





#### A GEOCHEMICAL CHARACTERIZATION OF THE GARDNOS IMPACTOR.



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Location of 176 currently recognized terrestrial impact structures, Koeberl (2007) for only 45 structures a type of projectile has been proposed Data from Earth Impact Database (2008), figure courtesy of Dr. L. Ferrière.

#### Projectile ID using crater impact melts & ejecta layers





# Meteoritic contribution to the melt rock between < 0.1 to 7 wt%

Ejecta layers enriched in PGE

Detect and identify type of projectile: siderophile elements and PGE elemental ratios, and osmium and chromium isotopes

# Compare projectile with meteorite classification...



... and then to asteroid spectral classification

#### Siderophile elements



Lappajärvi ~ H chondrite? (Koeberl et al., 2007)

Platinum Group Elements, analytical procedure

Nickel sulfide fire assay method combined with ICP-MS, analytical facilities at GFZ, Potsdam



#### Advantages:

- Low detection limit (60 ppt Ru, 20 ppt Rh, 190 ppt Pd, 60 ppt Ir, 70 ppt Pt)
- Up to 70 g per analysis (less nugget effect)
- Very good reproducibility down to 5 to 10 g material
   All PGE (except Os) determined at once



No need to subtract PGE target



### PGE, Cr, Ni system Tagle and Claeys 2005



#### Pattern vs CI

Ideal cases ID projectile down to type of chondrite No need to subtract PGE target



Compared PGE elemental ratios in impact melt or ejecta with meteorite database (Tagle 2004; Tagle and Hecht 2008)

		Number of analyses in the database								
Туре	Total	Ir	Ru	Pt	Rh	Pd	Ni			
Chondrite	605	549	269	163	31	158	386			
Achondrite*	600	168	12	3	0	5	315			
Iron	2,002	1,361	231	458	133	194	1,706			
Total	3,207	2,078	512	624	164	357	2,407			

\* Primitive & differentiated

CC, OC & EC have different patterns
Iron meteorites are richer in PGE but depleted in Cr compared to CI chondrites
Some analyses by NAA, on small samples, nugget effect ?
Continuously refined by new measurements



Osmium system Highly sensitive tool for detection of ET material, not for ID!  ${}^{187}\text{Re} - \beta \rightarrow {}^{187}\text{Os} = (42.3 \text{ Ga})$ 



#### Chromium system



#### Chromium system



Clear distinction between carbonaceous & other meteorites

Name	Country	Diameter (km)	Location (center)	Bolide type	Evidence	References
Wabar	Saudia Arabia	0.10 <sup>n</sup>	21°30'N, 50°28'E	IIIAB iron	M, S	Morgan et al. (1975), Mittlefehldt
						et al. (1992b)
Kaalijärvi	Estonia	0.11"	58°24'N, 22°40'E	IAB	M	Buchwald (1975)
Henbury	Australia	0.16 <sup>a</sup>	24°35'S, 133°09'E	IIIAB	M, S	Taylor (1967)
Odessa	USA	0.17 <sup>n</sup>	31°45'N, 102°29'W	IIIAB	M	Buchwald (1975)
Boxhole	Australia	0.17	22°37'S, 135°12'E	IIIAB	M	Buchwald (1975)
Macha	Russia	0.3 <sup>a</sup>	59°59'N, 118°00'E	Iron	MS	Gurov (1996)
Aouelloul	Mauritania	0.4	20°15'N, 12°41'W	Iron (IIIB, IIID?)	S, Os	Morgan et al. (1975), Koeberl et al.
Monturaqui	Chile	0.46	23°56'S, 68°17'W	IAB	M, S	Bunch and Cassidy (1972),
Kalkkop	South Africa	0.64	32°42'S, 24°26'E	Chondrite?	S, Os	Koeberl et al. (1994a), Reimold et al.
Walfe Creek	Amsterlin	0.0	10018/8 127046/E	IIIAD	MC	(1996) Attem at al. (1991)
Meteor (Parringer)	USA	1.2	35°02'N, 111°01'W	IAB	M, S M, S	Morgan et al. (1991) Morgan et al. (1975), Mittlefehldt
(Barringer)	Court Africa	1.2	25924/8 28905/8	Charletin	6.0.	et al. (1992a)
Saltpan	South Africa	1.2	25°24'S, 28°05'E	Chondrite	S, Os	Koeberl et al. (1994a)
Roter Kamm	Namibia	2.5	27°46'S, 16°18'E	Chondrite?	S	Reimold et al. (unpublished data
New Quebec	Canada	3.4	61°17'N, 73°40'W	Chondrite (L?)	S	Grieve et al. (1991)>, Evans et al. (1993)
Brent	Canada	3.8	46°05'N, 78°29'W	Chondrite	S	Palme et al. (1981), Evans et al. (1993)
Gow Lake	Canada	4	56°27'N, 104°29'W	Iron?	(S)	Wolf et al. (1980)
Rio Cuarto	Argentina	4.5ª	30°52'S, 64°14'W	Chondrite (H)	M, S, Os	Schultz et al. (1994), Koeberl (unpublished data)
Ilvinets	Ukraine	45	49°06'N 29°12'E	Iron?	\$	Grieve and Shoemaker (1994)
Sääksjärvi	Finland	5	61°24'N, 22°24'E	Stony-iron, iron?	S	Palme et al. (1980), Schmidt et al.
Gardnas	Mormore	6	60°40'N 00°00'E	Chandrite	S 0.	Erench at al (1007)
Wanamitai	Conodo	7.5	40 40 N, 09 00 E	Chondrite	5, 05	Wolf at al (1997)
Wanapiter	Canada	1.5	40 45 N, 80 45 W	Chondrite Storm?	5	Woll et al. (1980), Evans et al. (1995) Bolino et al. (1980)
Mien	Sweden	9	50°25'N, 14'52'E	Stoner	5	Paime et al. (1980)
Bosumtwi	Ghana	11	06°30'N, 01°25'W	L Chondrite	S, Os, Cr	et al. (2004)
Ternovka	Ukraine	12	48°01'N, 33°05'E	Chondrite?	S	Grieve and Shoemaker (1994)
Nicholson Lake	Canada	12.5	62°40'N, 102°41'W	Achondrite	S	Wolf et al. (1980)
Zhamanshin	Kazakhstan	13.5	48°20'N, 60°58'E	Chondrite (Iron?)	S	Glass et al. (1983), Palme et al. (1978)
Dellen	Sweden	15	61°55'N, 16°39'E	Stone?	S	Palme et al. (1980)
Obolon	Ukraine	15	49°30'N 32°55'E	Iron?	S	Grieve and Shoemaker (1994)
Lannajärvi	Finland	17	63°12'N 23°42'E	Chondrite	S	Göbel et al. (1980)
Flovovtovn	Russia	18	67°30/N 172°00/E	Achondrite?	\$	Grieve and Shoemaker (1994)
Clearwater East	Canada	22	56°05'N, 74°07'W	L Chondrite	S, Cr	McDonald (2002); Shukolyukov and
Rochechouart	France	23	45°50'N, 00°56'E	Chondrite? Iron?	S, Cr	Janssens et al. (1977), Wolf et al. (1980), Lambert (1982), Shekekeeserii (2000)
Ries	Germany	24	48°53'N, 10°37'E	Achondrite?	S	Morgan et al. (1979), Schmidt and Bamicka (1994)
Boltssh	Likmine	25	48°45'N 32°10'E	Chondrite?	\$	Grieve and Shoemaker (1994)
Strangeraue	Australia	25	15010/8 122025/F	Achondrite	S	Margan and Wandlage (1994)
Mistostin	Canada	20	55°52'N 62°19'W	Iron?	c	Wolf at al. (1080)
Manson	USA	38	42°35′N, 94°33′W	Chondrite	S, Os	Pernicka et al. (1996), Koeberl and Shiray (1996)
Mialnir	Norway	40	73°48'N 29°40'E	Iron	\$	Dumik and Attren (1999)
Morokweng	USA	70	26°20'S, 23°32'E	L Chondrite	S, Os, Cr	Koeberl et al. (1997a, 2002b), McDonald et al. (2001), Koeberl and Reimold (2003)
Chesaneake Bay	USA	85	37°16'N 76°01'W	Chondrite?	S Os	Lee et al. (2006)
Acraman	Australia	90	32°01'S, 135°27'E	Chondrite	Es	Gostin et al. (1989), Wallace et al.
Kara	Russia	65-100	69°12'N 65°00'E	Chondrite?	s	Nazarov et al (1989-1090)
Popigai	Russia	100	71°30'N, 111°00'E	L Chondrite	S	Masaitis and Raikhlin (1985), Masaitis (1994), Tagle and Claeys (2004)
Chicxulub	Mexico	180	21°20'N, 89°30'W	CM2 Chondrite	S, Os, Es, Cr	Koeberl et al. (1994b), Schuraytz et al. (1996), Shukolyukov and Lugmair (1998), Trinquier et al. (2006)
Vredefort	South Africa	300	27°00'S, 27°30'E	Chondrite	S, Os	Koeberl et al. (1996b)

Name	Country	Diameter (km)	Location (center)	Bolide type	Evidence	References
Wabar	Saudia Arabia	0.10 <sup>n</sup>	21°30'N, 50°28'E	IIIAB iron	M, S	Morgan et al. (1975), Mittlefehldt
						et al. (1992b)
Kaalijärvi	Estonia	0.11 <sup>m</sup>	58°24'N, 22°40'E	IAB	M	Buchwald (1975)
Henbury	Australia	0.16 <sup>n</sup>	24°35'S, 133°09'E	IIIAB	M, S	Taylor (1967)
Odessa	USA	0.17 <sup>n</sup>	31°45'N, 102°29'W	IIIAB	M	Buchwald (1975)
Boxhole	Australia	0.17	22°37'S, 135°12'E	IIIAB	M	Buchwald (1975)
Macha	Russia	0.3 <sup>a</sup>	59°59'N, 118°00'E	Iron	MS	Gurov (1996)
Aonellon	Mauritania	0.4	20°15'N 12°41'W	Iron (IIIB IIID?)	S Os	Morean et al. (1975) Koeberl et al.
Nouchour	Piduinama	0.4	20 15 14, 12 41 1	noa (mb, mb))	5, 03	(1998)
Monturaqui	Chile	0.46	23°56'S, 68°17'W	IAB	M, S	Bunch and Cassidy (1972), Bunch and Cassidy (1972),
Kalkkop	South Africa	0.64	32°42'S, 24°26'E	Chondrite?	S, Os	Koeberl et al. (1994a), Reimold et al.
Wolfe Creek	Amsteolio	0.0	10°18'S 127°46'E	IIIAD	MS	Attrep at al. (1991)
Meteor	USA	1.2	35°02'N, 111°01'W	IAB	M, S	Morgan et al. (1991) Morgan et al. (1975), Mittlefehldt
(Barringer)						et al. (1992a)
Saltran	South Africa	1.2	25°24'S 28°05'E	Chondrite	S. Os	Koeberl et al. (1994a)
Roter Kamm	Namibia	2.5	27°46'S 16°18'E	Chondrite?	S	Reimold et al (unpublished data
New Onebec	Canada	3.4	61º17'N 73º40'W	Chondrite (I 2)	S	Grieve et al (1991) > Evans et al
New Quebec	Callaua	3.4	01 17 14, 75 40 4	Cholunie (L:)	3	(1993)
Brent	Canada	3.8	46°05'N, 78°29'W	Chondrite	S	Palme et al. (1981), Evans et al. (1993)
Gow Lake	Canada	4	56°27'N, 104°29'W	Iron?	(S)	Wolf et al. (1980)
Rio Cuarto	Argentina	4.5ª	30°52'S, 64°14'W	Chondrite (H)	M, S, Os	Schultz et al. (1994), Koeberl
Ilminate	Illemine	4.5	40°06'NI 20°12'E	Iron?	e	Grinup and Shoomakar (1004)
Sääksjärvi	Finland	5	61°24'N, 22°24'E	Stony-iron, iron?	S	Palme et al. (1980), Schmidt et al.
			contraction and comp	-		(1997)
Gardnos	Norway	6	60°40'N, 09°00'E	Chondrite	S, Os	French et al. (1997)
Wanapitei	Canada	7.5	46°45'N, 80°45'W	Chondrite	S	Wolf et al. (1980), Evans et al. (1993)
Mien	Sweden	9	56°25'N, 14°52'E	Stone?	S	Palme et al. (1980)
Bosumtwi	Ghana	11	06°30'N, 01°25'W	L Chondrite	S, Os, Cr	Koeberl and Shirey (1993), Koeberl
Ternovka	Ukraine	12	48°01'N, 33°05'E	Chondrite?	S	Grieve and Shoemaker (1994)
Nicholson Lake	Canada	12.5	62°40'N, 102°41'W	Achondrite	S	Wolf et al. (1980)
Zhamanshin	Kazakhstan	13.5	48°20'N, 60°58'E	Chondrite (Iron?)	S	Glass et al. (1983), Palme et al. (1978)
Dellen	Sweden	15	61°55'N 16°30'E	Stone?	\$	Palme et el (1980)
Obolon	Ultraine	15	40°20/NI 23°55/E	Iron?	S	Grimus and Shoamakar (1904)
Loonoli	Ckrame	15	49 30 N, 32 33 E	Chandalta	5	Cibel et al (1080)
Lappajarvi	Finland	17	65 12 N, 25 42 E	Chondrite	5	Gobel et al. (1980)
Elgygytgyn	Russia	18	67°30'N, 172°00'E	Achondrite?	S	Grieve and Shoemaker (1994)
Clearwater East	Canada	22	56°05'N, 74°07'W	L Chondrite	S, Cr	McDonald (2002); Shukolyukov and Lugmair (2000)
Rochechouart	France	23	45°50'N, 00°56'E	Chondrite? Iron?	S, Cr	Janssens et al. (1977), Wolf et al. (1980), Lambert (1982), Shukeburkey and Lugmair (2000).
Ries	Germany	24	48°53'N, 10°37'E	Achondrite?	S	Morgan et al. (1979), Schmidt and
				~		Pernicka (1994)
Boltysh	Ukraine	25	48°45'N, 32°10'E	Chondrite?	5	Grieve and Shoemaker (1994)
Strangways	Australia	25	15°12'S, 133°35'E	Achondrite	S	Morgan and Wandless (1983)
Mistastin	Canada	28	55°53'N, 63°18'W	Iron?	S	Wolf et al. (1980)
Manson	USA	38	42°35′N, 94°33′W	Chondrite	S, Os	Pernicka et al. (1996), Koeberl and Shirey (1996)
Mjølnir	Norway	40	73°48'N, 29°40'E	Iron	S	Dypvik and Attrep (1999)
Morokweng	USA	70	26°20'S, 23°32'E	L Chondrite	S, Os, Cr	Koeberl et al. (1997a, 2002b), McDonald et al. (2001), Koeberl and Reimold (2003)
Chesapeake Bay	USA	85	37°16'N, 76°01'W	Chondrite?	S. Os	Lee et al. (2006)
Acraman	Australia	90	32°01'S, 135°27'E	Chondrite	Es	Gostin et al. (1989), Wallace et al.
Kara	Russia	65-100	69°12'N, 65°00'E	Chopdrite?	S	Nazarov et al. (1989, 1990)
Popigai	Russia	100	71°30'N, 111°00'E	L Chondrite	s	Masaitis and Raikhlin (1985), Masaitis (1994), Tagle and Claeys (2004)
Chicxulub	Mexico	180	21°20'N, 89°30'W	CM2 Chondrite	S, Os, Es, Cr	Koeberl et al. (1994b), Schuraytz et al. (1996), Shukolyukov and Lugmair (1998), Trinquier et al. (2006)
Vredefort	South Africa	300	27°00'S, 27°30'E	Chondrite	S, Os	(2006) Koeberl et al. (1996b)

Name	Country	Diameter (km)	Location (center)	Bolide type	Evidence	References
Wabar	Saudia Arabia	0.10 <sup>n</sup>	21°30'N, 50°28'E	IIIAB iron	M, S	Morgan et al. (1975), Mittlefehldt
6-117-16-16-						et al. (1992b)
Kaalijärvi	Estonia	0.11 <sup>n</sup>	58°24'N, 22°40'E	IAB	M	Buchwald (1975)
Henbury	Australia	0.16 <sup>n</sup>	24°35'S, 133°09'E	IIIAB	M, S	Taylor (1967)
Odessa	USA	0.17 <sup>n</sup>	31°45'N, 102°29'W	IIIAB	M	Buchwald (1975)
Boxhole	Australia	0.17	22°37'S, 135°12'E	IILAB	M	Buchwald (1975)
Macha	Russia	0.3 <sup>a</sup>	59°59'N, 118°00'E	Iron	MS	Gurov (1996)
Aouelloul	Mauritania	0.4	20°15'N, 12°41'W	Iron (IIIB, IIID?)	S, Os	Morgan et al. (1975), Koeberl et al.
Monturaqui	Chile	0.46	23°56'S, 68°17'W	IAB	M, S	Bunch and Cassidy (1972),
Kalkkop	South Africa	0.64	32°42'S, 24°26'E	Chondrite?	S, Os	Buchwald (1975) Koeberl et al. (1994a), Reimold et al.
Wolfe Creek	Anetrolio	0.9	10°18'S 127°46'E	IIIAD	MS	(1998) Attrap at al. (1991)
Moteor	LISA	1.2	35°02'N 111°01'W	IAB	M, S	Morean et al. (1991) Morean et al. (1975) Mittlefehldt
(Barringer)			55 02 IV, III 0I W		M, 3	et al. (1992a)
Saltpan	South Africa	1.2	25°24'S, 28°05'E	Chondrite	S, Os	Koeberl et al. (1994a)
Roter Kamm	Namibia	2.5	27°46'S, 16°18'E	Chondrite?	S	Reimold et al. (unpublished data
New Quebec	Canada	3.4	61°17'N, 73°40'W	Chondrite (L?)	S	Grieve et al. (1991)>, Evans et al. (1993)
Brent	Canada	3.8	46°05'N, 78°29'W	Chondrite	S	Palme et al. (1981), Evans et al. (1993)
Gow Lake	Canada	4	56°27'N 104°29'W	Iron?	(S)	Wolf et al. (1980)
Rio Cuarto	Argentina	4.5ª	30°52'S, 64°14'W	Chondrite (H)	M, S, Os	Schultz et al. (1994), Koeberl
Industry	Illumina	15	40906/NT 20912/E	F2	c	(unpublished data)
Sääksjärvi	Finland	4.5	61°24'N, 22°24'E	Stony-iron, iron?	s	Palme et al. (1980), Schmidt et al.
					1210	(1997)
Gardnos	Norway	6	60°40'N, 09°00'E	Chondrite	S, Os	French et al. (1997)
Wanapitei	Canada	7.5	46°45'N, 80°45'W	Chondrite	S	Wolf et al. (1980), Evans et al. (1993)
Mien	Sweden	9	56°25'N, 14°52'E	Stone?	S	Palme et al. (1980)
Bosumtwi	Ghana	11	06°30'N, 01°25'W	L Chondrite	S, Os, Cr	Koeberl and Shirey (1993), Koeberl et al. (2004)
Ternovka	Ukraine	12	48°01'N, 33°05'E	Chondrite?	S	Grieve and Shoemaker (1994)
Nicholson Lake	Canada	12.5	62°40'N 102°41'W	Achondrite	S	Wolf et al. (1980)
Zhamanshin	Kazakhstan	13.5	48°20'N, 60°58'E	Chondrite (Iron?)	S	Glass et al. (1983), Palme et al.
Dellan	Smadan	15	61055'N 16020'E	Stone?	e	Polmo at al (1080)
Obalan	Julimina	15	40°30/N 23°55/E	Stone:	S	Grinus and Sheamakar (1904)
Ubolon	Ukraine	15	49 30 N, 32 33 E	Chandalta	5	Grieve and Shoemaker (1994)
Lappajarvi	Finland	17	0312N, 2342E	Chondrite	3	Gobel et al. (1980)
Elgygytgyn	Russia	18	67-30 N, 172-00 E	Actionante?	3	Grieve and Shoemaker (1994)
Clearwater East	Canada	22	56°05'N, 74°07'W	L Chondrite	S, Cr	McDonald (2002); Shukolyukov and Lugmair (2000)
Rochechouart	France	23	45°50'N, 00°56'E	Chondrite? Iron?	S, Cr	Janssens et al. (1977), Wolf et al. (1980), Lambert (1982), Shukelurikov and Lummair (2000)
Ries	Germany	24	48°53'N, 10°37'E	Achondrite?	S	Morgan et al. (1979), Schmidt and
Boltvsh	Ukraine	25	48°45'N, 32°10'E	Chondrite?	S	Pernicka (1994) Grieve and Shoemaker (1994)
Strangways	Australia	25	15°12'S 133°35'E	Achondrite	S	Morgan and Wandless (1983)
Mistastin	Canada	28	55°53'N, 63°18'W	Iron?	S	Wolf et al. (1980)
Manson	USA	38	42°35'N, 94°33'W	Chondrite	S, Os	Pernicka et al. (1996), Koeberl and Shirey (1996)
Mielnir	Norway	40	73°48'N 29°40'E	Iron	S	Dynyik and Attrep (1999)
Morokweng	USA	70	26°20'S, 23°32'E	L Chondrite	S, Os, Cr	Koeberl et al. (1997a, 2002b), McDonald et al. (2001), Koeberl and Reimold (2003)
Chesaneake Bay	USA	85	37°16'N 76°01'W	Chondrite?	S Os	Lee et al. (2006)
Acraman	Australia	90	32°01'S, 135°27'E	Chondrite	Es	Gostin et al. (1989), Wallace et al.
Kara	Russia	65-100	69°12'N 65°00'E	Chopdrite?	S	Nazarov et al (1989-1990)
Popigai	Russia	100	71°30'N, 111°00'E	L Chondrite	s	Masaitis and Raikhlin (1985), Masaitis (1994), Tagle and Claeys (2004)
Chicxulub	Mexico	180	21°20'N, 89°30'W	CM2 Chondrite	S, Os, Es, Cr	Koeberl et al. (1994b), Schuraytz et al. (1996), Shukolyukov and Lugmair (1998), Trinquier et al. (2006)
Vredefort	South Africa	300	27°00'S, 27°30'E	Chondrite	S, Os	Koeberl et al. (1996b)

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Boxhole	Australia	0.17	22°37'S, 135°12'E	IIIAB	M	Buchwald (1975)
Macha	Russia	0.3 <sup>a</sup>	59°59'N, 118°00'E	Iron	MS	Gurov (1996)
Aouelloul	Mauritania	0.4	20°15'N, 12°41'W	Iron (IIIB, IIID?)	S, Os	Morgan et al. (1975), Koeberl et al.
Monturaqui	Chile	0.46	23°56'S, 68°17'W	IAB	M, S	Bunch and Cassidy (1972),
Kalkkop	South Africa	0.64	32°42'S, 24°26'E	Chondrite?	S, Os	Koeberl et al. (1994a), Reimold et al.
Walfa Cash	Amsterlie	0.0	10018/E 127046/E	IIIAD	MC	(1998)
Meteor	USA	1.2	35°02'N, 111°01'W	IAB	M, S M, S	Morgan et al. (1991) Morgan et al. (1975), Mittlefehldt
(Barringer)	Court Africa	1.2	25924/8 28905/8	Charletin	6.0.	et al. (1992a)
Saltpan	South Africa	1.2	25°24'S, 28°05'E	Chondrite	S, Os	Koeberl et al. (1994a)
Roter Kamm	Namibia	2.5	27°46'S, 16°18'E	Chondrite?	S	Reimold et al. (unpublished data
New Quebec	Canada	3.4	61°17'N, 73°40'W	Chondrite (L?)	S	Grieve et al. (1991) >, Evans et al. (1993)
Brent	Canada	3.8	46°05'N, 78°29'W	Chondrite	S	Palme et al. (1981), Evans et al. (1993)
Gow Lake	Canada	4	56°27'N, 104°29'W	Iron?	(S)	Wolf et al. (1980)
Rio Cuarto	Argentina	4.5ª	30°52'S, 64°14'W	Chondrite (H)	M, S, Os	Schultz et al. (1994), Koeberl (unpublished data)
Ilvinets	Ukraine	45	49°06'N 29°12'E	Iron?	\$	Grieve and Shoemaker (1994)
Sääksjärvi	Finland	5	61°24'N, 22°24'E	Stony-iron, iron?	S	Palme et al. (1980), Schmidt et al.
Gardnos	Norway	6	60°40'N 09°00'F	Chondrite	S O.	French et al. (1007)
Wananitai	Canada	7.5	46°45'NI 90°45'WI	Chondrite	5, US C	Wolf at al (1990) Evans at al (1992)
Mian	Canadan	1.5	40 40 IN, 80 40 W	Chondrite Storm?	e e	Balma et al. (1980), Evans et al. (1995)
Bosumtwi	Ghana	11	06°30'N, 01°25'W	L Chondrite	S, Os, Cr	Koeberl and Shirey (1993), Koeberl
Township	Thesian	12	4890101 22906/E	Charadaine?	e	et al. (2004)
Ternovka	Okraine	12	48.01 N, 33.05 E	Chondriter	5	Grieve and Shoemaker (1994)
Zhamanshin	Kazakhstan	12.5	62°40'N, 102°41'W 48°20'N, 60°58'E	Chondrite (Iron?)	S	Glass et al. (1980) Glass et al. (1983), Palme et al.
						(1978)
Dellen	Sweden	15	61°55'N, 16°39'E	Stone?	S	Palme et al. (1980)
Obolon	Ukraine	15	49°30'N, 32°55'E	Iron?	S	Grieve and Shoemaker (1994)
Lappajärvi	Finland	17	63°12'N, 23°42'E	Chondrite	S	Göbel et al. (1980)
Elgygytgyn	Russia	18	67°30'N, 172°00'E	Achondrite?	S	Grieve and Shoemaker (1994)
Clearwater East	Canada	22	56°05'N, 74°07'W	L Chondrite	S, Cr	McDonald (2002); Shukolyukov and Lugmair (2000)
Rochechouart	France	23	45°50'N, 00°56'E	Chondrite? Iron?	S, Cr	Janssens et al. (1977), Wolf et al. (1980), Lambert (1982), Sheledeneet Janeire (2000)
Ries	Germany	24	48°53'N, 10°37'E	Achondrite?	s	Morgan et al. (1979), Schmidt and
Deltash	Thereine	26	499467N1 22910/E	Chandrite?	c	Crime and Sharmahan (1004)
Bonysn	Okraine	25	46 43 N, 32 TUE	Chondhiter	5	Grieve and Shoemaker (1994)
Strangways	Australia	20	15-12 S, 135-35 E	Achonante	5	Morgan and Wandless (1985)
Manson	USA	38	42°35′N, 94°33′W	Chondrite	S, Os	Pernicka et al. (1980) Shirari (1996), Koeberl and
Mialair	Nome	40	73°48'N 30°40'E	Iron	\$	Dumik and Attract (1000)
Morokweng	USA	70	26°20'S, 23°32'E	L Chondrite	S, Os, Cr	Koeberl et al. (1997a, 2002b), McDonald et al. (2001), Koeberl
~ · · ·				-		and Reimold (2003)
Chesapeake Bay Acraman	USA Australia	85 90	37°16'N, 76°01'W 32°01'S, 135°27'E	Chondrite? Chondrite	S, Os Es	Lee et al. (2006) Gostin et al. (1989), Wallace et al.
		22 100	(0)1 0/2 ( (C)00/17)	CT 11.0		(1990)
Kara Popigai	Russia	65-100 100	69°12'N, 65°00'E 71°30'N, 111°00'E	Chondrite? L Chondrite	S S	Masaitis and Raikhlin (1985), Masaitis (1994), Tagle and Claeys
Chicxulub	Mexico	180	21°20'N, 89°30'W	CM2 Chondrite	S, Os, Es, Cr	(2004) Koeberl et al. (1994b), Schuraytz et al. (1996), Shukolyukov and Lugmair (1998), Trinquier et al.
Vredefort	South Africa	300	27°00'S, 27°30'E	Chondrite	S, Os	(2006) Koeberl et al. (1996b)

only, others with major elements in comomation with a number of trace elements that appeared to be sufficiently different

inglici deviations for Cao and MgO in the succites (Table 7). Discrepancy factors do not change significantly when a in abundance from component to component The conditions C-rich shale component is included. The results show that

Table 5. RE-OS abundances and isotopic compositions of Gardnos rocks.								
Sample	Re (ppb)	<sup>188</sup> Os	Os (ppb)	<sup>187</sup> Os (%)	<sup>187</sup> Re/ <sup>188</sup> Os	<sup>187</sup> Os/ <sup>188</sup> Os	( <sup>187</sup> Os/ <sup>188</sup> Os) <sub>650Ma</sub>	
Target rocks								
NG-94-2 (Amphibolite) NG-94-11 (Gneiss)	2.36 0.0029	18.2 2.34	0.0346 0.0035	26.0 4.62	435.2 4.17	2.605 0.363	-2.06 0.32	
NG-94-12 (Gneiss)	0.0003	3.71	0.0058	9.40	5.715	0.777	0.72	
Men-matrix drecclas								
NG-94-30	0.770	476	0.683	1.87	5.437	0.141	0.083	
(-12% Amphibolite)	0.48				3.442		0.104	
(-20% Amphibolite)	0.30				2.107		0.118	
NG-99	1.98	231	0.332	1.82	30.17	0.137	-0.19	
(-12% Amphibolite)	1.69				24.61		-0.127	
(-20% Amphibolite)	1.51				21.86		-0.097	

French et al. 1997

and warker, 1775), rotar analytical oranks used for corrections were / pg for Os and 12 pg for Ke, Os is given in units of to Os (ppb) is total Os including radiogenically-derived <sup>187</sup>Os, the percentage of which is given in the next column; the precision of abundance and isotopic compositions for Re and Os is usually about 0.5 rel%; total errors including error propagation from spike calibration are up to 1-3 rel%. -3 rel%. COTR/DQ Factor the two mel-masix breeches were also re-laiculated sunfig 12 and 100 langhibilites surfuliton there also were then used to calculate initial <sup>187</sup>Os/<sup>188</sup>Os ratios that are corrected for the high Re input from the amphibolite, to better show the possible presence of an extraterrestratement rites (e.g., Smoliar et al. 1996; Koeberl et al. 2002)

Possible amphibolitic contribution?

+ avg. Ir content of  $1.3 \pm 0.4$  ng/g in suevites



lithologies, modified after Kalleson et al. 2008





# 15 samples were analyzed for major, trace, and PGE content

Large variations in Ni (1–176 µg/g), Cr (1–71 µg/g), and Ir (bdl-1.926 ng/g) contents. Highest PGE at boundary between suevites and overlying post-impact sedimentary infill.







#### All extremely well correlated! = Single, common source





French et al. 1997 > chondrite? Compare to chondrites: Morokweng, Popigai, Lappajärvi







French et al. 1997 > chondrite? Compare to chondrites: Morokweng, Popigai, Lappajärvi

Close but no cigar!





# Recently, different type of projectile has been ID'ed: Non-magmatic iron (NMI) meteorites



#### What are NMI (IAB, IIICD, and IIE irons)?



IA Udei ~ 20 vol% silicates in iron matrix but can contain up to 90 vol% and more! (Mittlefehldt et al. 1998)

Second largest group of iron meteorites, including Canyon Diablo (Barringer Crater)

NMI are irons that underwent poorly understood processes Break-up and reassembly of the same parent body

IAB irons + primitive winonaites = common parent body and link with the IIICD irons (e.g., Mittlefehldt et al. 1998).

H chondrites + silicate inclusions in IIE irons = similar bulk and mineral compositions, textures, and O-isotopic compositions (Olsen et al. 1994; Casanova et al. 1995)

Main mineral phases are olivine, pyroxene, and metal = OC

= S-type asteroids?

However metallic iron has no characteristic absorption band and is hard to recognize from Earth (Burbine 2002)

Future plans: confirm + constrain metal/silicate ratio using Cr isotopes

# Implications?

Gardnos was not formed by an ordinary chondrite, but by a related type of impactor, namely an 'iron'

Meteorites, asteroids, and impactors = mixture with a range in compositions + different genesis

Building blocks were all the same = chondritic

>

Larger structures (~ 5 km) also created by iron meteorites

Thank you!