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A weathering index for CK and R chondrites

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Abstract–We present a new weathering index (wi) for the metallic-Fe-Ni-poor chondrite groups (CK and R) based mainly on transmitted light observations of the modal abundance of crystalline material that is stained brown in thin sections: wi-0, <5 vol%; wi-1, 5–25 vol%; wi-2, 25–50 vol%; wi-3, 50–75 vol%; wi-4, 75–95 vol%; wi-5, >95 vol%; wi-6, significant replacement of mafic silicates by phyllosilicates. Brown staining reflects mobilization of oxidized iron derived mainly from terrestrial weathering of Ni-bearing sulfide. With increasing degrees of terrestrial weathering of CK and R chondrites, the sulfide modal abundance decreases, and S, Se, and Ni become increasingly depleted. In addition, bulk Cl increases in Antarctic CK chondrites, probably due to contamination from airborne sea mist.

INTRODUCTION

Terrestrial weathering can significantly alter the bulk composition of silicate rocks (e.g., Parker 1970). There are two scales of terrestrial weathering effects that are currently applied to meteorites: one used for Antarctic meteorites based on surface rustiness and the presence or absence of surficial deposits of evaporite minerals (Table 1, based on Cassidy 1980) and one used mainly for ordinary chondrites (OC) based on oxidation effects of metallic Fe-Ni and troilite visible in polished thin sections (Table 2) (Wlotzka 1993). The latter scale is more useful because it describes weathering effects of meteorite interiors, but it is not strictly applicable to chondrite groups (e.g., CK and R) in which fresh samples have little or no metallic Fe-Ni. For example, the Karoonda CK4 chondrite fall contains essentially no metallic Fe-Ni (Mason and Wiik 1962; Kallemeyn et al. 1991; Geiger and Bischoff 1995), the Kobe CK4 fall also contains no metallic Fe-Ni (Tomeoka et al. 2000), and the Rumuruti R-chondrite fall contains 10^{-4} to 10^{-5} wt% metallic Fe-Ni (Schulze et al. 1994). A different weathering index is needed for these metal-poor chondrite groups.

RESULTS

Weathering Index

Basis for Index

We propose a new weathering index that can be applied to oxidized (e.g., CK and R) chondrites that is based mainly on brown staining of silicate grains (Table 3). The index requires only microscopic observations of meteorite thin sections in transmitted light. The proposed index follows the weathering scale for OC (Wlotzka 1993) in having seven categories, ranging from 0 for unweathered specimens (primarily falls) to 6 for specimens that have undergone appreciable replacement of mafic silicates by phyllosilicates.

Because oxidation of mineral grain surfaces can occur in thin sections stored in museum drawers, older thin sections can potentially yield anomalously high weathering index values. We therefore recommend determining the index only on freshly polished sections.

Manual for Establishing the Weathering Index of an Oxidized Chondrite

1. Obtain a freshly polished thin section. View the entire section microscopically in transmitted light. A magnification of ~100× seems optimal.
2. Visually estimate the modal abundance of brown-stained crystalline silicate material. Where possible, view the interior of the thin section >1 mm away from the sample surface.
3. Use Table 3 to determine the weathering index value.

Uncertainties

To test the reproducibility of the technique, we examined five thin sections of the 3.38-kg CK4-an chondrite, Maralinga (UCLA 431, 439, 440; AMNH 4742-1, 4742-2). The modal abundances of brown-stained crystalline material in these sections are approximately 60%, 40%, 60%, 40%, and 60%, respectively, corresponding to weathering index values of wi-3, wi-2, wi-3, wi-2 and wi-3. The mean value is wi-2.6 ± 0.5,

Table 1. Weathering categories for Antarctic meteorites.

Weathering category	Description	Remarks
A	Minor rustiness	Rust haloes on metal particles and rust stains along fractures are minor.
B	Moderate rustiness	Large rust haloes occur on metal particles and rust stains on internal fractures are extensive.
C	Severe rustiness	Metal particles have been mostly stained by rust throughout.
e	Evaporite minerals	Evaporite minerals visible to the naked eye.

After Cassidy (1980) and subsequent *Antarctic Meteorite Newsletters*.

Table 2. Weathering scale for ordinary chondrites.

Weathering scale	Description
W0	No visible oxidation of metal or sulfide. A limonitic staining may be noticeable in transmitted light.
W1	Minor oxide rims around metal and troilite; minor oxide veins.
W2	Moderate oxidation of metal, about 20–60% being affected.
W3	Heavy oxidation of metal and troilite, 60–95% being replaced.
W4	Complete (>95%) oxidation of metal and troilite.
W5	Beginning alteration of mafic silicates, mainly along cracks.
W6	Massive replacement of silicates by clay minerals and oxides.

After Wlotzka (1993).

which we round off to wi-3. The two-standard-deviation uncertainty is 1 wi unit. On the basis of the observed scatter, we suggest that the index is reliable to about ±1. Because of these uncertainties, we do not recommend assigning meteorites to fractional (e.g., wi-1.5) or intermediate (e.g., wi-2-3) weathering index values.

Some samples are appreciably more weathered within 1 mm of the fusion crust than in their interior. We recommend assigning a weathering index only on the basis of the characteristics of the sample interior. (For tiny samples wherein the interior is near the fusion crust, the entire sample may exhibit similar amounts of terrestrial weathering.)

Some meteorites exhibit minor inconsistencies in their weathering index characteristics. For example, in Asuka-880691 (CK4), ~70 vol% of the crystalline silicate material is stained brown, which is consistent with weathering index wi-3. However, in some sulfide-magnetite assemblages, much of the sulfide has been replaced by phyllosilicate (locally indicative of wi-6). In such cases, the overall modal abundance of stained silicate in the thin section is the principal parameter used for determining the weathering index.

Table 3. Weathering index for CK and R chondrites.

Weathering index	Description	Remarks
wi-0	Unweathered	<5 vol% of silicates stained brown
wi-1	Slightly weathered	5–25 vol% of silicates stained brown
wi-2	Moderately weathered	25–50 vol% of silicates stained brown
wi-3	Significantly weathered	50–75 vol% of silicates stained brown
wi-4	Highly weathered	75–95 vol% of silicates stained brown
wi-5	Severely weathered	>95 vol% of silicates stained brown
wi-6	Extremely weathered	Nearly complete brown staining of silicates. Significant replacement of mafic silicates by phyllosilicates.

Weathering Index Values for CK and R Chondrites

We examined 57 CK and R chondrites in thin section and visually estimated the percentage of stained silicate material in each sample. Depending on the size of the thin section, the estimates encompassed 10^3 to 10^4 grains with sizes ≥20 μm. The derived weathering indices are listed in Appendix 1 and illustrated in Fig. 1.

Our weathering indices for the Antarctic CK chondrites do not correlate well with the weathering categories based on their degree of surface rustiness. For example, meteorites designated weathering category A/B can be found among samples that we assigned weathering indices of 1 to 4 inclusive. In addition, the Antarctic CK chondrite in our set that has the highest degree of surface rustiness (QUE 99680, category Ce) is assigned a relatively low weathering index (wi-2). This lack of correlation calls into question the reliability of the Antarctic meteorite weathering categories for CK and R chondrites, although part of the discrepancy may be related to uncertainties in the proposed weathering index (Nevertheless, the utility of the Antarctic index for OC is shown by the correlation for three equilibrated H chondrites between their weathering category and concentrations of surficial F due to terrestrial contamination.) (Noll et al. 2003).

DISCUSSION

Source of Brown Staining

Even though no metallic Fe-Ni is present in most CK and R chondrites, the brown staining of silicates indicates that some oxidized iron is mobilized during terrestrial weathering and forms an oxide coating on mafic silicate grains. Keller et al. (1992) reported rust stains surrounding some magnetite aggregates in CK4-an Maralinga, but our observations indicate that sulfides are the primary source of oxidized iron. The rust stains around Maralinga magnetite may be due to

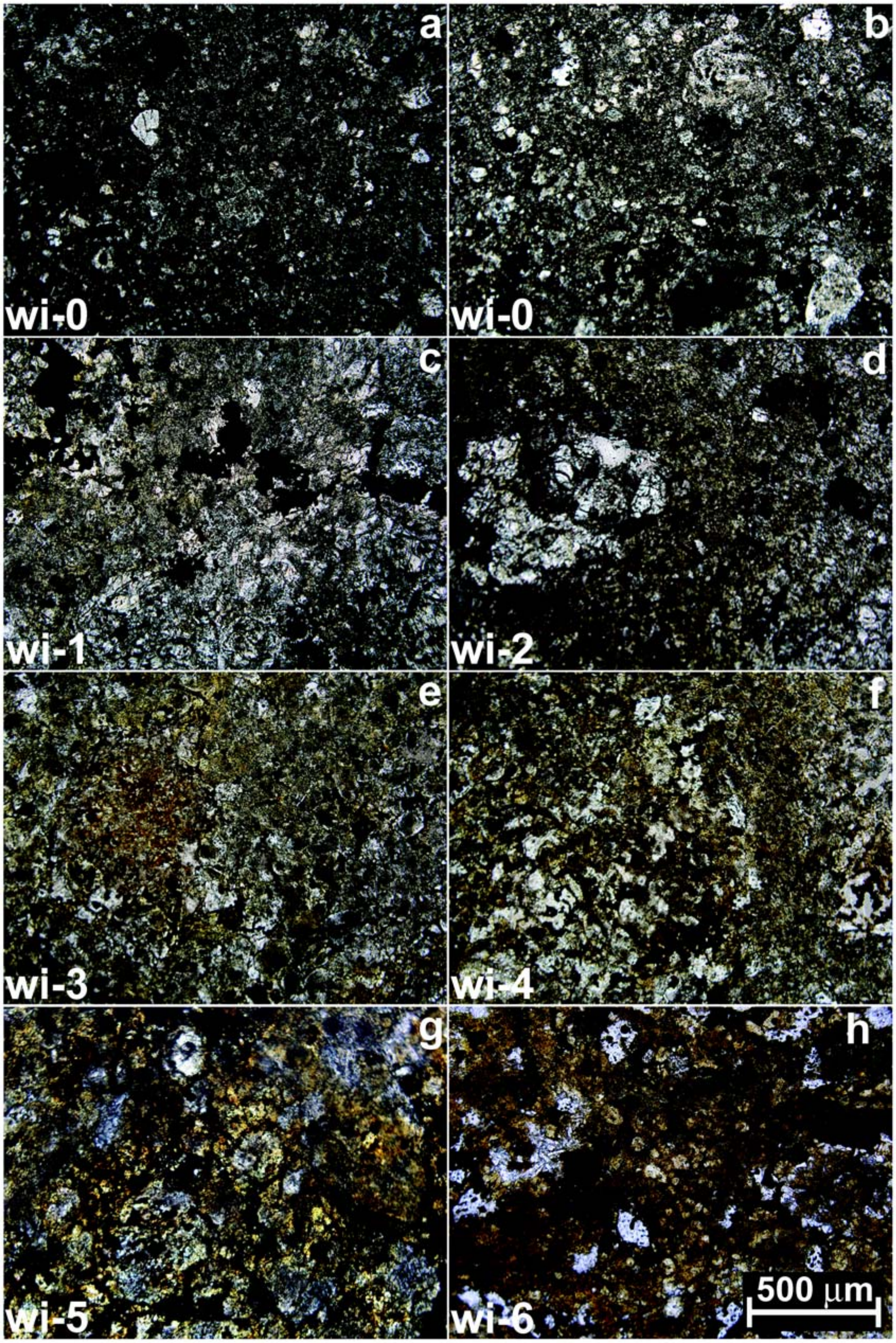

Fig. 1. Progressive brown staining of silicates with increased weathering index in CK carbonaceous chondrites: a) Karoonda, wi-0; b) ALH 82135, wi-0; c) ALH 85002, wi-1; d) Lucerne Valley 028, wi-2; e) PCA 82500, wi-3; f) Tanezrouft 057, wi-4; g) NWA 1563, wi-5; h) Dar al Gani 431, wi-6. All images are in plane-polarized transmitted light and are of the same scale.

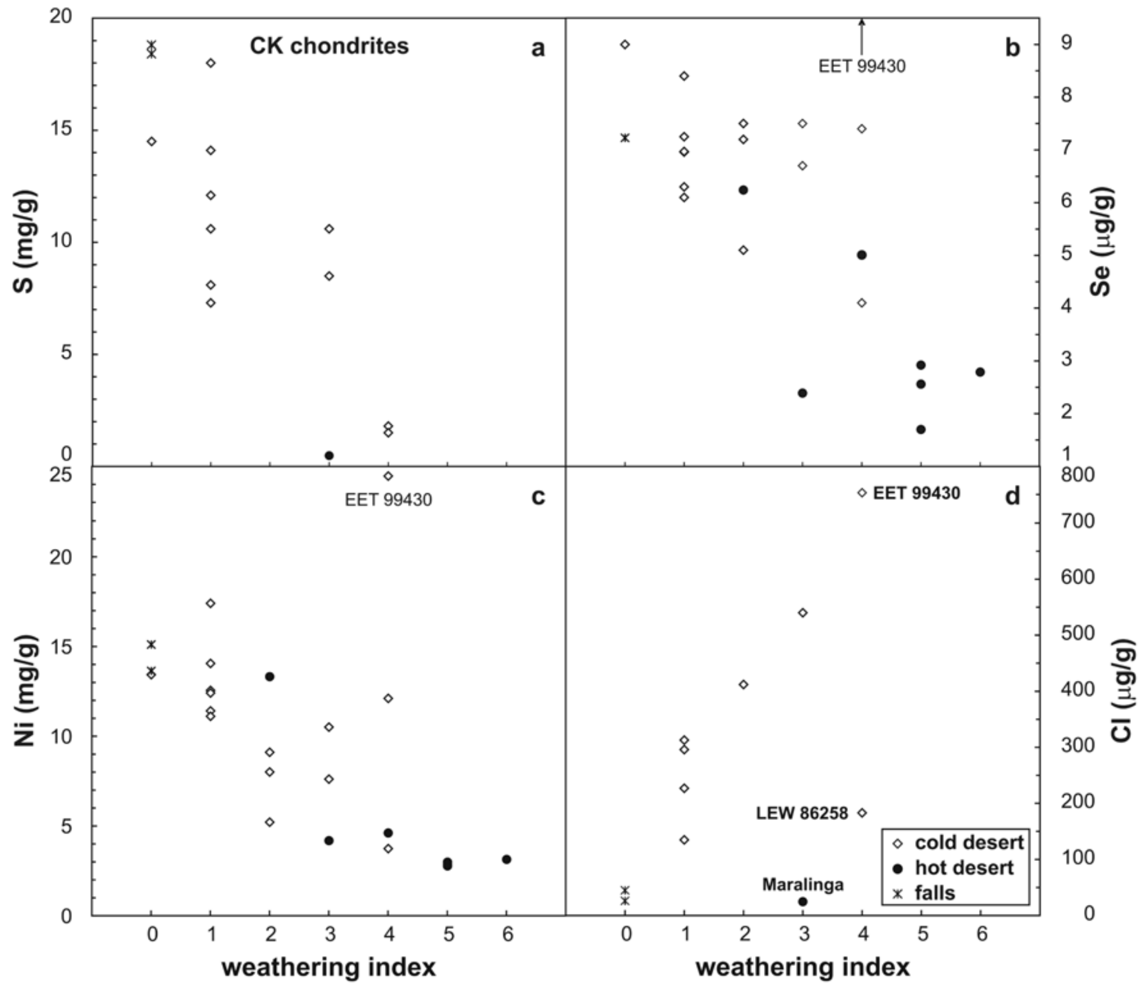

Fig. 2. Variation in the abundances of S, Se, Ni, and Cl with weathering index for CK chondrites. Samples include falls (Karoonda and Kobe) and finds from hot deserts (Australia, Northwest Africa) and cold deserts (Antarctica). a) S versus weathering index. There are no S data available for CK chondrites with index values of 5 and 6, but sulfide, and hence, bulk S, is mostly gone by wi-4. b) Se versus weathering index. Selenium is concentrated in sulfide and thus also marks the progressive disappearance of sulfide with increasing terrestrial weathering. EET 99430, an anomalously Se-rich sample, plots off scale at 12.8 μg/g Se. Samples from hot deserts tend to have less Se than those from cold deserts. c) Ni versus weathering index. Pentlandite is a major Ni-rich phase in CK chondrites. The compositionally anomalous sample EET 99430 is the only one that plots significantly away from the inverse trend between Ni and weathering index. d) Cl versus weathering index. There is a positive correlation among the Antarctic CK chondrites due to terrestrial contamination. LEW 86258 plots off the trend. Bulk compositional data from Quijano-Rico and Wänke (1969), Kallemeyn et al. (1991), Dreibus et al. (1995), Oura et al. (2002, 2004), and Huber et al. (2004, Forthcoming).

decomposition of associated sulfide. We identified 2–8-μm-thick rinds of phyllosilicate around small (5–10-μm-size) sulfide grains within a 420 × 550-μm-size ellipsoidal magnetite-sulfide nodule in CK4/5 PCA 82500. We also observed rare small (2-μm-size) sulfide grains in CK5 NWA 060 that are surrounded by thick limonite rinds. In the R4 chondrite, NWA 800, there are patchy 6-μm-thick rust stains around many of the sulfide grains.

The occurrence of weathering rinds around sulfide grains in CK and R chondrites indicates that sulfide reacts to form other phases that are lost during terrestrial weathering. In fact, recognizable (≥4 μm) sulfide grains are rare to absent in CK chondrites of weathering indices 3 and higher. For example, NWA 060 (wi-5) contains only rare ~2-μm-sized sulfide grains scattered throughout the matrix, and, in somewhat higher concentrations, inside a few chondrules. Because chondrules are less porous than matrix material, the preferential survival of sulfides within chondrules probably results from greater insulation from terrestrial water.

Although sulfide is present in all R chondrites irrespective of weathering index, the modal abundance of sulfide is lower in the highly-to-extremely weathered samples. For example, Rumuruti (wi-0) contains 8.0 wt% sulfide (Schulze et al. 1994), Carlisle Lakes (wi-3) contains 6.0 wt% sulfide (Weisberg et al. 1991), and Acfer 217 (wi-6) contains 0.2 wt% sulfide (Bischoff et al. 1994).

Sulfur and Se occur nearly exclusively in sulfide minerals. As sulfide decreases, bulk S and Se should also decrease. Figure 2a shows the anticorrelation of S with weathering index for CK chondrites ($r = -0.824$, $n = 14$, $2\alpha = 0.0001$ for a two-tailed test, significant at the 99.99% confidence level). There are no S data for CK chondrites with weathering index values of 5 and 6, but sulfide and bulk S are mostly gone in chondrites of wi-4. Selenium shows a similar trend relative to weathering index in CK chondrites (Fig. 2b): $r = -0.528$, $n = 23$, $2\alpha = 0.015$ for a two-tailed test, significant at the 98.5% confidence level. Only 22 points appear on the plot in Fig. 2b; this is because two wi-4 samples (ALH 82135 and ALH 85002) have nearly identical Se concentrations (6.96 and 6.97 µg/g, respectively) and plot on top of one another. If EET 99430 (with its anomalously high Se value of 12.8 µg/g is excluded), the anticorrelation between Se and weathering index becomes much more significant: $r = -0.778$, $n = 22$, $2\alpha = 0.0001$ for a two-tailed test, significant at the 99.99% confidence level.

Pentlandite [$(Fe,Ni)_9S_8$] is a major Ni carrier in CK chondrites; e.g., Karoonda pentlandite contains 37.7 ± 1.4 wt% Ni (Noguchi 1993). The other major carrier of Ni in CK chondrites is olivine; Karoonda olivine averages 0.51 ± 0.16 wt% NiO (i.e., 0.40 ± 0.13 wt% Ni) (Noguchi 1993). Terrestrial weathering of pentlandite should thus cause loss of Ni, producing an anticorrelation between bulk Ni and weathering index. This is indeed the case. If the compositionally anomalous sample EET 99430 is excluded from the data set, the anticorrelation is very strong: $r = -0.834$, $n = 23$, $2\alpha = 0.00001$, significant at the 99.999% confidence level (Fig. 2c). (If EET 99430 is included, the significance of the correlation diminishes: $r = -0.575$, $n = 24$, $2\alpha = 0.005$, significant at the 99.5% confidence level.)

Figure 3a shows the anticorrelation of S with weathering index for R chondrites ($r = -0.885$, $n = 7$, $2\alpha = 0.01$ for a two-tailed test, significant at the 99% confidence level). The anticorrelation of Se with weathering index (Fig. 3b) is not as strong, but is still significant: ($r = -0.744$, $n = 7$, $2\alpha = 0.06$ for a two-tailed test, significant at the 94% confidence level). As in the CK chondrites, Ni anticorrelates with weathering index in R chondrites (Fig. 3c): $r = -0.878$, $n = 8$, $2\alpha = 0.005$, significant at the 99.5% confidence level. (PCA 91002 and PCA 91241 are paired; the S, Se and Ni values used in these correlations are the averages for these two specimens.)

The anticorrelations of S, Se and Ni with weathering index in both CK and R chondrites (Figs. 2a–c and 3a–c) presumably reflect conversion of sulfide to soluble forms (e.g., SO_4^{-2} and $S_2O_3^{-2}$) followed by leaching during terrestrial weathering. Some S could also have been converted to SO_2 or SO_3 (Dreibus et al. 1995). Pentlandite is the most abundant sulfide in CK chondrites (Kallemeyn et al. 1991) and the second most abundant sulfide (after pyrrhotite) in R chondrites (Kallemeyn et al. 1996). Dissolution of pentlandite and mobilization of its constituents in these meteorites is supported by the occurrence of veins in the Acfer 217 R

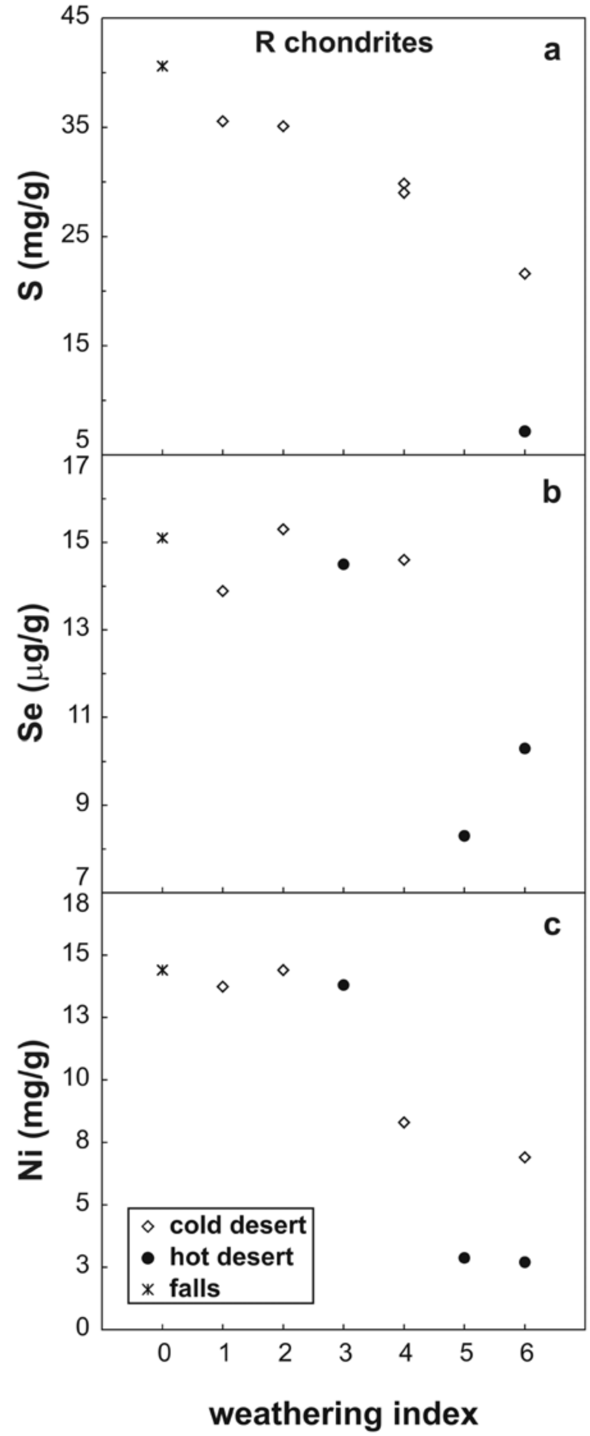

Fig. 3. Variation in the abundances of S, Se, and Ni with weathering index for R chondrites: a) S versus weathering index. b) Se versus weathering index. Both elements are mainly concentrated in sulfide; their bulk concentrations decrease as sulfide is lost during progressive terrestrial weathering. c) Ni versus weathering index. Pentlandite is a major Ni carrier in R chondrites; loss of pentlandite is responsible for the anticorrelation between weathering index and bulk Ni concentration. Bulk compositional data from Yanai et al. (1995), Dreibus et al. (1995), Kallemeyn et al. (1996), Palme et al. (1996), and M. Ebihara (personal communication, 2005).

chondrite breccia of (presumably) hydrous alteration products averaging 1.8 wt% NiO and 1.2 wt% S (Bischoff et al. 1994). The anticorrelations of weathering index with S are stronger than with Se in both CK and R chondrites because S and Se behave differently during weathering. Sulfur is converted into soluble and volatile compounds and lost, but some Se can be converted into SeO_2, a solid that could remain within the meteorites (Dreibus et al. 1995).

The Karoonda and Kobe CK falls contain very little Cl (45 and 26 μg/g, respectively; Quijano-Rico and Wänke 1969; Oura et al. 2002) as does the Maralinga CK-an find from South Australia (25 μg/g; Oura et al. 2002). In contrast, the Cl contents of Antarctic CK finds are generally enhanced, probably as a result of terrestrial contamination of the finds with Cl derived from airborne sea mist (Langenauer and Krähenbühl 1993; Oura et al. 2004). Akaganéite (β-FeOOH) is the principal Cl-bearing phase in Antarctic iron meteorites and in metallic-Fe-Ni-bearing chondrites (Buchwald and Clarke 1989; Lee and Bland 2004). It generally forms by corrosion of meteoritic metal in these rocks and has a typical composition of $[Fe_{15}Ni][O_{12}(OH)_{20}]Cl_2(OH)$ (Buchwald and Clarke 1989). Akaganéite can also form from sulfide (Buchwald and Clarke 1989). If akaganéite is present in Antarctic CK chondrites, it presumably formed by terrestrial alteration of sulfide.

Figure 2d shows that there is a strong correlation of Cl content with weathering index in CK chondrites; if Karoonda and Kobe are included as representing uncontaminated samples (and Maralinga is excluded as a weathered non-Antarctic sample recovered >140 km from the ocean), then $r = 0.671$, $n = 10$, $2\alpha = 0.03$ for a two-tailed test, significant at the 97% confidence level. The only Antarctic sample that lies significantly off the trend is LEW 86258; if this sample is excluded as compositionally anomalous, then the correlation becomes much more significant: $r = 0.939$, $n = 9$, $2\alpha = 0.0001$, significant at the 99.99% confidence level. This trend further confirms the utility of the weathering index.

SUMMARY

The proposed weathering index for the metallic-Fe-Ni-poor CK and R chondrite groups is based mainly on the modal abundance of crystalline silicate material that is stained brown in thin section: wi-0, <5 vol%; wi-1, 5–25 vol%; wi-2, 25–50 vol%; wi-3, 50–75 vol%; wi-4, 75–95 vol%; wi-5, >95 vol%; wi-6, significant replacement of mafic silicates by phyllosilicates. Brown staining is due mainly to mobilization of oxidized iron derived from terrestrially weathered Ni-bearing sulfide grains. Consequently, the sulfide modal abundance and bulk S, Se and Ni abundances of CK and R chondrites inversely correlate with the weathering index. Chlorine contamination of Antarctic CK chondrites, probably by airborne sea mist, correlates positively with weathering index.

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APPENDIX

Appendix 1. Weathering indices of CK and R chondrites.

Meteorite	Petrologic type	Thin section numbers[a]	Weathering category	Weathering index
CK chondrites				
ALH 82135	4	9	A	wi-0
ALH 85002	4	22	A	wi-1
Asuka-87127	6	51-1, 51-2		wi-1
Asuka-880691	4	51-1		wi-3
Asuka-880718	5	51-1		wi-3
Asuka-881725	4	51-1		wi-2
DaG 431	3	UCLA 1802		wi-6
EET 83311	5	9	A/B	wi-1
EET 87507	5	18	B	wi-1
EET 87514	5	8	B	wi-2
EET 87519	5	6	A/Be	wi-3
EET 87527	5	2	A/B	wi-2
EET 87860	5/6	13	A/B	wi-1
EET 90007	5	10	A/Be	wi-2
EET 99430	4	11	A/B	wi-4
Karoonda	4	FMNH		wi-0
Kobe	4	–		wi-0[b]
LAP 03784	5	12	B	wi-0
LEW 86258	4	9	B	wi-4
LEW 87009	6	15	Ae	wi-1
LEW 87250	4	3	A/B	wi-4
Lucerne Valley 028	4	UCLA 1742		wi-2
MAC 02453	5	9	A	wi-0
Maralinga	4	UCLA 431, 439, 440; AMNH 4742-1, 4742-2		wi-3
MET 00739	4	8	B	wi-2
NWA 060	5	UCLA 852		wi-5
NWA 521	5	UCLA 1071		wi-5
NWA 718	5	UCLA 1094		wi-5
NWA 765	4/5	UCLA 1848		wi-0
NWA 1112	5	UCLA 1634		wi-5
NWA 1558	5	UCLA 1798		wi-5
NWA 1563	5	UCLA 1799		wi-5

Appendix 1. *Continued.* Weathering indices of CK and R chondrites.

Meteorite	Petrologic type	Thin section numbers[a]	Weathering category	Weathering index
PCA 82500	4/5	34	Be	wi-3
QUE 93007	5	12	A/Be	wi-2
QUE 99680	5	5	Ce	wi-2
Tanezrouft 057	5	UCLA 1801		wi-4
Y-693	4/5	92-1	A	wi-0
Y-82102 (Y-82103, Y-82104, Y-82105)	5	71-9 (51-2, 51-2, 51-1)		wi-0
Y-82191	6	61-4		wi-1
R chondrites				
Acfer 217	3.8-5	PL92003		wi-6
ALH 85151	3.6	9	B	wi-2
Asuka-881988	4	52-2		wi-3
Carlisle Lakes	3.8	13449		wi-3
DaG 013	3.5-6	PL96037		wi-5
LAP 02238		10	B	wi-4
LAP 03645		8	B	wi-4
NWA 800	4	UCLA 1354		wi-5
NWA 830	5	UCLA 978		wi-6
NWA 978	3.8	UCLA 1411		wi-5
NWA 2198	4	UCLA 1572		wi-1
NWA 2201	3.8	UCLA 1650		wi-6
PCA 91002	3.8	29	A/B	wi-1
PCA 91241	3.8	10	Be	wi-1
Rumuruti	3.8	Ru2		wi-0
Y-75302	3.8	51-2		wi-4
Y-791827	4	51-4		wi-6
Y-793575	3.8	60-1, 60-2		wi-4
Y-82002	3.9	61-3		wi-5

[a]AMNH = American Museum of Natural History. FMNH = Field Museum of Natural History. Many Antarctic samples are from NASA Johnson Space Center. Asuka- and Yamato- (Y-) samples are from the National Institute of Polar Research in Japan. The Acfer and Dar al Gani (DaG) samples are from the Institute of Planetology at the University of Münster. Carlisle Lakes is from the Western Australian Museum. Rumuruti is from the Museum for Natural History at Humboldt University. The weathering categories for the Antarctic meteorites are from the *Antarctic Meteorite Newsletter.* The CK5 samples Y-82102, Y-82103, Y-82104 and Y-82105 look essentially identical in thin section and are probably paired.

[b]The weathering index of the Kobe CK4 fall (wi-0) was inferred from the petrographic descriptions of Tomeoka et al. (2000) and Tachibana et al. (2002).