphides were also found. Iron-nickel sulphides are sometimes in the form of spherules.

The two spinel group minerals present, spinel and chromite, are further described below.

4.1.1 Spinel

A total of 58 spinel grains were found in the area examined (65 mm^2), corresponding to 0.07 wt%, see Table 4. Spinel is found in CAIs, as isolated grains in the matrix and in the rim of one chondrule, see Table 6. Most abundant is spinel in CAIs, where a total of 43 grains constitute 64 wt% of the spinel found in the sample (Table 6). The spinel-rich CAIs are relatively small; ranging in size between 100 and 250 µm with a mean diameter of 145 µm. A total of ten spinel-rich

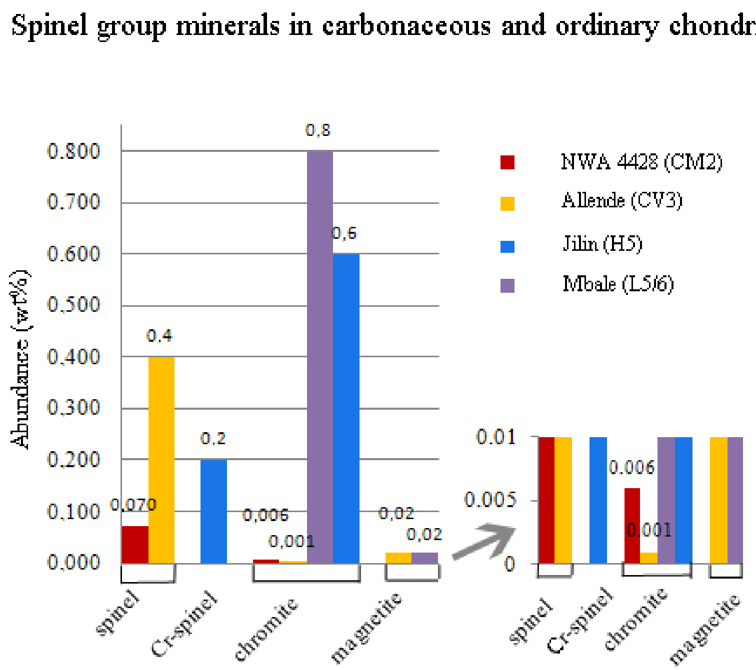


Fig. 3. The amount of spinel group minerals in NWA 4428 (CM2), Allende (CV3), Mbale (L5/6) and Jilin (H5) in wt%. To the right a close-up of the 0-0.01 wt% interval.

Table 4. Spinel group minerals in NWA 4428 (CM2), Allende (CV3), Mbale (L5/6) and Jilin (H5). Shows the area studied of each meteorite, the spinel group minerals found, size distribution of the different minerals in the different chondrites and abundance of the minerals in vol% and wt%.

Class	Meteorite	Area mm^2	Mineral	No. of grains >10µm	No. of grains 10-20µm	No. of grains 20-63µm	No. of grains 63-180µm	No. of grains >180µm	Mean D >10µm	D_{max} µm	Abundance vol%	Abundance wt%*
CM2	NWA	65	spinel	58	20	32	6	-	34	99	0.047	0.074
			chromite	9	5	4	-	-	17	26	0.0028	0.0064
CV3	Allende	220	spinel	1086	320	661	105	-	34	163	0.31	0.39
			chromite	8	7	1	-	-	15	24	0.00056	0.0010
			magnetite	78	57	20	1	-	18	63	0.0093	0.017
L5/6	Mbale	37	chromite	196	89	88	13	6	35	289	0.53	0.81
			magnetite	10	5	5	-	-	25	48	0.0076	0.019
H5	Jilin	19	Cr-spinel	11	1	10	-	-	32	58	0.16	0.22
			chromite	113	66	40	6	1	28	249	0.39	0.57

*wt% was obtained using mean values of density calculated from Flynn et al. (1999), for NWA 4428 density for CM2 chondrites was used, for Allende density of Allende was used, for Mbale density of Mbale was used and for Jilin densities of two H5 chondrites were used. The hercynitic component of the spinel was neglected and all chromite was assumed to be pure $FeCr_2O_4$, specific gravity of Cr-spinel was estimated to 4.58, specific gravities of the minerals are taken from Deer et al. (1992)

Table 5. Summary of element concentrations in wt% of spinel group minerals in NWA 4428 (CM2), Allende (CV3), Mbale (L5/6) and Jilin (H5). Maximum, minimum and mean concentration of each type of occurrence is presented. For all analyses see Appendix 1.

Mineral	Class (meteorite)	Occurrence	No.* grains	Mg0	Al_2O_3	TiO_2	V_2O_3	Cr_2O_3	MnO	FeO	ZnO	#Cr**
Spinel	CM2	CAI min-max	3	27.55-28.00	67.06-69.99	0-0.43	n.d.	n.d.	n.d.	0.53-0.71	n.d.	
	(NWA4428)	CAI mean		27.78	68.38	0.14	n.d.	n.d.	n.d.	0.64	n.d.	
		Matrix min-max	3	25.38-29.05	62.10-72.5	n.d.	0-0.36	n.d.	n.d.	0.69-0.86	n.d.	
		Matrix mean		27.32	67.57	n.d.	0.12	n.d.	n.d.	0.80	n.d.	
	CV3	CAI min-max	11	12.46-29.75	63.68-73.64	0-0.93	0-0.78	n.d.	n.d.	0-23.72	0-0.56	
	(Allende)	CAI mean		20.81	68.26	0.13	0.29	n.d.	n.d.	12.32	0.10	
		Matrix min-max	3	12.51-14.73	64.28-66.67	n.d.	0-0.70	n.d.	n.d.	21.84-24.00	0-0.57	
		Matrix mean		13.36	65.58	n.d.	0.23	n.d.	n.d.	22.92	0.19	
		Chondr. min-max	2	17.02-17.83	66.26-66.3	n.d.	n.d.	1.18-1.49	n.d.	16.75-18.27	0-0.55	
		Chondr. mean		17.43	66.28	n.d.	n.d.	1.34	n.d.	17.51	0.275	
Magnetite	CV3	Spherules min-max	7	0-0.58	1.00-1.21	n.d.	n.d.	0.49-1.09	n.d.	93.61-101.09	n.d.	
	(Allende)	Spherules mean		0.24	1.11	n.d.	n.d.	0.91	n.d.	97.25	n.d.	
Chromite	CM2	Chondr. min-max	6	4.36-8.07	5.67-19.67	0.52-1.34	0.66-0.81	41.55-48.20	n.d.	22.43-25.24	n.d.	59-85
	(NWA4428)	Chondr. mean		6.67	12.85	0.88	0.48	44.90	n.d.	23.47	n.d.	71
	CV3	Chondr. min-max	8	1.21-2.69	7.88-17.00	0.52-1.39	0.49-0.78	42.75-54.56	n.d.	32.37-36.44	n.d.	63-82
	(Allende)	Chondr. mean		1.83	11.93	0.84	0.63	50.06	n.d.	34.47	n.d.	74
	L5/6	Coarse min-max	7	2.48-3.38	5.82-7.16	1.62-2.90	0.59-0.93	50.05-53.20	0-0.92	35.32-37.58	0-0.88	82-85
	(Mbale)	Coarse mean		2.79	6.49	2.44	0.76	51.61	0.38	36.62	0.13	84
	H5	Coarse min-max	8	2.28-3.51	6.34-7.46	1.5-2.41	0.57-0.89	55.64-59.05	0.80-1.27	27.72-29.68	0-0.80	84-86
	(Jilin)	Coarse mean		3.04	6.91	1.87	0.73	57.38	1.05	28.67	0.19	85
Cr-spinel	H5	Aggregate min-max	3	7.42-7.98	20.72-21.99	0.86-0.89	n.d.	42.99-43.61	0.80-0.87	29.18-29.98	0.81-0.81	57-58
	(Jilin)	Aggregate mean		7.62	21.17	0.87	n.d.	43.34	0.56	29.69	0.27	58

*No. of grains analysed of each mineral in each occurrence

**#Cr: Cr/(Cr+Al) in mol%

n.d.: not detected

CAIs were found. Nine of these were irregular in shape and one was rounded. The rounded CAI had abundant cavities, possibly an effect of the polishing process, see Fig. 4. The spinels in CAIs have a maximum diameter of 78 µm and a mean diameter of 31 µm. Of the spinel found in NWA 4428, 27 wt% occur as isolated grains in the matrix (Table 6). The grains have a D_{max} of 82 µm and a mean diameter of 36 µm.

In addition to the CAI and the matrix grains, spinel also occurs in the rim of one chondrule. Two large grains, constituting 9 wt% of the spinel in NWA 4428, were situated next to each other in the dust mantle surrounding one chondrule. One of the grains was the largest spinel found in the sample, having a diameter of 99 µm.

Spinels in CAIs and in the matrix have similar compositions. All analysed spinel crystals are essentially pure $MgAl_2O_4$, with minor amounts of FeO, 0.5-0.7 wt% for spinel in CAIs and 0.7-0.9 wt% for spinel in matrix. One spinel grain contained ~0.4 wt% TiO_2 and another ~0.3 wt% V_2O_3, see Table 5 and Appendix 1.

Table 6. The distribution of spinel in NWA 4428 (CM2)

	No. grains >10 µm	Abundance wt%	D_{max} µm	Mean D >10µm
Matrix	13	27.4	82	36
CAIs	43	64.1	78	31
Rim of chondrule	2	8.5	99	86
Whole sample	58	100	99	34

4.1.2 Chromite

Chromite is not a common mineral in NWA 4428, only nine chromite grains were identified in the 65 mm^2 studied. Chromite constitutes 0.006 wt% of the total area studied, equivalent to 64 wt ppm (Table 4). Five of the chromite grains were situated in porphyritic olivine chondrules, one chromite grain was found in a barred olivine chondrule and three chromite grains were situated in the matrix, associated with larger olivine grains (Table 7). The chromite-bearing porphyritic olivine chondrules typically contain small amounts of iron-nickel sulphides in addition to olivine and chromite, see Fig. 5. The chromite-bearing porphyritic olivine chondrules have diameters of 200-400 µm, and the chromite-bearing barred olivine chondrule a diameter of ~270 µm. The five largest chromite grains (16-26 µm) are all in the porphyritic olivine chondrules. Two of the smallest grains (11 µm each) are situated in the matrix, associated with isolated larger grains of olivine.

Table 7. The distribution of chromite in NWA 4428 (CM2)

	No. grains >10 µm	Abundance wt%	D_{max} µm
PO* chondrule	5	74	26
BO* chondrule	1	7	15
Matrix	3	19	12
Whole sample	9	100	26

*PO: porphyritic olivine chondrule
BO: barred olivine chondrule

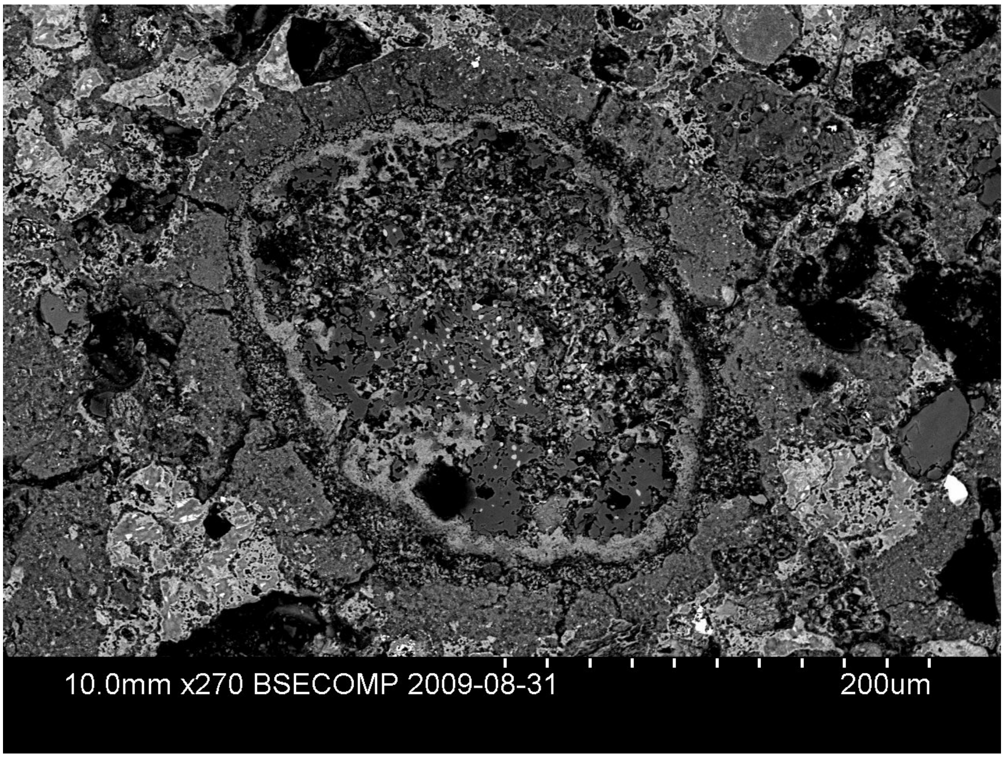


Fig. 4. Backscattered image of rounded spinel-rich CAI in NWA 4428 (CM2) surrounded by a fine grained dust mantle.

Chromite from three of the chondrules was analysed. The composition of the chromite varies with a #Cr between 59 and 85. The composition varies from chondrule to chondrule, but also from grain to grain within the same chondrule, see Appendix 1. The maximum, minimum and mean values of the element concentrations in chromite in NWA 4428 are summarised in Table 5.

4.2 Allende (CV3)

In the carbonaceous chondrite Allende, three types of spinel group minerals were found: spinel, chromite and magnetite.

4.2.1 Spinel

Spinel constitutes 0.4 wt% of the area studied in Allende. The vast majority of the Allende spinel is found in CAIs (97.6 wt%), but spinel is also present in chondrules (0.6 wt%) and as isolated larger grains in matrix (1.7 wt%), see Table 8. Part of a spinel rich CAI is shown in Fig. 6. Three isolated grains (or one fragmented) are shown in Fig. 7. Spinel in a granular olivine chondrule is shown in Fig. 8. The spinel grains in the chondrules have a smaller D_{max} (58 µm) than the spinel in CAIs and in the matrix (163 and 106 µm, respectively), but the mean diameter is similar in all three occurrences, 31 µm in matrix and in chondrules and 34 µm in CAIs (Table 8). The spinel-rich CAIs in Allende are considerably larger than in NWA 4428 and have a maximum size of 2.7 mm.

The spinel in the CAIs displays a large variation in composition, from pure $MgAl_2O_4$ to FeO contents as high as 23.7 wt%, see Table 5. Spinel grains within one CAI tend to be similar in composition. All analysed spinel in the matrix and in the chondrules contained considerable amounts of iron (16.8-24.0 wt% FeO). The spinel grains in chondrules are similar in composition and differ from the other spinel in Allende in that they contain chromium (~1.3 wt% Cr_2O_3).

Table 8. The distribution of spinel in Allende (CV3)

	No. grains >10 µm	Abundance wt%	D_{max} µm	Mean D >10µm
Matrix	17	1.7	106	31
CAIs	1058	97.6	163	34
Chondrules	11	0.6	58	31
Whole sample	1086	100	163	34

4.2.2 Chromite

Only eight chromite grains larger than 10 µm were found, representing 0.001 wt% of the total area examined. The grains have a D_{max} of 24 µm and a mean diameter of 15 µm. All chromite with a diameter larger than 10 µm in Allende is situated in porphyritic

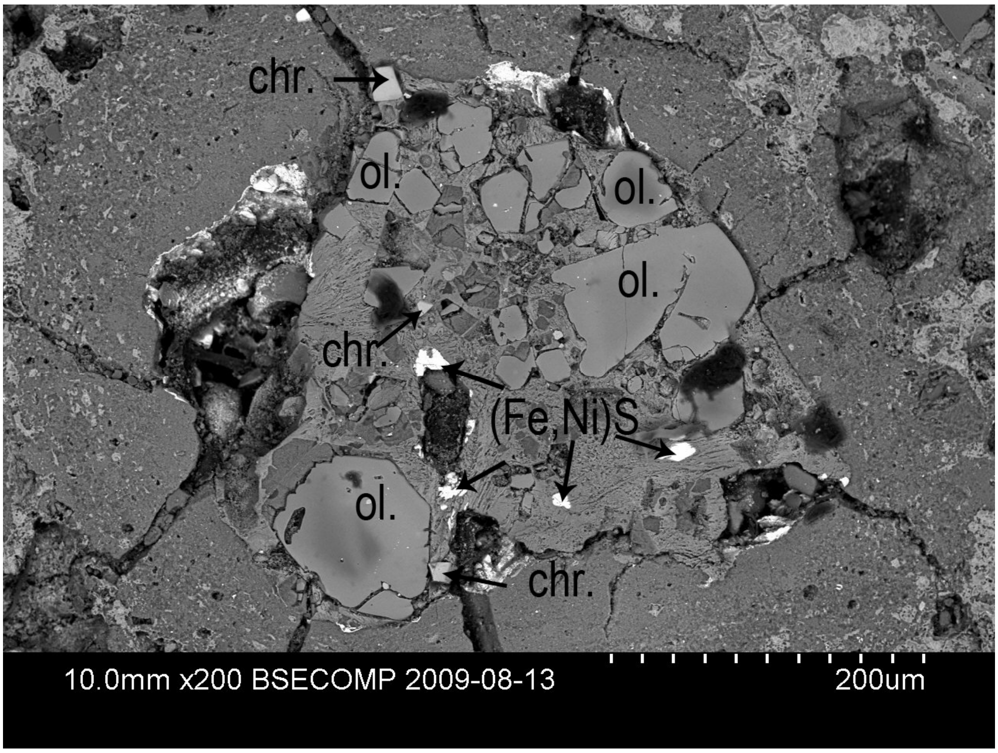


Fig. 5. Backscattered image of porphyritic olivine chondrule in NWA 4428 (CM2). Olivine (ol.), chromite (chr.) and ((Fe,Ni)S) are marked in the picture. The chondrule is surrounded by a fine grained dust mantle.

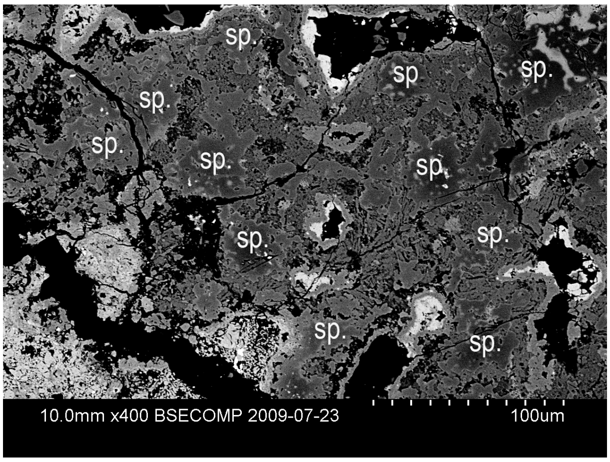


Fig. 6. Backscattered image of part of spinel-rich CAI in Allende (CV3). Spinel grains are marked with sp.

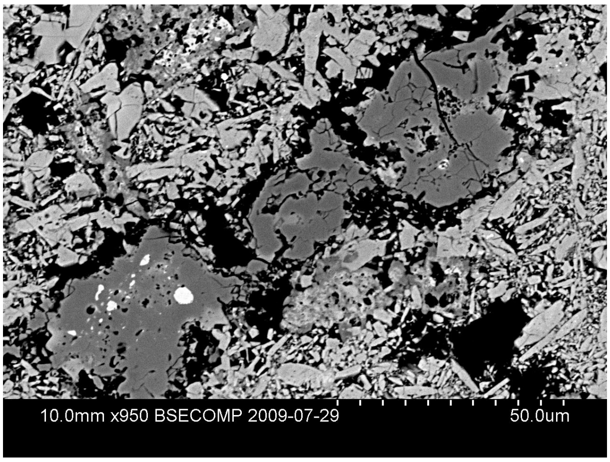


Fig. 7. Backscattered image of three spinel grains, or one fragmented, in olivine-rich matrix in Allende. Bright inclusions in the lower grain are perovskite.

olivine chondrules. A total of three such chondrules were found in the area studied, diameters of the chromite-bearing chondrules range between 400 and 500 µm. Chromite grains smaller than 10 µm also occur in the porphyritic olivine chondrules. In addition to the chondrule chromite, chromite occurs in the matrix but always has a diameter less than 10 µm, typically 1-3 µm.

The chromite composition varies both between chondrules and within chondrules, see Appendix 1. The #Cr range is 63-82 with an average of 74.

4.2.3. Magnetite

Magnetite constitutes 0.02 wt % of the area studied. There are two different types of magnetite in Allende; magnetite present as spherules (Fig. 9) and poorly defined magnetite (Fig. 10). The poorly defined magnetite is typically situated at the margins of chondrules but is also present within chondrules and associated with larger grains of other phases in the matrix. The poorly defined magnetite is often intimately integrated with iron-nickel alloys or iron-nickel sulphides. Of the 50 magnetite grains which were found, 28 are spherules. The spherules constitute 47 vol% of the total amount of magnetite in the sample, see Table 9. The spherules are present inside chondrules, often together with spherules of iron-nickel sulphides. Some of the spherules partly consist of magnetite and partly of iron-nickel sulphides or iron-nickel metal.

D_{max} of the poorly defined grains is almost double the D_{max} of the spherules, 63 µm compared to 32 µm. Analyses on magnetite grains belonging to the spherule type reveal a composition that is essentially pure Fe_3O_4 with Al_3O_4 contents between 1.0 and 1.2 wt% and Cr_2O_3 contents between 0.5 and 1.1 wt%, some of the grains contain minor amounts of MgO, see Table 5.

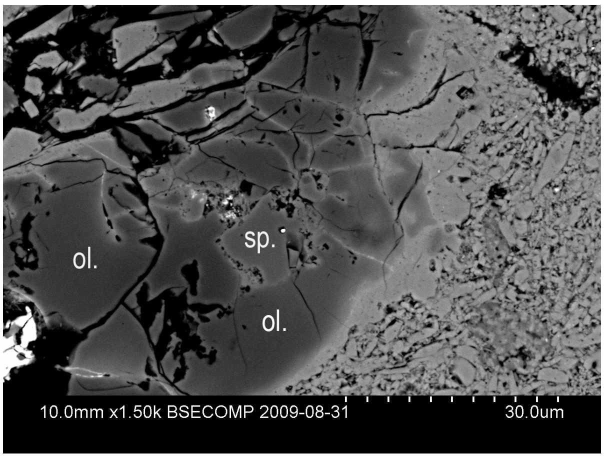


Fig. 8. Backscattered image of spinel (sp.) surrounded by olivine (ol.) in a granular olivine chondrule in Allende (CV3). To the right olivine-rich matrix.

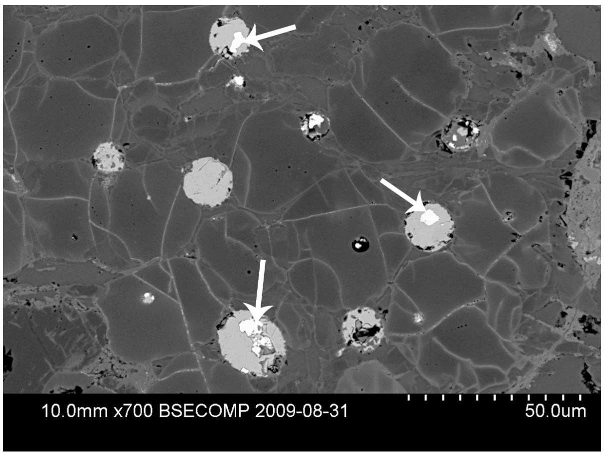


Fig. 9. Backscattered image of spherules of magnetite in an olivine chondrule in Allende. Some spherules contain Fe,Ni metal in addition to magnetite. Arrows point at Fe,Ni metal.

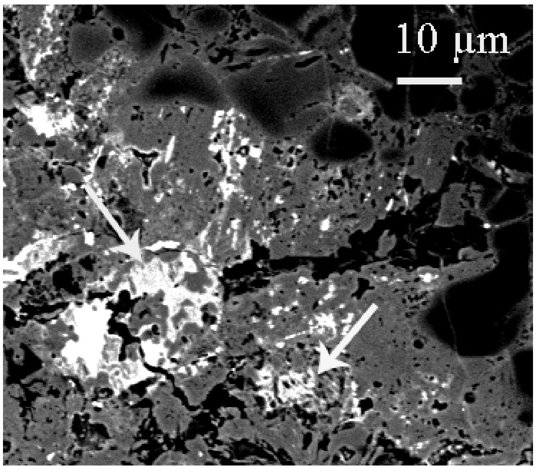


Fig. 10. Arrows point at poorly defined magnetite grains at the margin of one porphyritic olivine chondrule in Allende. Dark grains in the upper right corner are olivine. Backscattered image

Table 9. The distribution of magnetite in Allende (CV3)

	No. grains >10 µm	Abundance wt%	D_{max} µm	Mean D >10µm
Spherules	50	46.9	32	16
"Poorly defined"	28	53.1	63	22
Whole sample	78	100	63	18

4.3 Mbale (L 5/6)

In Mbale, an L chondrite of petrological type 5/6, two types of spinel group minerals were found; chromite and magnetite.

4.3.1 Chromite

The most abundant spinel group mineral in Mbale is chromite. Chromite grains with a diameter >10 µm constitute 0.75 wt% of the area studied, see Table 4. Following the classification by Ramdohr (1973) the most common type of chromite in the sample is coarse chromite (Fig. 11) but decomposition chromite and exsolution chromite are also present. The decomposition chromite and the exsolution chromite are present as grains smaller than 10 µm in addition to the ones included in this study. Analyses display low Al_2O_3 and MgO concentrations and #Cr between 82 and 85, with a mean value of 84 (Table 5).

4.3.2 Magnetite

Magnetite constitutes 0.02 wt% of the sample. A total of 10 magnetite grains were found, they have a D_{max} of 48 µm and a mean diameter of 25 µm. The magnetite is present at the margins of Fe-Ni metal or Fe-Ni sulphides, it often includes other phases and always has irregular outlines.

4.4 Jilin (H5)

Jilin is an ordinary H5 chondrite. In Jilin two spinel group minerals were found; chromite and Cr-spinel.

4.4.1 Chromite

Chromite constitutes 0.54 wt% of the area studied (19 mm^2). Following the classification by Ramdohr (1973) the chromite in Jilin is mostly coarse chromite, but exsolution chromite, with grains too small to be included in this study, also occur. The grains have a D_{max} of 249 µm and a mean diameter of 28 µm. Analyses were performed on coarse chromite in Jilin. The grains that were analysed have low Al_2O_3 and MgO contents and #Cr between 84 and 86 with a mean value of 85, see Table 5.

4.4.2 Cr-spinel

Cr-spinel constitutes 0.22 wt% of the area studied. All 11 grains that were found are situated in the same aggregate, see Fig. 12. The maximum diameter of the grains is 58 µm and the mean diameter is 32 µm. The three analysed grains have #Cr between 57 and 58, see Table 5. The mesostasis surrounding the Cr-spinel is albitic with minor amounts of Ca, K and Zn.

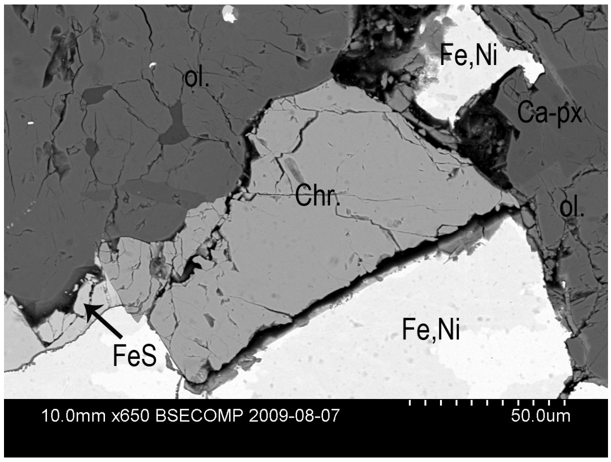


Fig. 11. Backscattered image of coarse chromite (Chr.) in Mbale (L5/6) occurring together with olivine (ol.), Fe,Ni metal, Ca-pyroxene (Ca-px) and troilite (FeS).

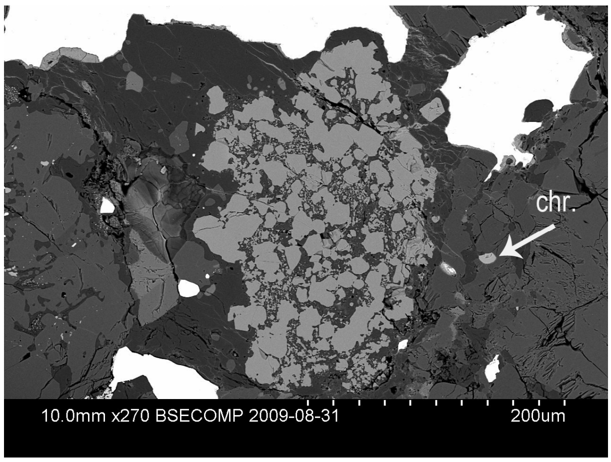


Fig. 12. Backscattered image of aggregate of Cr-spinel in Jilin (H5). To the right of the aggregate one chromite grain (chr.).

5 Discussion

5.1 Accuracy and precision

The heterogeneity of the samples gives the largest errors in the estimation of abundance of spinel group minerals. This is most prominent in the Allende (CV3) sample which contains spinel-rich CAIs with diameters up to 2.7 mm, but is true for all the meteorites examined. The only way to increase the accuracy of the estimated abundance of spinel group minerals is to investigate larger samples. Since spinels are more heterogeneously distributed in Allende than in NWA 4428 a larger area of Allende was studied than of NWA 4428. In Jilin (H5) one Cr-spinel aggregate was present which gives a high abundance of Cr-spinel. The amount of Cr-spinel in Jilin would probably be lesser if a larger area was examined.

The PCI quartz program was used to measure areas of the spinel group minerals grains. Ellipses were drawn over the grains and the program calculated the areas of the ellipses. Even though the result is an estimate of the area that the grain occupies, the error can be considered small due to the large number of grains measured, supposing no systematical errors are present. The random error decreases due to the large number of measurements. The errors are thus expected to be larger for spinel group minerals which are uncommon, e.g. chromite in Allende, than for more common spinel group minerals e.g., spinels in Allende.

Another source of error is the possibility that some spinels were not detected. The risk of that is probably largest for the iron-rich spinels in olivine chondrules which are hard to distinguish from the olivine, see Fig. 8. Olivine and iron-rich spinels have similar densities and therefore similar contrast in backscatter images in the scanning electron microscope. The possibility that chromite and Cr-spinel grains passed unnoticed is less, due to the fact that chrome-rich spinels are easy to recognise in the scanning electron microscope. Chrome-rich spinels have densities between silicates and more high density sulphides and metal, which give them a distinct tone. Spinel in spinel-rich CAIs as well as in the matrix is also easy to detect.

No other quantitative study of spinel group minerals in carbonaceous chondrites is available to compare the results of this study with. Such studies are on the other hand available for ordinary chondrites. Keil (1962) determined average proportions of chromite in L and H chondrites to 0.27 and 0.22 wt%, respectively, by point counting. However mean values of individual chondrites are as high as 0.54 wt% chromite for L-chondrites and 0.61 wt% for H-chondrites (Keil 1962). Abundance of chromite is here calculated to 0.81 wt% in one L5/6 chondrite and to 0.57 wt% in one H5 chondrite. There are two possible explanations for the discordance; first the methods used differ from each other. Keil (1962) used point counting with an optical microscope, whereas a systematical search for spinel group minerals with a scanning electron microscope has been done here. It is possible that the method used in this study is more effective in finding chromite; e.g. by including smaller grains. Secondly, the samples of ordinary chondrites used here are small, 37 mm^2 and 19 mm^2 and chondrites are heterogeneous. It might be that the areas examined in this study have anomalously high chromite concentrations. Kimura et al. (2006) used the same method as used here to investigate the amount of spinel group minerals in LL chondrites. Their results show an increase in the amount of spinel group minerals with increasing petrological type. In LL5 Kimura et al. (2006) calculated the abundance of spinel group minerals to 0.41 vol% and in LL6 to 0.48 vol% which is rather similar to the amount of chromite found here; 0.53 vol% for L5/6 chondrite and 0.39 vol% for H5.

Keil (1962) pointed out the importance of measuring different meteorites. Therefore the results here should be considered as a value of the amount of spinel group minerals in NWA 4428, Allende, Mbale and Jilin rather than as the amount of spinel group minerals in CM2, CV3, L5/6 and H5 chondrites in general. Fuchs et al. (1973) reported that chromite was more abundant than spinel and magnetite in Murchison (CM2). In the CM2 chondrites investigated here (NWA 4428) spinel is considerably more abundant than chromite and magnetite is not found at all. The difference between the abundance of spinel group minerals in Murchison and NWA 4428 point to the variation which might be present within the same group.

Jilin, Mbale and Allende were available as polished thin sections, whereas NWA 4428 was in cm-sized pieces, which were mounted in epoxy resin and polished. Difference in hardness of the matrix and other components in NWA 4428 made it difficult to get a perfectly flat surface. The fact that NWA 4428 was not completely polished had two implications on the study of the meteorite. Firstly, parts of the surface were lost and the cavities were not considered when calculating the total sample area. This makes the abundance of spinel group minerals in NWA 4428 less reliable than the abundance in the other chondrites. The possibility that at least some of the parts which were lost were spinel-bearing cannot be excluded. Secondly, it was hard to get good elemental analyses of the spinel group minerals in the sample. Therefore these analyses should be considered semi-quantitative.

Chromite in Jilin (H5) has a composition close to the mean composition of chromite in H chondrites (Wlotzka 2005; Fig.13). Chromite in Mbale (L5/6) is considerably higher in FeO than average L chondritic chromite. It is possible that the analyses made here are incorrect. On the other hand concentrations of other elements in Mbale are close to the mean L chondritic chromite values and Mbale might be anomalously high in FeO.

5.2 Characteristic features of and differences between spinel group minerals in the different meteorites

Four spinel group minerals were identified; chromite, Cr-spinel, spinel and magnetite. There are obvious differences between the spinel group minerals in the two carbonaceous chondrites compared to the two ordinary chondrites examined. There are also differences between the meteorites within the same class, i.e. between NWA 4428 (CM2) and Allende (CV3) and between Mbale (L5/6) and Jilin (H5).

5.2.1 Chromite

Chromite is the most abundant spinel group mineral in the ordinary chondrites, comprising 0.6 wt% and 0.8 wt%, respectively, of Jilin (H5) and Mbale (L5/6). In the carbonaceous chondrites chromite is the least abundant of the spinel group minerals present and constitutes 0.001 wt% and 0.006 wt% respectively of Allende and NWA 4428 (Fig. 3). L and H chondrites are somewhat higher in Cr than CV and CM chondrites (Wasson & Kallemeyn 1988) which might contribute to the higher amount of chromite in the ordinary chondrites compared to the carbonaceous chondrites. Another explanation is that Jilin and Mbale are of higher petrological type than NWA 4428 and Allende and have experienced more thermal metamorphism. Thermal metamorphism has resulted in exsolution of the $FeCr_2O_4$ component from olivine, thus enabling the formation of more chromite (Johnson & Prinz 1991).

Carbonaceous chondritic chromite displays a larger range and a higher mean of Al_2O_3, is lower in TiO_2, varies more and has a lower mean Cr_2O_3, than chromite in ordinary chondrites, especially for NWA 4428 CM2 (Table 5). Carbonaceous chondritic chromite also has a more variable #Cr than ordinary chondritic chromite, see Fig. 13a. All analysed chromite contains TiO_2. The analyses indicate a trend with increasing TiO_2 concentrations from the carbonaceous chondrites to Jilin (H5) to Mbale (L5/6). V_2O_3 concentrations are similar in all chromite except a few grains in NWA 4428 in which V_2O_3 were not detected, see Fig. 13c.

Allende (CV3) has a FeO content which is more simi-

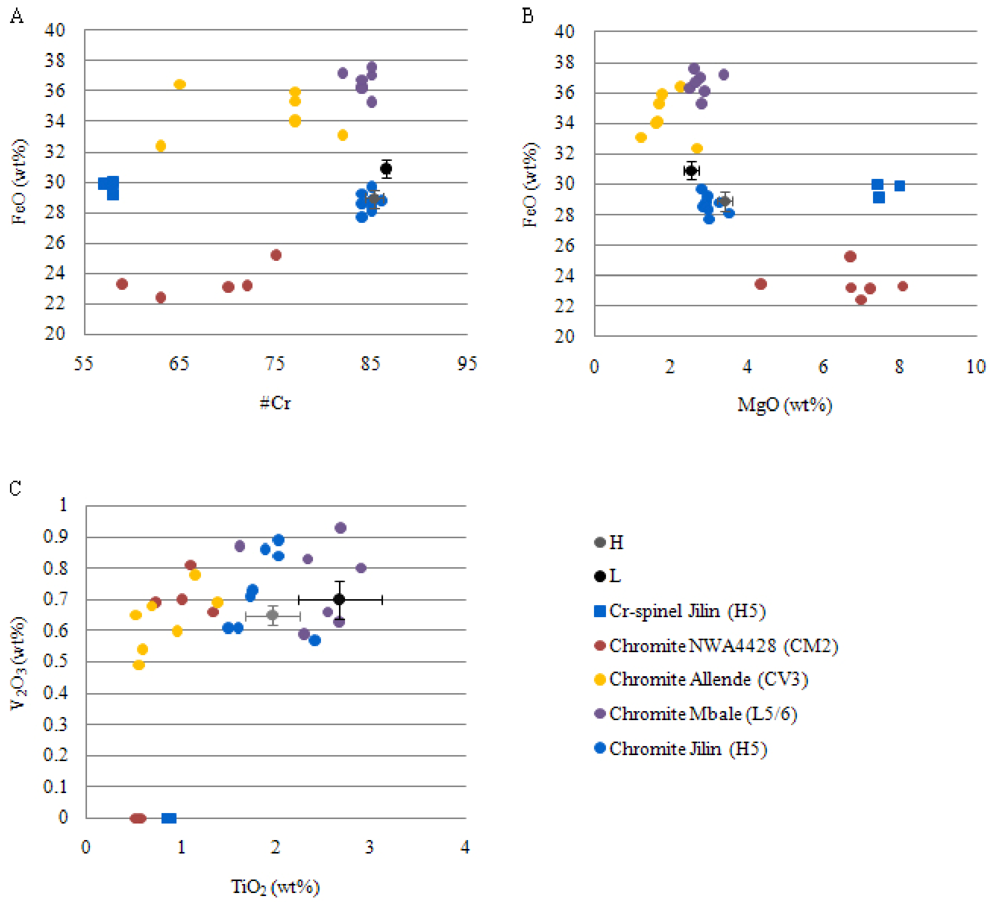


Fig.13. Element concentrations of individual grains chrome-rich spinels in NWA 4428 (CM2), Allende (CV3), Mbale (L5/6) and Jilin (H5). Also mean elemetal concentrations of H and L chondritic chromite from Wlotzka (2005). A) #Cr ((Cr/(Cr+Al) in mol%) vs. FeO (wt%) B) MgO (wt%) vs. FeO (wt%) C) TiO_2 (wt%) vs. V_2O_3 (wt%).

lar to the FeO content of Mbale (L5/6) than NWA 4428 (CM2) and considerable higher than the FeO content of NWA 4428, see Fig. 13a,b. Other differences between NWA 4428 (CM2) and Allende (CV3) is that Allende is lower in MgO (1.2-2.7 % Allende, 4.4-8.1 % NWA 4428 see Fig. 13b) and that Cr_2O_3 is somewhat higher in Allende than in NWA 4428 (42.8-54.6 % Allende, 41.6-48.2 % NWA 4428), see Table 5.

Figure 13a,b shows that the carbonaceous chondritic chromite varies more in composition than ordinary chondritic chromite. The larger variety in composition of the carbonaceous chondritic chromite compared to the ordinary chondritic chromite can be explained by the fact that the two ordinary chondrites examined have experienced thermal metamorphism whereas the two carbonaceous chondrites have not been subjected to thermal metamorphism, or only experienced some thermal metamorphism. Differences between chromite composition in Allende (CV3) and NWA 4428 (CM2) can be explained by the observations made by Johnson & Prinz (1991) that chromite-bearing porphyritic olivine chondrules appear to have different initial compositions in different chondrite groups. Another plausible explanation for the compositional differences is that Allende probably experienced local thermal metamorphism (Kojima & Tomeoka 1996). If the Allende sample investigated here is metamorphosed, then the chromite composition could be affected by that metamorphism. Chromite compositions in CM chondrites have not been affected by thermal metamorphism (Johnson & Prinz 1991).

Chromites in the ordinary chondrites studied here are about ten times the size of chromites in the carbonaceous chondrites studied, see Table 4. Bridges et al. (2007) showed that grain size of chromite in L chondrites is controlled by the amount of thermal metamorphism on the parent body. Of the carbonaceous chondrites examined here NWA 4428 (CM2) has probably not experienced any thermal metamorphism and Allende (CV3) might have been subjected to local thermal metamorphism (Kojima & Tomeoka 1996). The ordinary chondrites Jilin (H5) and Mbale (L5/6) on the other hand have been thermally metamorphosed and the larger grain size of chromite in these chondrites can be explained by the metamorphism.

5.2.2 Cr-spinel

Cr-spinel was only found in one of the chondrites: Jilin (H5). The results here indicate that Cr-spinel is a rather common spinel in Jilin (0.2 wt%). As mentioned under section 5.1 the high abundance of Cr-spinel is probably due to a combination of heterogeneous distribution of Cr-spinel in Jilin and the small area investigated (19 mm^2). In composition the Cr-spinel is approaching some of the carbonaceous chondritic chromite. The Cr-spinel displays a narrow range in compositions, see Fig. 13 and Table 5. All Cr-spinel was located in the same aggregate. The narrow composition range should therefore not be interpreted as being characteristic for all Cr-spinel in Jilin, but only for Cr-spinel of this particular aggregate.

5.2.3 Spinel

Pure spinel or spinel with some FeO is the most common spinel group mineral in the carbonaceous chondrites, but is absent from the ordinary chondrite samples. CV and CM chondrites have a higher Al/Si ratio than L and H chondrites (Wasson & Kallemeyn 1988) which promotes crystallisation of spinel. Spinel is considerable more common in Allende CV3 (0.39 wt%) than in NWA 4428 CM2 (0.07 wt%). This is linked to the fact that CAIs are more abundant in Allende (CV3) than in NWA 4428 (CM2). The spinel in Allende is also more concentrated to the CAIs than the spinel in NWA 4428, see Table 6 & 8. The CAIs in NWA 4428 (CM2) are small and all but one are irregular in shape,

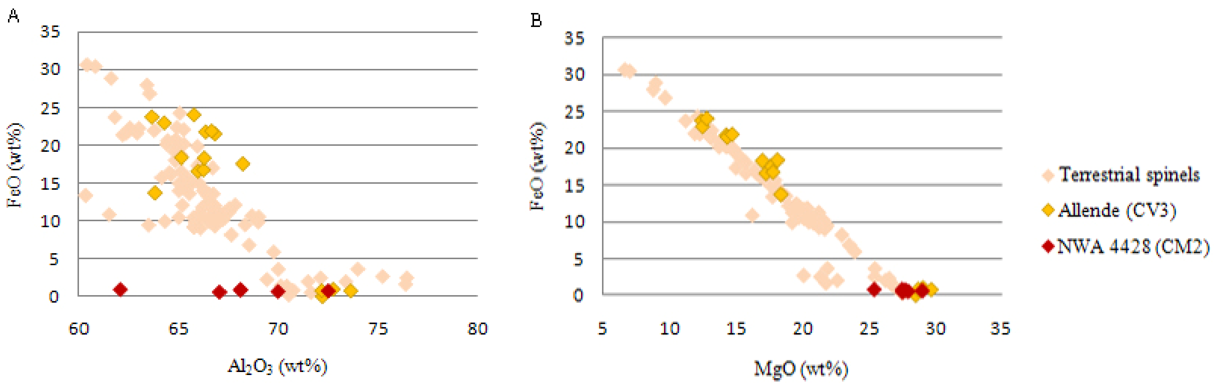


Fig. 14. Element concentrations of spinel in NWA 4428 (CM2), Allende (CV3) and of terrestrial spinels. A) Al_2O_3 (wt%) vs. FeO (wt%) B) MgO (wt%) vs. FeO (wt%). Terrestrial spinel compositions from Barnes & Roeder (2001), see Appendix 2 for complete compositions of the terrestrial spinels.

in contrast to CAIs in Allende (CV3) which are considerable larger than the CAIs in NWA 4428 and more often rounded, or at least less irregular in shape. Greenwood et al. (1994) made the same observations in CV3 and CM2 chondrites and interpreted them as different amounts of early fractionation in the solar nebula. If the CM2 CAIs are more fractionated, many of the isolated grains of spinel in the matrix of NWA 4428 might be parts of fractionated CAIs whereas there are less spinel grains in the matrix of Allende since the CAIs in CV3 chondrites are more intact. It is imaginable that the more fractionated the CAI the more sensitive to alteration. If this is true, spinels in NWA 4428 might be less common than spinels in Allende as they to a larger extent have been altered. Another explanation to the different amount of spinels in NWA 4428 and Allende could be that the different parent bodies contained different proportions of CAIs.

Spinel in NWA 4428 (CM2) appears to be iron-poor. Here only six analyses of spinels in NWA 4428 are presented, but analyses of spinel in CM chondrites published in Brearley and Jones (1998) are also iron-poor, see Table 3 & 5 and Fig. 14. The spinels in Allende appear to be bimodal with one iron-rich variety and one variety which is essentially pure $MgAl_2O_3$ (Fig. 14). This is not in agreement with previous studies which show a continuous series from pure $MgAl_2O_4$ to FeO contents as high as 20.7 wt% (Brearley & Jones 1998 and references therein) and is probably just a coincidence. There is a negative correlation between FeO and MgO, see Fig. 14b. This is expected due to the solid solution between $MgAl_2O_4$ and $FeAl_2O_4$.

5.2.4 Magnetite

According to Rubin (1997) magnetite is the most common oxide in all CV chondrites. In the CV chondrite studied here (Allende) spinel was found to be much more abundant than magnetite (0.4 and 0.02 wt% respectively), see Fig. 3. Hyman & Rowe (1983) found that Allende (CV3) contains ≤1.03 wt% magnetite by using Faraday balance. Here only grains above 10 µm are considered, thus resulting in a lower abundance than if all magnetite is measured as is done in Hayman & Rowe (1983). It is also possible that some magnetite was mistaken for other minerals in this study and/or, that the Allende sample investigated was abnormally low in magnetite.

The poorly defined magnetite in Allende (CV3) and all magnetite in Mbale (L5/6) had irregular outlines and were often included in other phases such as metal and sulphides. The poorly defined magnetite in Allende and the magnetite in Mbale are probably later than the phases with which it is associated. Magnetite has only been reported from ordinary chondrites of petrological type 3 (Krot et al. 1997). It is possible that the magnetite in Mbale and the poorly defined magnetite in Allende is an effect of terrestrial alteration. The spherule magnetite in Allende (CV3) only shows small compositional variations. It is essentially pure Fe_3O_4 with 1.0-1.2 wt% Al_2O_3 and 0.5-1.1 wt% Cr_2O_3, see Table 6.

5.3 The possibility to find fossil spinel group minerals of carbonaceous chondrites in sediment and suggestions for further studies

To detect extraterrestrial spinels in sediment, these spinels have to differ from their terrestrial equivalents. It is preferable that the differences are in the composition of the mineral rather than on an isotopic level, due to costs and availability of analytical methods. Chromite from ordinary chondrites has proven to be a successful tool in tracing ordinary chondrites in sediments (e.g. Schmitz & Häggström 2006, Alwmark & Schmitz 2007). The carbonaceous chondritic chromite analysed here, and by others (Fuchs et al. 1973, Johnson & Prinz 1991), differs in composition from the ordinary chondritic chromite. There also appears to be differences between chromite from different carbonaceous chondrite groups, see section 5.2. All carbonaceous chondrites belong to petrological types 1-3, except for CK chondrites, of which some belongs to petrological type 4-6 (Hutchison 2004). Chromite composition is partly dependent on the amount of thermal metamorphism of the chondrite, chromite in CM2 and some CV3 chondrites have kept their initial crystallisation composition whereas all ordinary chondritic chromite (petrological type 3-6) have been equilibrated (Johnson & Prinz 2001). It is possible that the chromite in CK chondrites of high petrological types resembles the ordinary chromite in their composition. Carbonaceous chondritic chromite varies more in composition than ordinary chondritic chromite. Some carbonaceous chondritic chromite is rather close to the chromite in ordinary chondrites in its composition, whereas other is close to the Cr-spinel in Jilin (H5), see Fig. 13. The variation of carbonaceous chondritic chromite composition probably makes it less suitable as a proxy for cosmic influx than ordinary chondritic chromite. Further studies must, however, be made in order to determine the possibility to distinguish carbonaceous chondritic chromite from terrestrial and ordinary chromite.

The spinel in NWA 4428 (CM2) analysed here is essentially pure $MgAl_2O_4$ with minor amounts of FeO. The spinel in Allende (CV3) analysed here has one variety which is essentially pure $MgAl_2O_4$ and one more iron-rich variety. Both the spinel in CV3 (Allende) and the spinel in CM2 (NWA 4428) have compositions which occur in terrestrial spinels as well (Barnes & Roeder 2001; Fig. 14 & Appendix 2). To distinguish the CM2 and CV3 spinel from terrestrial spinel on compositional bases is probably not possible. However, only 6 analyses of CM2 chondrite spinels and 16 analyses of CV3 chondrite spinel are presented here. Further studies of spinel in carbonaceous chondrites might uncover compositions which differ from compositions of terrestrial spinel.

The CV3 spherule magnetite analysed here displays a narrow compositional range (Table 5). Choi et al. (1997) found similar compositions of magnetite in CV chondrites as the ones obtained here. Terrestrial magnetite in Barnes & Roeder (2001) does not have compositions similar to the compositions of CV3 magnetite. The terrestrial magnetite is either higher in SiO_2, TiO_2 and V_2O_3 or lower in Al_2O_3 and Cr_2O_3. On the other hand magnetite is oxidised to maghemite at low temperatures (Liu et al. 2004) and therefore less suitable as a proxy for carbonaceous chondrites in old sediments

This project would benefit from a more extensive investigation on the composition of the spinel group minerals in CV3 and CM2 chondrites. Some of the analyses performed on the spinel group minerals in NWA 4428 and Allende are too low or high to be satisfying. In the case of NWA 4428 this is due to the different hardness on the matrix and other components which resulted in a surface which was not completely flat, as mentioned earlier. More precise analyses of spinels in NWA 4428 and other CM2 chondrites would be possible if the spinels were separated from the sample and polished flat. Separating the spinel grains from the sample would also give an opportunity to look at characteristics which are not viewable in the scanning electron microscope, e.g. color.

This study could be continued with quantitative investigations of the other carbonaceous chondrites. CI chondrites could maybe be excluded from such studies since they consist of 99 % phyllosilicate-rich matrix (Hutchison 2004), on the other hand spinels might be present in the matrix as isolated grains, which did escape aqueous alteration.

The long term aim of this project is to establish a method for detecting spinel group minerals from carbonaceous chondrites in sedimentary rocks. This study shows that to find spinels from CM2 and CV3 chondrites, grains with a diameter less than 180 µm must be investigated, see Table 3. Both Allende (CV3) and NWA 4428 (CM2) contain spinels with diameters between 63 and 180 µm, but spinels with a diameter between 20 and 63 µm are more common. Some chromite grains are between 20 and 63 µm but most are between 10 and 20 µm with mean diameters of 17 µm for NWA 4428 and 15 µm for Allende. Thus, to find chromite from CM2 and CV3 chondrites in sediment, grains less than 63 µm must be studied. Magnetite in Allende is between 10 and 63 µm, the larger grains are mainly of secondary nature. If magnetite should be used as a proxy for carbonaceous chondrites, the spherule type is probably more suitable as the poorly defined magnetite is very irregular in shape and partly includes other phases. The poorly defined magnetite is probably more easily altered than the spherules. To find magnetite spherules in sediment grains less than 63 µm must be studied, the magnetite spherules have a D_{max} of 32 µm, see Table 9.

6 Conclusions

- Comparison with previous quantitative studies of spinel group minerals in ordinary chondrites and the ones made here shows that the method used there for mineral quantification is reliable.

- Spinel is found in NWA 4428 (CM2) and Allende (CV3), chromite is present in all chondrites included in this study. Magnetite is present in Allende (CV3) and Mbale. Cr-spinel is found in Jilin (H5).

- Spinel is the most common spinel group mineral in NWA 4428 (0.07 wt%) and Allende (0.4 wt%). Spinel is mostly present in CAIs. The CAI spinel is more dominating in Allende (CV3) than in NWA 4428 (CM2) which probably is an effect of more intense early fractionation in the solar nebula of the CM2 CAIs than the CV3 CAIs. In the carbonaceous chondrites spinel is the largest spinel group mineral (D_{max} 99 µm for NWA 4428 and 163 µm for Allende). Spinel in NWA 4428 is essentially pure $MgAl_2O_4$. Spinel in Allende varies from pure $MgAl_2O_4$ to FeO contents of 24.0 wt%.

- Chromite is the most common spinel group mineral in Jilin (0.6 wt%) and Mbale (0.8 wt%). Chromite is present in small amounts in NWA 4428 (0.006 wt%) and Allende (0.001 wt%). Most of the chromite in Jilin (H5) and Mbale (L5/6) is present as coarse chromite and some is present as exsolution chromite and decomposition chromite. All chromite in Allende (CV3) and the majority of the chromite in NWA 4428 (CM2) is present in porphyritic olivine chondrules. Chromite in NWA 4428 also occurs in one barred olivine chondrule and in the matrix. Largest of the spinel group minerals is the ordinary chondritic chromite (D_{max} 249-289 µm), the carbonaceous chondritic chromite is considerable smaller (D_{max} 24-26 µm). Ordinary chondritic chromite has a narrow compositional range whereas carbonaceous chondritic chromite shows a large variation in element concentrations. The main reason for the difference is probably that the ordinary chondrites have experienced more intense thermal metamorphism than the carbonaceous chondrites.

- Magnetite is present in small amounts in Allende (0.02 wt%) and Mbale (0.02 wt%). Magnetite in Allende is present as spherules and as poorly defined grains. Magnetite in Mbale is of poorly defined type. The poorly defined magnetite is interpreted as later than the phases with which it is associated. Magnetite grains are larger in Allende than in Mbale (D_{max} 63 resp. 48 µm). Spherule magnetite is essentially pure Fe_3O_4 with minor amounts of Al_2O_3 and Cr_2O_3.

- Cr-spinel is relatively common in Jilin (0.2 wt%). It is however probable that the small area examined and the heterogeneous distribution of Cr-spinel resulted in an overestimation of the amount of Cr-spinel in Jilin. Cr-spinel in Jilin has a D_{max} of 58 µm.

- To distinguish the CM2 and CV3 spinel analysed here from terrestrial spinel on compositional bases is probably not possible. The carbonaceous chondritic chromite displays a large variation of compositions and is therefore probably less suitable as a proxy than chromite in ordinary chondrites. Magnetite spherules in Allende (CV3) appear to have a composition distinct from terrestrial magnetite. Magnetite might however be unsuitable as a proxy due to oxidation on the Earth surface. Further studies are needed in order to obtain a clear picture of the compositions of spinel group minerals in carbonaceous chondrites.

7 Acknowledgements

Special thanks to my supervisor Carl Alwmark for his great commitment to this project; for providing literature, giving helpful instructions on how to use the SEM, EDS and PCI Quartz, for rigorously reading outcasts and giving carefully prepared feed-back. Thanks to Birger Schmitz for providing the samples and literature. Thanks also to Anders Lindh for help with the carbon coating machine and the SEM.

8 References

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

Barnes, S.J. & Roeder, P.L, 2001 (16.11.2009) http://www.em.csiro.au/terrain_studies/aboutus/people/stephen_barnes/roeder_spinels.htm

Bevan, A.W.R, Bland, P.A. & Jull, J.T, 1998: Meteorite flux on the Nullarbor Region, Australia. *In* Grady, M., Hutchison, R., McCall, G.J.H & Rothery, D.A. (eds.): *Meteorites: Flux with Time and Impact Effects*. Geological Society, London, Special Publications, 140, 59-73

Bischoff, A. & Keil, K., 1983: Ca-Al-rich chondrules and inclusions in ordinary chondrites. *Nature 303*, 588-592.

Brearley A. J. & Jones, R. H., 1998: Chondritic Meteorites. *In* Papike J.J (eds.): Planetary Materials. *Reviews in Mineralogy 36*, 3.1- 3.398.

Bridges J.C, Schmitz, B., Huchison, R., Greenwood, R.C, Tassinari, M. & Franchi, I.A., 2007: Petrographic classification of Middle Ordovician fossil meteorites from Sweden. *Meteoritics & Planetary Science 42*, 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*, 1569-1582.

Choi, B-G., McKeegan, K.D., Leshin, L.A. & Wasson, J.T., 1997: Origin of magnetite in oxidized CV chondrites: in situ measurements of oxygen isotope compositions of Allende magnetite and olivine. *Earth and Planetary Science Letters 146*, 337-349.

Deer, W.A., Howie, R.A., Zussman, J., 1992: An introduction to the Rock-forming minerals. 2nd edition. Pearson Prentice Hall, Harlow. 696 pp.

Farley K.A., Montanari, A., Shoemaker, E.M. & Shoemaker, C.S., 1998: Geochemical Evidence for a Comet Shower in the Late Eocene. *Science 280*, 1250-1253.

Fectay, B. & Bidaut, C., 2009. (05.08.2009) http://www.meteorite.fr/en/forsale/NWA3340.htm

Flynn, G.J., Moore, L.B. & Klöck, W., 1999: Density and Porosity of Stony Meteorites: Implications for the Density, Porosity, Cratering, and Collistional Disruption of Astroids. *Icarus 142*, 97-105.

Fuchs, L.H., Olsen, E. & Jensen, K.J.,1973: Mineralogy, Mineral-Chemistry, and Composition of the Murchison (C2) Meteorite. *Smithsonian Contribution to the Earth Sciences 10,* 1-39.

Greenwood, R.C., Lee, M.R., Hutchison, R. & Barber, D.J., 1994: Formation and alteration of CAIs in Cold Bokkeveld (CM2). *Geochimica et Cosmochimica Acta 58*, 1913-1935.

Grossman, L., 1980: Refractory inclusions in the Allende meteorite. *Annual Reviews of Earth and Planetary Science 8*, 559-608.

Huchison, R., 2004: *Meteorites: A Petrologic, Chemical and Isotopic Synthesis*. Cambridge University Press, Cambridge. 506 pp.

Hyman, M. & Rowe, M.W., 1983: The origin of magnetite in carbonaceous chondrites (abstract). *Lunar Planetary Science 14*, 341-342.

Johnson, C.A. & Prinz, M., 1991: Chromite and olivine in type II chondrules in carbonaceous chondrites: Implications for thermal histories and group differences. *Geochimica et Cosmochimica Acta 55*, 893-904.

Kimura, M., Nakajima, H., Hiyagon, H. & Weisberg, M.K., 2006: Spinel group minerals in LL3.00-6 chondrites: Indicators of nebular and parent body processes. *Geochimica et Cosmochimica Acta 70*, 5634-5650.

Klein C.& Hurlbut, C.S., 1993: *Manual of Mineral ogy*. 21st edition. John Wiley & Sons, New York. 681 pp.

Kojima, T. & Tomeoka, K., 1996: Indicators of aqueous alteration and thermal metamorphism on the CV parent body: Microtextures of a dark inclusion from Allende. *Geochimica et Cosmochimica Acta 60*, 2651-2666.

Krot, A., Ivanova, M.A. & Wasson, J.T., 1993: The origin of chromatic chondrules and the volatility of Cr under a range of nebular conditions. *Earth and Planetary Science Letters 119*, 569-584.

Krot, A.N., Zolensky, M.E., Wasson, J.T., Scott, E.R., Keil, K. & Ohsumi, K., 1997: Carbide-manetite assemblages in type-3 ordinary chondrites. *Geochimica et Cosmochimica Acta 61*, 219-237.

Keil, K., 1962: On the Phase Composition of Meteorites. *Journal of Geophysical Research 67*, 4055-4061.

Lui, Q., Banerjee, S.K., Jackson, M.J., Deng, C., Pan, Y. & Rixiang, Z., 2004: New insights into partial oxidation model of magnetites and thermal alteration of magnetic mineralogy of the Chinese loess in air. *Geophysical Journal International 158*, 506-514.

McCoy, T.J., Pun, A. & Keil, K., 1991: Spinel-beaing, Al-rich chondrules in two chondrite f-inds from Roosevelt County, New Mexico: Indicators of nebular and parent body processes. *Meteoritics 26*, 301-309.

McSween, H.Y., 1977a: On the nature and origin of isolated olivine grains in carbonaceous chondrites. *Geochimica et Cosmochimica Acta 41*, 411-418.

McSween, H.Y., 1977b: Petrographic variations among carbonaceous chondrites of the Vigarano type. Geochimica et Cosmochimica Acta 41, 1777-1790.

Meteoritical Bulletin Database, 2009: NWA 4428 (01.11.2009)http://tin.er.usgs.gov/meteor/metbull.php?sea=NWA+4428&sfor=names&ants=&falls=&valids=&stype=contains&lrec=50&map=ge&browse=&country=All&srt=name&categ=All&mblist=All&rect=&phot=&snew=0&pnt=Normal table&code=45441

Perron C. & Zanda, B., 2005: Meteorites: samples of NEOs in the laboratory. *C.R. Physique 6*, 345-360.

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*, 1965-1970.

Quitté, G., Robin, E., Levasseur, S., Capmas, F., Rocchia, R., Birck, J-L. & Allégre C.J., 2007: Osmium, tungsten, and chromium isotopes in sediments and in Ni-rich spinel at the K-T boundary: Signature of a chondritic impactor. *Meteoritics & Planetary Science 42*, 1567-1580.

Ramdohr, P., 1973: *The Opaque Minerals in Stony Meteorites*. Elsevier, Amsterdam. 245 pp.

Rubin, A.E., 1997: Mineralogy of meteorite groups. *Meteoritics & Planetary Science 32*, 231-247.

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*, 455-466.

Schmitz, B., Peucker-Ehrenbrink, B., Lindström, M. & Tassinari, M., 1997: Accretion Rates of Meteorites and Cosmic Dust in the Early Ordovician. *Science 278*, 88-90.

Schuraytz, B.C., Lindström, D.J. & Sharpton, V.L., 1997: Constraints on the Nature and Distribution of Iridium Host-phases at the KT Boundary: Implications for Projectile Identity and Dispersal on Impact. *Large Meteorite Impacts and Planetary Evolution*, 50-51.

Shukolyukov, A. & Lugmail, G.W., 1998: Isotopic evidence for the Cretaceous-Tertiary Impactor and Its Type. *Science 282*, 927-929.

Simon, S.B., Grossman, L., Podosek, F.A., Zinner, E. & Prombo, C.A., 1994: Petrography, composition, and origin of large, chromian spinels from the Murchison meteorite. *Geochimica et Cosmochimica Acta 58*, 1313-1334.

Snetsinger , K.G., Keil, K. & Bunch, T.E., 1967: Chromite from ”equilibrated” chondrites. *American Mineralogist 52*, 1322-1331.

Van Schmus, W.R. & Wood, J.A., 1967: A chemical-petrologic classification of the condritic meteorites. *Geochimica et Cosmochimica Acta 31*, 747-765.

Wasson, J.T. & Kallemeyn, G.W., 1988: Compositions of chondrites. *Philosophical Transactions of the Royal Society of London. A 325*, 535-544.

Wlotzka, F., 2005. Cr spinel and chromite as petrogenetic indicators in ordinary chondrites: Equilibrium temperatures of petrologic types 3.7 to 6. *Meteoritics & Planetary Science 40*, 1673-1702.

Zanda, B. & Rotaru, M., 2001: *Meteorites: Their Impact on Science and History*. Cambridge University Press, Cambridge.128 pp.

Appendix 1. Element concentrations in wt% of spinel group minerals in CM2, CV3, L5/6 and H5 chondrites.

Analyses were made on randomly chosen grains which were large enough to secure that inclusions or neighboring grains did not affect the analyses.

Mineral	Class		MgO	Al_2O_3	TiO_2	V_2O_3	Cr_2O_3	MnO	FeO	ZnO	Total	
Spinel	CM2	CAI	28.00	69.99	-	-	-	-	0.60	-	98.59	
	(NWA 4428)	CAI	27.55	67.06	0.43	-	-	-	0.53	-	95.57	
		CAI	27.78	68.10	-	-	-	-	0.78	-	96.66	
		Matrix	25.38	62.10	-	-	-	-	0.86	-	88.34	
		Matrix	27.53	68.11	-	-	-	-	0.86	-	96.50	
		Matrix	29.05	72.50	-	0.36	-	-	0.69	-	102.61	
Spinel	CV3(Allende)	CAI	29.12	72.75	-	0.55	-	-	0.96	-	103.38	
		CAI	28.61	72.21	-	-	-	-	-	-	100.82	
		CAI	28.79	72.17	-	0.38	-	-	0.78	-	102.12	
		CAI	29.75	73.64	-	0.49	-	-	0.75	-	104.64	
		CAI	12.46	63.68	-	-	-	-	23.72	0.56	100.42	
		CAI	18.42	63.83	0.93	0.53	-	-	13.70	-	97.41	
		CAI	17.29	65.98	0.47	0.50	-	-	16.57	-	100.81	
		CAI	17.69	68.22	-	-	-	-	17.52	-	103.44	
		CAI	18.16	65.15	-	-	-	-	18.34	-	101.65	
		CAI	14.28	66.37	-	-	-	-	21.73	-	102.37	
		CAI	14.35	66.84	-	0.78	-	-	21.47	0.48	103.92	
		Matrix	14.73	66.67	-	-	-	-	21.84	0.57	103.81	
		Matrix	12.51	64.28	-	-	-	-	22.92	-	99.71	
		Matrix	12.83	65.78	-	0.70	-	-	24.00	-	103.3	
		Chondr.	17.83	66.26	-	-	1.18	-	16.75	0.55	102.57	
		Chondr.	17.02	66.30	-	-	1.49	-	18.27	-	103.07	
Magnetite	CV3(Allende)	Grain1	0.58	1.00	-	-	1.07	-	93.61	-	96.26	
		Grain2	-	1.19	-	-	1.05	-	97	-	99.24	
		Grain3	0.57	1.21	-	-	0.95	-	95.36	-	98.1	
		Grain4	0.56	1.11	-	-	1.09	-	100.26	-	103.01	
		Grain5	-	1.06	-	-	0.79	-	95.36	-	97.21	
		Grain6	-	1.13	-	-	0.96	-	98.07	-	100.16	
		Grain7	-	1.09	-	-	0.49	-	101.09	-	102.67	#Cr
Cr-spinel	H5 (Jilin)	Grain 1	7.98	21.99	0.86	-	42.99	-	29.91	-	103.74	57
		Grain 2	7.46	20.72	0.89	-	43.43	0.8	29.18	0.81	103.29	58
		Grain 3	7.42	20.8	0.86	-	43.61	0.87	29.98	-	103.54	58
Chromite	CM2	Chondr.1	6.71	11.58	1.01	0.7	44.25	-	23.23	-	87.48	72
	(NWA 4428)	Chondr.1	7.22	12.87	1.1	0.81	44.93	-	23.15	-	90.07	70
		Chondr.1	6.68	10.81	1.34	0.66	48.20	-	25.24	-	92.93	75
		Chondr.2	6.98	16.48	0.57	-	42.43	-	22.43	-	88.89	63
		Chondr.2	8.07	19.67	0.52	-	41.55	-	23.34	-	93.13	59
		Chondr.3	4.36	5.67	0.73	0.69	48.04	-	23.45	-	82.95	85
Chromite	CV3(Allende)	Chondr.1	1.64	10.63	0.69	0.68	52.11	-	34.13	-	99.88	77
		Chondr.1	1.61	10.39	0.52	0.65	52.55	-	34.00	-	99.73	77
		Chondr.1	1.76	10.82	1.15	0.78	52.67	-	35.94	-	103.11	77
		Chondr.2	1.21	7.88	0.59	0.54	54.56	-	33.07	-	97.84	82

Mineral	Class		MgO	Al_2O_3	TiO_2	V_2O_3	Cr_2O_3	MnO	FeO	ZnO	Total	#Cr
		Chondr.2	1.21	7.88	0.59	0.54	54.56	-	33.07	-	97.84	82
		Chondr.3	2.69	17.00	0.55	0.49	42.75	-	32.37	-	95.84	63
		Chondr.3	1.70	10.33	0.96	0.60	50.74	-	35.33	-	99.65	77
		Chondr.3	2.23	16.45	1.39	0.69	45.06	-	36.44	-	102.26	65
Chromite	L5/6 (Mbale)	Grain1	2.76	6.37	2.3	0.59	53.04	-	37.04	0.88	102.98	85
		Grain2	2.48	6.81	1.62	0.87	53.2	-	36.31	-	101.3	84
		Grain3	2.63	6.55	2.67	0.63	52.41	-	36.74	-	101.62	84
		Grain4	2.61	6.29	2.55	0.66	51.99	0.9	37.58	-	102.58	85
		Grain5	2.87	6.43	2.68	0.93	50.33	-	36.14	-	99.37	84
		Grain6	3.38	7.16	2.34	0.83	50.05	0.92	37.2	-	101.89	82
		Grain7	2.81	5.82	2.9	0.8	50.22	0.86	35.32	-	98.72	85
Chromite	H5(Jilin)	Grain1	3.01	6.99	1.75	0.73	57.36	1.12	27.72	-	98.67	84
		Grain2	2.98	6.57	2.03	0.84	55.81	1.04	28.38	0.80	98.45	85
		Grain3	2.85	7.00	1.6	0.61	55.64	1.07	28.58	-	97.37	84
		Grain4	3.25	6.34	2.41	0.57	57.05	0.80	28.79	-	99.21	86
		Grain5	3.51	6.62	2.03	0.89	57.26	1,19	28.10	-	99.61	85
		Grain6	2.97	7.46	1.5	0.61	58.43	0.94	29.26	0.70	101.87	84
		Grain7	2.91	7.16	1.73	0.71	58.43	0.95	28.83	-	100.72	85
		Grain8	2.81	7.11	1.89	0.86	59.05	1.27	29.68	-	102.67	85

Appendix 2. Element concentrations of terrestrial spinels

MgO	Al_2O_3	TiO_2	V_2O_3	Cr_2O	MnO	FeO	Fe_2O_3	ZnO	NiO	SiO_2	Total
18	65	0.31	-	0.13	0.14	14.98	1.69	-	-	-	100.25
17.83	60.32	0.62	0.81	-	-	13.39	0.94	-	-	2.44	96.35
11.27	61.78	0.02	-	0.09	0.38	23.72	1.74	-	0.23	0.02	99.25
13.1	62.9	-	-	-	0.27	21.61	1.98	-	-	-	99.86
12.47	63	-	-	0.21	0.18	22.26	0.72	-	0.17	-	99.01
17.8	65.2	-	-	0.88	-	15.38	1.62	-	-	-	100.87
17.9	66	-	-	-	-	15.01	0.87	-	-	-	99.79
21.92	63.48	1.06	0.78	0.48	-	9.45	1.73	0.25	0	1.34	100.49
18.14	64.99	-	-	0.39	-	14.01	1.93	-	0.55	-	100.01
18	65.44	0.02	0.78	0.25	0.1	15.67	1.58	0.25	-	-	102.09
20.43	66.17	0.06	0.78	0.48	0.12	11.80	1.10	0.25	-	-	101.19
20.45	67.04	-	0.78	0.34	0.05	11.07	-	0.25	-	-	99.98
23.05	67.61	0.03	0.91	0.2	0.13	8.19	1.34	0.3	-	-	101.75
12.34	62.47	-	-	-	-	21.93	0.88	0.4	0.16	-	98.18
11.96	63.76	-	0.611	0.34	0.27	21.97	-	-	-	0.58	99.49
14.32	64.37	0.02	-	0	-	20.17	1.72	0.46	0.09	-	101.15
16.7	64.5	-	-	0.87	-	16.43	0.70	-	-	-	99.20
15.11	64.76	0.03	-	-	-	19.16	1.65	0.4	-	-	101.12
15.8	64.8	0.02	-	0.1	0.21	17.99	1.34	-	-	0.04	100.31
13.22	64.88	0	0.039	0.02	-	22.38	1.59	0.33	0.29	-	102.75
14.84	64.93	0.02	-	-	-	19.77	1.89	0.49	0	-	101.94
12.16	65.03	0.03	0.026	0.16	-	24.26	0.91	0.32	0.2	-	103.10
21.32	65.74	0.07	-	1.32	0.05	9.20	1.15	-	0.37	-	99.23
20.9	65.8	0.03	-	0.05	0.07	9.80	1.91	0.23	0	-	98.79
14.88	65.92	0.02	-	-	-	19.85	0.46	0.24	0.13	-	101.50
19.8	66.1	-	-	0.09	0.01	10.82	1.31	0.6	0.6	-	99.33
19.5	66.3	-	-	0.05	-	12.04	0.07	-	-	-	97.96
18.8	66.4	0.01		0.03	0.09	13.46	0.49	-	-	0.04	99.32
19.4	66.6	0.02	-	0.06	0.17	12.00	0	-	-	-	98.25
19.6	66.6	-	-	0.1	0.06	12.40	0.89	-	-	-	99.65
19.5	66.7	-	-	0.09	0.01	11.62	0.54	0.5	0.5	-	99.45
19.8	66.8	-	-	0.06	0	12.02	0.42	-	-	-	99.10
21.6	66.8	-	-	0.05	0.03	9.29	1.57	-	-	-	99.34
20.3	66.9	-	-	0.09	0.01	11.24	0.51	-	-	-	99.05
21.3	66.9	-	-	0.05	0.05	9.88	1.58	-	-	-	99.76
20.2	67.5	-	-	0.08	0.01	11.67	0.14	-	-	-	99.60
26.6	69.4	0.26	-	0.04	0.05	2.27	0.93	0.11	-	-	99.66
26.8	70.1	0.08	-	0.04	0.02	1.43	-	0.02	-	-	98.49
26.9	70.4	0.08	-	0.05	0.01	1.40	-	0.09	-	-	98.93
27.6	70.5	-	-	0.01	0.01	0.21	-	0.17	-	-	98.50
27.2	70.7	0.01	-	0.01	0.01	0.85	-	0.11	-	-	98.89
27.5	71.6	0	-	0.03	-	0.55	-	0.08	-	-	99.76

MgO	Al_2O_3	TiO_2	V_2O_3	Cr_2O	MnO	FeO	Fe_2O_3	ZnO	NiO	SiO_2	Total
17.22	64.12	0.02	-	1.44	0.01	15.77	1.22	-	-	-	99.79
16.89	64.6	-	-	0.9	0.09	16.17	0.90	-	-	0.05	99.60
20.16	64.98	0.03	-	0.61	0.1	10.45	1.51	-	0.36	0.14	98.34
18.49	65.51	0.02	-	0.26	0.08	13.62	0.71	-	-	0.03	98.73
21.66	66.81	-	1.131	0.14	0.07	10.17	0.29	-	-	-	100.25
20.9	67.2	0.04	0.026	0.09	0.12	10.19	0.85	0.22	0.15	-	99.79
16.29	61.5	8.65	-	0.14	0.08	10.85	0	0	0.18	0.05	97.74
25.52	69.97	0.01	-	0.02	0.11	3.63	0.47	0.36	0.02	0.04	100.15
6.69	60.39	0.09	-	0.06	0.43	30.63	0.51	-	-	-	98.80
7.07	60.8	0.21	-	0.15	0.53	30.41	0.55	-	-	0.01	99.73
13.11	62.34	0.6	-	0.19	0.16	21.59	0.69	0.35	-	-	99.03
12.95	62.54	0.63	-	0.11	0.16	22.31	1.07	0.22	-	-	99.99
8.82	63.4	0.03	-	0.03	0.8	27.94	-	-	-	0.1	101.12
9.72	63.53	0.03	-	-	0.78	26.85	0.28	-	-	0.07	101.26
20.55	64.28	0.11	-	1.51	0.09	9.93	1.88	-	0.44	0.03	98.82
14.11	64.42	0.31	-	0.13	0.07	20.62	0.47	0.45	-	-	100.58
14.44	64.66	0.4	-	0.1	0.14	20.29	0.46	0.44	-	-	100.93
13.89	64.83	0.35	-	0.19	0.22	20.77	-	0.15	-	-	100.40
15.4	65.09	0.19	-	0.12	0.08	18.69	0.60	0.37	-	-	100.54
18.06	65.2	0	-	1.73	0.12	14.48	0.02	0	-	-	99.61
13.06	65.23	0.22	-	0.07	0.2	22.07	-	0.37	-	-	101.22
13.77	65.24	0.32	-	0.16	0.2	20.16	-	0.16	-	-	100.01
18.15	65.39	0.37	-	0.26	-	14.67	0.29	-	-	-	99.13
17.58	65.68	0.02	-	0.17	0.16	15.10	0.82	-	0.19	0.06	99.78
20.72	65.72	0.19	-	0.41	0.03	10.44	1.75	-	0.26	-	99.52
21.68	65.75	0.17	-	0.8	0.07	9.16	1.87	-	-	0.03	99.54
15.04	65.93	0.26	-	0.16	0.13	17.35	0	0.21	-	-	99.08
21.78	66.07	0.19	-	0.66	0.07	9.04	1.95	-	0.19	-	99.95
18.32	66.3	0.34	-	0.13	0.09	14.03	0.50	0.98	-	-	100.69
21.17	66.43	0.34	-	0.16	0.09	10.23	1.73	0.12	0.14	-	100.41
21.31	66.51	0.11	-	0.26	0.12	9.87	1.86	0.01	0.06	-	100.11
20.34	66.63	0.07	-	0.75	0.05	10.76	0.70	-	0.73	0.16	100.19
16.47	66.69	0.09	-	-	-	17.04	-	-	-	-	100.29
18.68	66.72	0.14	-	0.44	-	13.59	0.50	0.94	-	-	101.01
19.29	66.91	0.29	-	1.26	0.31	11.22	-	-	0.74	-	100.02
21.3	67.5	0.07	-.637	0.34	0.1	11.22	1.45	-	0.12	-	102.73
19.02	67.8	0.29	-	0.21	0.09	12.13	-	0.19	0.2	-	99.93
19.28	68.96	0.36	-	0.58	0.11	9.86	-	0.98	-	-	100.13
19.78	68.99	0.03	-	0.03	0.06	10.55	-	-	0.26	-	99.70
24.01	69.74	0.1	-	0.19	-	5.94	0.38	0.99	-	-	101.35
26.33	71.45	-	0.78	0.19	-	2.01	-	0.32	-	-	101.08
25.51	72.08	0.13	0.78	0.23	-	2.48	-	0.87	-	-	102.08
22.7	73.35	0.57	0.78	0.25	0.23	2.00	-	-	-	-	99.88
21.95	73.95	-	0.78	-	-	3.65	-	0.13	-	-	100.46

MgO	Al_2O_3	TiO_2	V_2O_3	Cr_2O	MnO	FeO	Fe_2O_3	ZnO	NiO	SiO_2	Total
20.15	75.18	0.4	0.78	0.33	0.11	2.69	-	0.27	-	-	99.91
21.85	76.34	0.19	0.91	0.19	-	1.63	-	-	-	-	101.11
21.42	76.4	-	0.78	-	-	2.51	-	-	-	-	101.11
9	61.6	0.55	0.117	0.04	-	28.83	0.85	0.11	-	-	101.10
13.2	62.18	0.28	-	0.57	0.02	21.38	1.74	0.52	-	-	99.88

From Barnes & Roeder (2001)

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

203. Jansson, Ida-Maria, 2006: An Early Jurassic conifer-dominated assemblage of the Clarence-Moreton Basin, eastern Australia.
204. Striberger, Johan, 2006: En lito- och biostratigrafisk studie av senglaciala sediment från Skuremåla, Blekinge.
205. Bergelin, Ingemar, 2006: ^{40}Ar/^{39}Ar geochronology of basalts in Scania, S Sweden: evidence for two pulses at 191-178 Ma and 110 Ma, and their relation to the break-up of Pangea.
206. Edvarsssson, Johannes, 2006: Dendrokronologisk undersökning av tallbestånds etablering, tillväxtdynamik och degenerering orsakat av klimatrelaterade hydrologiska variationer på Viss mosse och Åbuamossen, Skåne, södra Sverige, 7300-3200 cal. BP.
207. Stenfeldt, Fredrik, 2006: Litostratigrafiska studier av en platåformad sand- och grusavlagring i Skuremåla, Blekinge.
208. Dahlenborg, Lars, 2007: A Rock Magnetic Study of the Åkerberg Gold Deposit, Northern Sweden.
209. Olsson, Johan, 2007: Två svekofenniska graniter i Bottniska bassängen; utbredning, U-Pb zirkondatering och test av olika abrasionstekniker.
210. Erlandsson, Maria, 2007: Den geologiska utvecklingen av västra Hamrångesynklinalens suprakrustalbergarter, centrala Sverige.
211. Nilsson, Pernilla, 2007: Kvidingedeltat – bildningsprocesser och arkitektonisk uppbyggnadsmodell av ett glacifluvialt Gilbertdelta.
212. Ellingsgaard, Óluva, 2007: Evaluation of wireline well logs from the borehole Kyrkheddinge-4 by comparsion to measured core data.
213. Åkerman, Jonas, 2007. Borrkärnekartering av en Zn-Ag-Pb-mineralisering vid Stenbrånet, Västerbotten.
214. Kurlovich, Dzmitry, 2007: The Polotsk-Kurzeme and the Småland-Blekinge Deformation Zones of the East European Craton: geomorphology, architecture of the sedimentary cover and the crystalline basement.
215. Mikkelsen, Angelica, 2007: Relationer mellan grundvattenmagasin och geologiska strukturer i samband med tunnelborrning genom Hallandsås, Skåne.
216. Trondman, Anna-Kari, 2007: Stratigraphic studies of a Holocene sequence from Taniente Palet bog, Isla de los Estados, South America.
217. Månsson, Carl-Henrik & Siikanen, Jonas, 2007: Measuring techniques of Induced Polarization regarding data quality with an application on a test-site in Aarhus, Denmark and the tunnel construction at the Hallandsås Horst, Sweden.
218. Ohlsson, Erika, 2007: Classification of stony meteorites from north-west Africa and the Dhofar desert region in Oman.
219. Åkesson, Maria, 2008: Mud volcanoes - a review. (15 hskp)
220. Randsalu, Linda, 2008: Holocene relative sea-level changes in the Tasiusaq area, southern Greenland, with focus on the Ta1 and Ta3 basins. (30 hskp)
221. Fredh, Daniel, 2008: Holocene relative sea-level changes in the Tasiusaq area, southern Greenland, with focus on the Ta4 basin. (30 hskp)
222. Anjar, Johanna, 2008: A sedimentological and stratigraphical study of Weichselian sediments in the Tvärkroken gravel pit, Idre, west-central Sweden. (30 hskp)
223. Stefanowicz, Sissa, 2008: Palynostratigraphy and palaeoclimatic analysis of the Lower - Middle Jurassic (Pliensbachian - Bathonian) of the Inner Hebrides, NW Scotland. (15 hskp)
224. Holm, Sanna, 2008: Variations in impactor flux to the Moon and Earth after 3.85 Ga. (15 hskp)
225. Bjärnborg, Karolina, 2008: Internal structures in detrital zircons from Hamrånge: a study of cathodoluminescence and back-scattered electron images. (15 hskp)
226. Noresten, Barbro, 2008: A reconstruction of subglacial processes based on a classification of erosional forms at Ramsvikslandet, SW Sweden. (30 hskp)
227. Mehlqvist, Kristina, 2008: En mellanjurassisk flora från Bagå-formationen, Bornholm. (15 hskp)
228. Lindvall, Hanna, 2008: Kortvariga effekter

av tefranedfall i lakustrin och terrestrisk miljö. (15 hskp)
229. Löfroth, Elin, 2008: Are solar activity and cosmic rays important factors behind climate change? (15 hskp)
230. Damberg, Lisa, 2008: Pyrit som källa för spårämnen – kalkstenar från övre och mellersta Danien, Skåne. (15 hskp)
331. Cegrell, Miriam & Mårtensson, Jimmy, 2008: Resistivity and IP measurements at the Bolmen Tunnel and Ådalsbanan, Sweden. (30 hskp)
232. Vang, Ina, 2008: Skarn minerals and geological structures at Kalkheia, Kristiansand, southern Norway. (15 hskp)
233. Arvidsson, Kristina, 2008: Vegetationen i Skandinavien under Eem och Weichsel samt fallstudie i submoräna organiska avlagringar från Nybygget, Småland. (15 hskp)
234. Persson, Jonas, 2008: An environmental magnetic study of a marine sediment core from Disko Bugt, West Greenland: implications for ocean current variability. (30 hskp)
235. Holm, Sanna, 2008: Titanium- and chromium-rich opaque minerals in condensed sediments: chondritic, lunar and terrestrial origins. (30 hskp)
236. Bohlin, Erik & Landen, Ludvig, 2008: Geofysiska mätmetoder för prospektering till ballastmaterial. (30 hskp)
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)
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)

LUNDS UNIVERSITET

Geologiska institutionen
Centrum för GeoBiosfärsvetenskap
Sölvegatan 12, 223 62 Lund