The Search for a Meteorite Concentration Mechanism in the Allan Hills Icefields

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Introduction

The search for meteorites on the continent of Antarctica is an activity that has taken place for a relatively short period of time in history, yet the discoveries have been extremely prolific. The first reported Antarctic meteorite was found by Douglas Mawson's team during the 1911-14 Australasian Antarctic Expedition, only a year after man had first reached the South Pole. The next documented meteorite discovery wasn't until 1961, which was followed by another find in 1961 and a subsequent find in 1964. The finds up to this time were too few to indicate anything special about this place, yet all of the finds thus far were on blue ice surfaces, bare surfaces of the Antarctic glacier blown free of snow.

In 1969, a Japanese expedition stumbled across two stony meteorite pieces on a blue ice surface far from moraines and local rock concentrations, and over the next few days, they recovered 7 more meteorites. After return and analysis of these unexpected finds and 12 more finds in 1973, the Japanese decided to organize a special meteorite searching party in 1974, to see if they had indeed come across a meteorite concentration area. Not only did they find an astonishing 663 meteorite fragments that year, but the following year's search yielded 307 more pieces, all in the same blue ice field surrounding the Yamato Mountains. This blue ice field covers 4000 square kilometers in area, and to this day it remains one of the most productive fields on Earth [12].

In 1976, a joint U.S.-Japanese party searched across the continent from the Yamato Mountains in Victoria Land, near McMurdo Sound and the American research station, in order to ascertain whether other blue ice fields yielded meteorites. Nine specimens were found 230 kilometers northwest of McMurdo, in a series of blue ice fields near the Allan Hills (see Figure 1). This discovery led to the question of whether meteorite concentration fields existed elsewhere in Antarctica, and since that time, Japan and the United States have sponsored annual meteorite hunting expeditions [12]. To this day, thousands and thousands of meteorites have been found in blue ice fields all over the continent of Antarctica, and the knowledge gained from these finds with respect to the history of the solar system and its formation, the rate of influx of meteorites to the Earth, and even with respect to the movements of the Antarctic ice sheet, has been enormous. The Allan Hills Icefields have proven to be one of the most prolific sites of them all.

Ice Dynamics

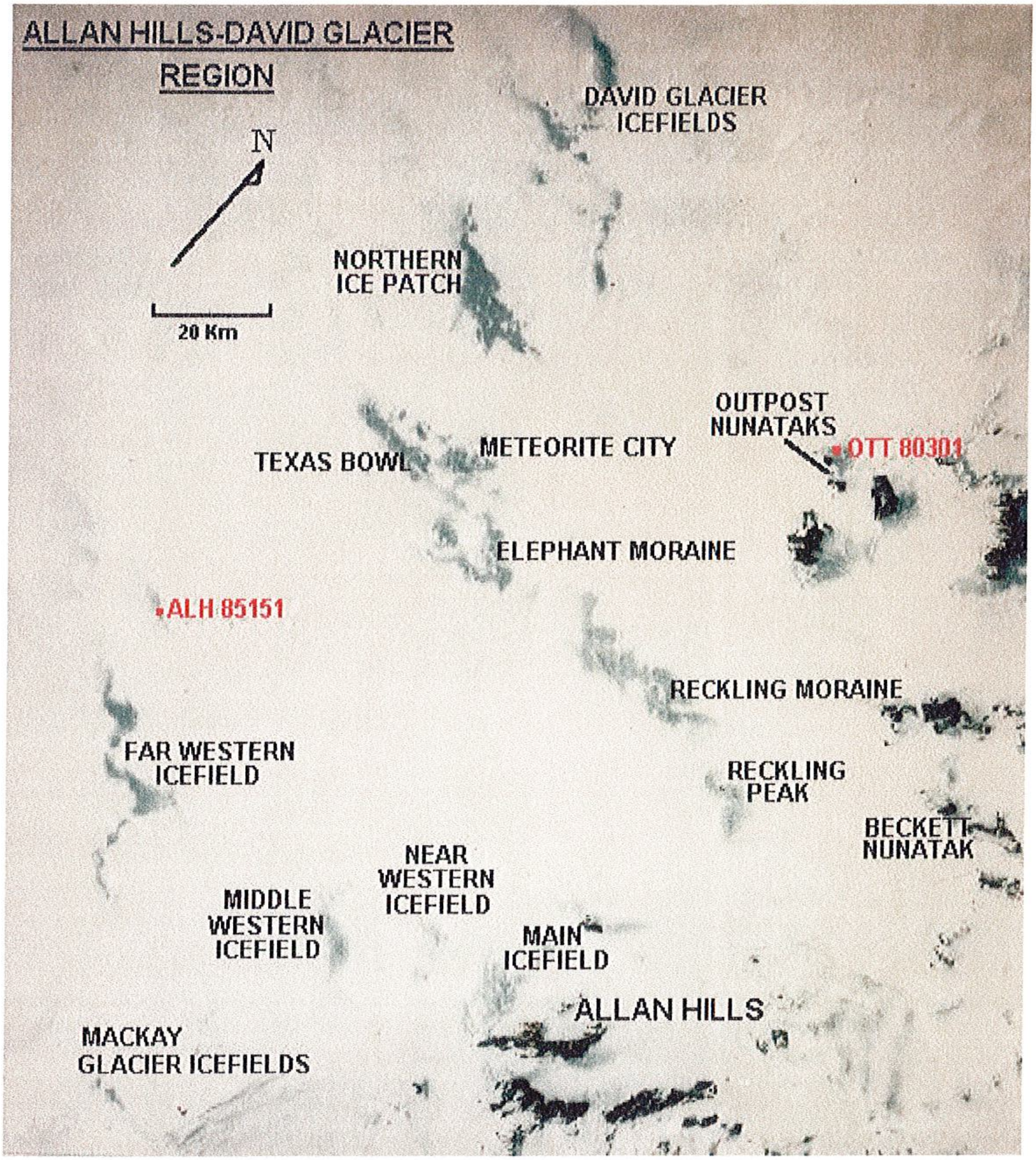

Figure 1. Geography of the Allan Hills Icefields and surroundings. Ice flow around the Allan Hills Icefields is generally west to east. The eastern edge of the Main Icefield is the most heavily concentrated find area, and represents that part of the ice which is stagnant due to flow blockage by the Allan Hills (courtesy AMLAMP, 2001).

Since almost all Antarctic meteorites have been found at or near blue ice fields, that is a clue that there is something special about these fields. What makes them, and why are they meteorite gold mines? That is a question that has driven much geophysical research, yet still has not been completely answered. To attack the problem, we must look at the mile-thick Antarctic ice sheet, its dynamics, and the ground that it is moving over. The Antarctic ice sheet is one large glacier, the size of a continent. Its topography can be described as a large dome, with the highest point in the center. At this center is the thickest part of the whole sheet, and the rest of the sheet is moving radially outward from that center, due to gravity and the plastic behavior of the ice itself. Ideally, each part of the outward-moving ice (and its contents) would just travel out beyond the edge of the continent and over the sea, to eventually calve off, become an iceberg, and spill its contents into the ocean.

However, mountains, escarpments, and rugged topography below the glacier create blockages and diversions to the ice flow. In the case of the Allan Hills, a sub-glacial monocline coupled with a series of nunataks (mountains or rock outcrops above the ice surface) creates an ice escarpment and blockage that leaves parts of the ice with nowhere to go, so that the resulting ice field becomes stagnant. High winds blowing off the higher glacial slopes blow the snow away from the ice surface in places, exposing bare ice fields that shine a deep blue. As up-glacier ice (to the west) keeps flowing eastward downstream and adds to the Allan Hills Main Icefield, that glacial volume has nowhere to go but straight up, turned upward by the nunatak obstructions. This phenomenon is the key for understanding meteorite concentrations associated with blue ice fields.

Meteorite Concentration Mechanisms

As meteorites fall onto the Antarctic ice sheet, they are eventually incorporated into the glacier itself, as snow builds up over several years and attains a great enough thickness to compress the underlying snow into ice. Once a meteorite is incorporated into the ice sheet, it is carried along a flow line characteristic to that particular ice stream. Meteorites subsequently appear along with emerging ice on the bare blue ice surfaces produced by sub-glacial obstructions. Unincorporated meteorites are also moved on top of the ice sheet by surficial glacial movement. The "stranding surfaces" of the Allan Hills Main, Near Western, Middle Western, and Far Western Icefields (see Figure 1) are fed from the catchment or source region found near Dome Circe in North Victoria Land [1].

There are several theories of meteorite concentration by ice, yet they all share a common bond: meteorite transport by the ice sheet to stranding blue ice surfaces. The two most prevalent theories differ in relation to emergent location and concentration by either surface and/or internal movement. An early study [4] shows that the Allan Hills Main Icefield has a concentration of specimens that are terrestrially older than those found on the icefields to the west. The age discrepancy between icefields may shed light upon which mechanisms are at work, or it may be the result of a lack of interconnectedness among the fields.

Wind and direct falls are other factors of meteorite concentration [5]. Wind tends to move smaller specimens below 100 grams and concentrates them downwind in snow patches, generally to the east of the Allan Hills Main Icefield. Some researchers have suggested that direct falls imply a vertical, rather than horizontal, concentration mechanism [5]. Some meteorites are attributed to direct falls if their terrestrial ages are less than 10^5 years [2].

Study and Method

Since a great number of meteorites have been recovered from the Allan Hills Icefields, they are ideal for the study of specimen locations and characteristics. There is quite an extensive data base on these finds, which includes terrestrial residence ages, radionuclide activity levels, natural thermoluminescence (NTL), weathering data, size distributions, pairing, and locations [3]. Specific aspects of the data set, such as terrestrial residence ages and weathering classes, are compared to meteorite locations in an attempt to define a mechanism of concentration.

The terrestrial residence ages of selected specimens (>100 grams, to rule out wind transport as a location changing factor) have been listed for each of the four icefields. To insure a level of accuracy in ages, primarily both ^{36}Cl and ^{26}Al have been utilized. Since most Allan Hills specimens are terrestrially younger than 300,000 years, the ^{36}Cl age (with a half-life of 301,000 years) is probably more reliable than the ^{26}Al age, which has a half-life of 710,000 years. A gauge for the ^{26}Al equation (as outlined below) has been set with respect to ordinary chondrites, of which most of the listed specimens are.

The location of the found meteorites is an indication of both the emergence and accumulation zones [5]. Supra-glacial, or surficial, ice transport is generally faster than englacial transport within the ice sheet. Therefore, if the oldest specimens are always found near or at the eastern end of the Main Icefield, then surficial ice transport is not important, since that would tend to concentrate younger specimens to the east. On the other hand, if old specimens are found in any of the icefields to the west and/or at the western end of the Main Icefield, then supra-

Allan Hills Main Icefield

Number	Type	Mass (g)	Weathering	NTL	Terrestrial Age(10^3)	Ref.
ALH78043	L6	680	B		500± 80	[4]
ALH78076	H6	275.6	B		130± 70	[4]
ALH78102	H5	336.9	B/C		220± 80	[4]
ALH78105	L6	941.7	B		260± 70	[4]
ALH78109	LL5	233.2	A/B		240± 80	[4]
ALH78112	L6	2485	B		230± 70	[9]
ALH78114	L6	808.1	B/C		460± 80	[9]
ALH78128	H5	154.7	C	4.4± 0.2	180± 70	[4]
ALH78131	L6	268.8	B/C		360± 80	[4]
ALH79007	L6	142.3	A/B		45 ± 45	[4]
ALH79025	H5	1208	C	0.33± 0.07	>38	[7]
ALH79033	L6	280.8	B		110± 70	[4]
ALH80101	L6	8725	Be		>49	[7]
ALH80104	Iron	882			55 ± 55	[4]
ALH80132	H5	152.8	B		~95	[11]
ALH81009	Euc	229	A		120± 40	[8]
ALH81011	Euc	405.7	A/B		>49	[10]
ALH81107	L6	139.6	B		~171	[11]
ALH81115	H5	154.9	C		~226	[11]
ALH81183	H5	104.2	C		~26	[11]
ALH83003	H5	321.8	A/B		~244	[11]
ALH83005	H5	227.9	C		~341.5	[11]
ALH83011	L5	213.3	C		~158	[11]
ALH83013	H6	246.3	A/B		~37.7	[11]
ALH84056	L6	2140.3	Be		~171	[11]
ALH84071	H6	797.7	B		~142.5	[11]
ALH84101	H6	220.9	C		~129.5	[11]
ALH84111	H5	131.5	B		~53.6	[11]
ALH84118	H6	113.7	B		~26	[11]
ALH84167	H5	150.7	C		~25	[11]
ALH85035	LL6	420.1	C	6± 0.1	~191.5	[11]
ALH85037	H6	141.2	B/Ce	6.2± 0.4	~13	[11]
ALH85044	H6	104.8	C	20.2± 0.3	~532	[11]
ALH86603	H5	104.5	A/B	80 ± 2	~142	[11]
ALH90411	L3.7	5836.5	Be	20.5± 0.1	~37.7	[11]

Near Western Icefield

Number	Type	Mass (g)	Weathering	NTL	Terrestrial Age (10^3)	Ref.
ALH81015	H5	5489	Be		~19.6	[11]
ALH81104	H4	183.8	C		~25	[11]
ALH81113	H5	111.1	B/C		~74	[11]
ALH81119	L4	107.4	B		~300	[11]
ALH81161	H5	122.2	C		~13	[11]
ALH81247	L6	104.2	A/B		~158	[11]
ALH81295	H5	105.1	C		~40	[11]
ALH83001	L4	1568.6	B		~226	[11]
ALH83002	L5	367.1	B		~480	[11]
ALH83006	H5	230.2	B/C		~26.3	[11]
ALH83012	H5	202.7	B/C		~68	[11]
ALH84006	H4-5	16000	B/Ce		~158	[11]
ALH84055	H5	6900.5	Be		~26.3	[11]
ALH84066	L6	355.8	B	0.4± 0.1	~201	[11]
ALH84069	H5	1136.3	A		~226	[11]
ALH84083	H6	419.7	B/C		~263	[11]
ALH84100	H5	110.3	B		~50	[11]
ALH84110	H6	318.5	B/C		~85	[11]
ALH84121	H5	141.4	C		~108	[11]
ALH84131	H5	107.9	C		~50	[11]
ALH84139	H5	157.1	A		~161	[11]
ALH84159	H6	100.8	C		~226	[11]

Far Western Icefield

Number	Type	Mass (g)	Weathering	NTL	Terrestrial Age (10^3)	Ref.
ALH82103	H5	2529.2	B		~25	[11]
ALH82104	L5	398.8	A		~85	[11]
ALH82105	L6	363.3	A/B		~140	[11]
ALH82118	L6	110.9	A/B		21	[4]
ALH82122	H5	142	B		~158	[11]
ALH82123	L6	110.8	B		~13	[11]
ALH83010	L3.3	395.2	B		35± 35	[4]
ALH83101	L6	639.2	A		65± 65	[4]
ALH83102	CM2	1786.2	B/Ce		10± 1	[10]
ALH84001	SNC	1930.9	A/B	1.3± 0.1	11± 1	[10]
ALH84044	CM2	147.4	Ae		~971	[11]
ALH84062	L6	958.2	A/B		~127	[11]
ALH84068	H5	1114.1	B		~127	[11]
ALH84076	H5	368.7	B/C		~108	[11]
ALH84080	L6	286.8	B		~532	[11]
ALH84086	LL3.8	234	A/B		~13	[11]
ALH84091	H5	214.6	B/C		~68	[11]
ALH84097	L6	388.7	B		~96	[11]
ALH84104	L6	201.1	B		~142	[11]
ALH84114	H6	119.9	B		~68	[11]
ALH84134	L6	113.4	B		~266	[11]
ALH84155	H5	113.9	B/C		~373	[11]
ALH85013	C2	130.4	A		~341	[11]
ALH85019	LL6	632.8	A	17.9± 0.1	~161	[11]
ALH85022	L6	951.5	B	55± 4	~112	[11]
ALH85024	H5	387.7	B/C	<0.1	~74	[11]
ALH85027	L6	370.4	B	67± 4	~108	[11]
ALH85031	H6	200.6	B/C	0.9± 0.4	~82	[11]
ALH85034	L6	343.9	A	40± 3	~54	[11]
ALH85039	L6	140.2	A	26.6± 0.3	~40	[11]
ALH85045	L3.8	145	A/B	63± 2	~505	[11]
ALH85129	LL6	127.4	A/B	36± 2	~40	[11]

glacial transport may be an important factor.

Weathering Categories [11]

A≡ Minor Rustiness: minor rust haloes on metal particles, minor rust stains along fractures

B≡ Moderate Rustiness: large rust haloes on metal particles, extensive rust stains on internal fractures

C≡ Severe Rustiness: metal particles have been mostly stained by rust throughout

e≡ Visible evaporite minerals

One important note is that these categories are empirically determined, and thus can reflect subjectivity from find to find.

NTL (in krad@250°C) [11]

For meteorites with levels between 5 and 100 krad, NTL (Natural ThermoLuminescence) is related primarily to terrestrial history. Samples with levels <5 krad have NTL levels below that which can reasonably be ascribed to long terrestrial ages, and have probably had their thermoluminescence lowered by heating in the last million years or so (by close solar passage, shock heating, or atmospheric entry). Those samples with NTL >100 krad are suggested candidates for unusual orbital/thermal histories [6].

Terrestrial Ages

Listings with references from [4] are obtained from ^{36}Cl alone, and those from [9] are obtained from both ^{36}Cl and ^{53}Mn. Entries referenced to [7] and [10] are obtained from ^{14}C. Those listings from [8] are obtained from ^{81}Kr-Kr. These above ages may represent our most reliable data. Listings with references from [11] are obtained from ^{26}Al activity levels, as calculated using the decay equation:

$$\text{Age (in yrs)} = 710{,}000 \cdot \ln(A_a/A_m)$$

where 710,000= half-life; $A_a \equiv$ activity of meteorite; $A_m \equiv$ modern activity (~55 dpm/kg for ordinary chondrites) [courtesy John F. Wacker, Battelle, Pacific Northwest Laboratories]. Due to the long half-life of ^{26}Al, these may be our most unreliable data. Absolute values of all numerical results have been taken. Due to the nature of this logarithmic equation, when A_a/A_m gets small enough, the absolute value of the numerical result approaches infinity, and unreliably large figures result. Also, when A_a approaches 55, the numeric result's absolute value gets unreliably small. Initially, there had been a misunderstood factor of 1/ln(2) in this equation, and was omitted with the reasoning that a relative comparison of the results could still be made.

Conclusions

1. Meteorites with long terrestrial ages are indeed found in all four ice fields, according to the calculations.
2. There appears to be no correlation between weathering data and terrestrial ages. If there were, heavy weathering would accurately lead to an old terrestrial age, and light weathering would lead to the conclusion of a young terrestrial age. However, many more factors are involved than just weathering, and the system deserves to be looked at further with more factors added in, such as time within the glacier and surface exposure age.
3. Terrestrially younger meteorites may indicate direct falls.
4. Thermoluminescence data is sketchy and not easily correlated with terrestrial ages.

5. Suggestion: the Allan Hills Icefields may not be connected. The Middle and Far Western Icefields appear to be moving toward the Mawson and David Glaciers and do not feed the main Allan Hills region. Crevasse patterns [12] in the Near Western Icefield indicate a motion toward the Mawson Glacier also, but this icefield could be a possible feed into the Main Icefield (see Figure 1).

6. Meteorites presumably can surface anywhere blue ice is seen, and transport to outlet snouts can be classed as both supra-glacial and englacial.

Summary

The mechanism of the concentration of meteorites is a complex problem that deserves more research and attention. Data pertaining to NTL, terrestrial residence ages, and weathering should be continued for all available specimens and icefield recovery sites. The Allan Hills region is an area where a combination of concentration processes appear to be plausible. This particular region and subject needs further study, utilizing both past and future data sets.

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