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METEORITE CONCENTRATION MECHANISMS IN ANTARCTICA

by John O. Annexstad
NASA/Johnson Space Center
Houston, Texas 77058

Introduction The location of most Antarctic meteorite finds has been on stagnant, highly ablative surfaces known as "blue ice." A few fragments, mainly irons, have been discovered on mountain sides and within moraine fields but these finds are exceptions to the rule. The role of "blue ice" is that of transporter, concentrator and preserver of specimens from the time of fall until find. The actual processes involved in this role are imperfectly understood at present but a basic theory of the mechanism of concentration can be proposed from the ideas suggested by various researchers.

Blue Ice Blue ice is formed by the compression of sucessive layers of snow accumulation when the density reaches 830 kg/m^3 (60 to 100 m depth in Antarctica) and the air spaces between the grains are closed off. This high density ice reaches the surface when sub-glacial peaks or mountains and nunataks force the moving ice sheet upward. In general, surface blue ice is found near coastal mountains, moves very slowly if at all and is presumed to be quite old.

Physical descriptions of blue ice fields have been reported [1], [2], [3], [4]. All authors reported that the blue ice fields were regions of high ablation, of little or no surface melting and of high and rather constant wind velocities. Other features characteristic of surface blue ice fields are:

Surface cracks - small crack systems 1 to 5 mm wide interlace the surface ice and are oriented along and perpendicular to the direction of surface motion. The cracks are presumed to be tension features which contract and expand with changing air temperature. Whaleback forms - the ice surface is rippled or cupped in areas exposed constantly to the prevailing winds. This feature is elongated in the direction of wind motion, protrudes 5 to 10 cms above the surface and is separated from an adjacent cup by about 20 cms. Flow line streaks - surface bands of tephra or dust extend in a parabolic curve across blue ice fields. The bands are easily seen from the air. Moraines - medial and terminal moraines such as boulder fields and/or elongated strips of detritus related to nearby outcrops are commonly seen near the regions of highest ablation. Step features - these are ice cliffs produced by a sub-glacial obstruction (monocline) or the retarded motion of the ice sheet (compressive) that tend to be located upstream from the stagnant portions of the ice field. These features are quite often synonymous with large concentrations of meteorite specimens.

Concentration of Meteorities by Blue Ice - Hypotheses

Yanai-Nagata Model They [5], [6] discussed the concentration of meteorites found near the Yamato Mountains and concluded in their papers that transport by ice flow was the most plausible mechanism. Their model predicts that meteorites which fall in an accumulation area become an integral part of the ice sheet and are eventually transported along flow lines to the coastal regions of Antarctica. As the flowing ice reaches a mountain barrier which impedes forward progress the ice tends to flow upward (upwells) in a region where ablation removes the emerging ice. Meteorites entrapped within the ice are eventually exposed by ablation and remain uncovered on the ice surface.

This model assumes a steady state condition in the concentration area where the emerging ice is continuously scraped away by the ablation process at an equal rate. One author [6] suggested a rather long path length from the accumulation zone to the ablation zone and predicted that most meteorites fell at least 10^4-10^5 years ago.

Nishio et al. Model The ice taken from a borehole (8 meter) near the geographical center of the Allan Hills Icefield was examined petrographically [7]. The age of the ice was estimated at 20,000 yrs by using accumulation and uplift rates and the growth rate of grains in the samples. This model suggests that meteorites fell in an area within 25-40 km upstream of the concentration zone between 20 and 100×10^3 years B.P. The specimens were then transported slowly in submerged ice to a stagnant blue ice area which was produced by the barrier effect of the Allan Hills.

To explain the existence of large numbers of meteorites and the old terrestrial ages, the authors proposed that: 1 - during the last ice age the catchment (accumulation) area was expanded greatly and meteorites which fell during this time are still emerging in the concentration zone, 2 - the maximum terrestrial age of the meteorites could be an indicator of the time when the ice sheet covering the Allan Hills began to recede.

This model is based upon an estimated depth of the depositional ice between 500 and 1000 meters. The path length of meteorite travel within the ice is very short, but it does agree with their estimated age of the ice.

Whillans-Cassidy Model This model [8] employs standard glaciological considerations in the hypothesis and predicts that the exposed ice in the concentration zone must be very old.

Meteorites that fall onto the ice sheet are incorporated into the ice and normally carried to the sea without being concentrated. In special places, the ice is prevented from reaching the sea, ablates away at the surface, thereby exposing the contained meteorites. A characteristic of such ablation zones is compressive ice flow which helps to concentrate the specimens.

The rate of surface concentration of meteorites (M) is represented by

$$\frac{dM}{dt} = \gamma A_b + f - \dot{\varepsilon}_s M$$

where γ = rate of reappearance of meteorites which fell in the accumulattion area at the ablation zone

A_b = rate of ice loss in the ablation zone, f = direct meteorite falls in the ablation zone, $\dot{\varepsilon}_s$ = sum of the two horizontal strain rates (a negative quantity). This model assumes a steady state condition between the meteorite infall rate and snow accumulation and that meteorites are concentrated by steady ice sheet flow and that ice mass is lost through evaporative sublimation in the ablation zone. The authors predict that the ice in the ablation zone can be as old as 600×10^3 years, that the older meteorites (terrestrial age) are found nearer the snout of the glacier and the flowline is hundreds of kilometers long. The combination of catchment area size and meteorite infall calculations predicts accurately the number of specimens found in the Allan Hills Icefield.

Annexstad-Schultz Model In this model [9] meteorites which fall upon the Antarctic ice sheet are incorporated into the ice and transported along flow lines toward coastal areas. In a region like the Allan Hills Icefield where the seaward motion of the ice sheet is blocked from further movement, the encased meteorites are brought to the surface with the emerging ice and uncovered by the ablation process. Meteorites do not emerge only in the concentration zone, but anywhere between the snout of the glacier and the equilibrium line. The emergence zone can be many kilometers long and is produced by ice flowing over a subglacial obstruction, which causes uplift, and the flow blocking action of a mountain or nunatak. The emerging meteorites are transported by horizontal compressive movement toward the concentration zone where they are joined by direct falls on the ice surface. The time it takes for the meteorite to move from its emergent location to the concentration area is short in comparison to its terrestrial age.

State of Knowledge The hypotheses presented all agree on a basic theory of "blue ice" as a transport and concentration mechanism but they differ on the path length between accumulation and ablation zones. The path length will have a definite bearing on the terrestrial residence age of a specimen which falls in the accumulation area. Weathering as the main destructive force of a meteorite proceeds at a much faster rate if the specimen is exposed on the surface than if the specimen is encased within the ice.

The Annexstad-Schultz model uses quantitative data based upon surface ice movement and ablation measurements from the Allan Hills triangulation network [10]. The other hypotheses are generally based upon qualitative assumptions derived from general ice flow considerations and visual observations. Before a complete picture of the concentration of meteorites by the moving ice sheet can be derived the following data must be obtained:

Accumulation/ablation rates from the source region and the find area.

Surface flow parameters including accurate strain rates and vertical emergence/submergence data.

Sub-glacial topographic features from the source region to the find area.

Oxygen/hydrogen isotopic ratios from ice cores along the path length.

Weathering rates of meteorites showing the ice encased time and the surface exposure time.

Terrestrial residence ages of all found specimens as a function of find location.

From the data presented to date the hypotheses can be condensed to the statement: Meteorites that fall upon the Antarctic ice sheet are transported within the sheet along flow lines to emergent zones of high ablation. The uncovered specimens are transported by horizontal surface movement of the ice sheet to stranding zones produced by the retardation effect of a mountain or nunatak.

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