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Entrainment, transport and concentration of meteorites in polar ice sheets

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Glaciers and ice sheets act as slow-moving conveyancing systems for material added to both their upper and lower surfaces. Because the transit time for most materials is extremely long (10^2 - 10^4 a) the ice acts as a major global storage facility. Ice flow is not uniform, however, with considerable horizontal and vertical motions leading to concentration or dispersion in 3-dimensions. Externally induced changes to ice volume and and tectonic uplift of adjacent mountainous areas present complicating factors to meteorite accumulation.

Plainimetric concentration

The pattern of flow in the Antarctic ice sheet exhibits partitioning into distinctive drainage basins which may possess varying degrees of dynamic independence. Fig. 1 illustrates the principal ice drainage basins of the ice sheet as defined from the most recent geophysical studies (Drewry 1983).

It is quite clear that some of these basins are capable of concentrating, into quite small outlets, material accumulated over a very extensive inland catchment. The largest basins are the Amery-Lambert, the Byrd and Slessor Glaciers. They could be considered the ideal source areas for meteorite collection and plantimetric concentration. Meteorites discovered in Antarctica to date, however, show that in most cases their locations are peripheral to the large ice drainage basins. In certain localities they have no present-day relationship with major basins. This establishes a paradox between the apparent need to concentrate ice from as large an area as possible and the actual occurrence of meteorites in regions which at present possess only limited potential for such focussing.

This problem introduces the notion of stagnant inter-basin regions where the considerably smaller size of the catchment is compensated by its very sluggish dynamics. Consider a drainage basin such as the Byrd Glacier (Fig. 2). It has an area of $\sim$ 1 M km^2. Assuming a mean basin velocity of 50 m a^{-1}, a random infall of $\sim$ 5.2 meteorites per 10^6 km^2 a^{-1} (Olsen 1983) a steady state meteorite density would be achieved in $\sim$10 Ka with a steady-state population of 26000 meteorites. Consider a small adjacent basin near Darwin Glacier with an area of only 50000 km^2 and an average ice velocity of only 10 m a^{-1}. The steady-state population is 52000 - twice that of the more dynamic and considerably larger outlet. Although this is a simplistic result it nevertheless underscores the real situation that meteorite accumulation is favoured by areas of slow-moving ice which are found in zones between the major outlet glaciers. These regions are characterized by small ice thicknesses, and low driving stresses (Drewry 1982).

<u>Horizontal/Vertical motions in the Ice Sheet</u>

Meteorite collections require that material be brought to the local ice surface. The path traced out by a meteorite within an ice sheet can be separated into horizontal and vertical motion (Fig. 3).

The horizontal <u>direction</u> travelled by a meteorite will be determined by the maximum regional surface slope. The <u>distance</u> moved, per unit time (δt):

$$\delta x = \bar{U}\,\delta t$$

where $\bar{U}$ = column balance velocity

$$= \frac{1}{\rho_i} h \int_0^x M\,\delta x$$

where ρ_i = ice-column averaged ice density

h = ice thickness

M = surface mass balance

The vertical path per unit time is a function of the surface accumulation:

$$\delta_z = U_z\,\delta t$$
$$= M \left[\frac{H - h_m}{H}\right] \delta t$$

where

H = total ice depth

h_m = depth to meteorite below the ice surface

U_z = vertical ice velocity

In most parts of Antarctica M is usually positive (i.e. there is a net gain in mass) and meteorites are buried their depth increasing down the flowline. In certain peripheral regions M is negative (i.e. there is net ablation). In these areas there is upward ice motion which may eventually bring meteorites to the ice surface where they accumulate at a rate determined by U_z and the meteorite density in the ice.

Long-term ice sheet variations

A consequence of the model which suggests inter-drainage basin regions as key locations for meteorite accumulation is the need for long term stability of the ice sheet to allow concentration to take place. Drewry (1980) showed that at Allan Hills any ice sheet thickening of the order of $\gtrsim$ 100 m would effectively "flush-out" meteorites into Mawson Glacier and hence there had been little change to the ice thickness during the period of accumulation which was estimated, conservatively, between 17 and 33 ka BP.

Significant fluctuations in the extent and thickness of the East Antarctic Ice Sheet are known and on scales of 10^4 - 10^5 years which span the range of meteorite ages found at places like Allan Hills. Detailed discussions of these variations have been given elsewhere (Stuvier et al 1981). It appears that in places the ice sheet has thickened considerably (by more than several hundreds of metres) particularly in its outer regions such as the Transantarctic Mountains. Such thickening during the Wisconsin maximum (~ 17-20 ka BP) would be more than sufficient to destroy meteorite accumulation sites.

It would appear, however, that in places such as the Transantarctic Mountains Ice Age-induced thickness changes have not everywhere been of the same magnitude. Referring to the model of drainage basins, the major ice streams discharging through the Transantarctic Mountains act as the principal and sensitive regulators of the ice sheet to changes in inland mass balance, and sea level. In this manner they tend to buffer the inter-basin areas from all but the most extreme ice fluctuations and therefore preserve their slowly operating concentration mechanism.

Vertical tectonics

Bull and Lipschutz (1982) draw attention to the role that uplift in the Transantarctic Mountains may have played in disrupting ice flow and providing at least a partial cause for the initiation of meteorite accumulation areas. There is considerable evidence for uplift but until recently rates have been difficult to determine with any consistency or precision. Smith and Drewry (1984) in presenting a new theory for the uplift mechanisms of the Transantarctic Mountains discussed a number of uplift rates which indicate a consistent pattern of elevation of the order of 90 m Ma^{-1} (Fig 4) and sustained over the last 45 Ma.

This rate would suggest that the continued vertical motion of the mountain range has been a contributing factor within the period of the oldest meteorite found at Allan Hills when uplift would have been in the order of 70 M. 500 m of uplift would have occurred during the last 5.6 Ma. Such values suggest that the accumulation of meteorites may pregressively migrate inland and, in their present-day location, may be only relatively recent. [Fig. 5].

Proxy tracers in the Ice sheet

The determination of the source areas of meteorites and their transport paths is a problem of central importance since it relates not only directly to concentration mechanisms but to wider issues in glaciology and meteoritics.

Elucidation of past flow conditions is fundamental to a number of glaciological studies and any assessment of ice sheet margin stability or instability will assist in reconstructing the configuration and dynamics of the Antarctic ice sheet in the past and the resolution of a number of problems related to former ice sheet extent. If for instance meteorites with terrestrial ages in excess of 125 Ka BP were located in central west Antarctica (in the region of Mount Woollard or Mount Moore or the Whitmore Mountains) they would testify to the continued presence of the ice sheet in West Antarctica during the last interglacial and to long-term stability of that region. Such results are important in glaciology to evaluating the stability of West Antarctica particularly in predicting its response to CO_2 induced climate changes.

Accurately determined source areas and flow paths for meteorite accumulations, combined with good terrestrial dates on those recovered, will measurably assist in refining the meteorite infall rate to the Earth's surface, possibly elucidating variations due to latitude and certainly improving the various weighting factors devised for fragmentation and observational bias.

Meteorites per se do not allow their source areas within the ice to be pin-pointed. However the ice and snow into which a meteorite falls, and which moves with it to the concentration area, will encode information about the infall location. The principal environmental conditions being former elevation, temperature (also related to elevation) and age of the ice.

Elevation of the source area for instance, may be derived from the fact that pores within the snowpack or firn close-off at a given density and thereafter preserve a record of former ambient atmospheric pressure (Reynaud 1983, Jenssen 1983). Total gas content (V) (reduced to standard temperature and pressure) may be expressed in terms of pressure (P) and temperature (T) at pore close-off and a standard pressure (P_O) and temperature (T_O):

$$V = V_C \frac{P}{T} \cdot \frac{T_O}{P_O}$$

where V_C = proportional gas volume at close-off. Various corrections and refinements are required to the technique as described by Reynaud (1983) but it is possible to obtain a proxy indicator of the elevation of the surface entrainment location by analysis of the total gas content.

Temperature and hence also elevation may be obtained by determination of the isotopic composition of the ice. Oxygen (^{16}O, ^{18}O) and hydrogen (D) isotopes are principally used and their ratios relate to the condensation temperature of water droplets which precipitate as snow onto the ice sheet surface. The technique has been extensively used in Antarctica in yielding valuable information of former ice sheet temperatures as well as elevations and flow properties (see Robin (1983).

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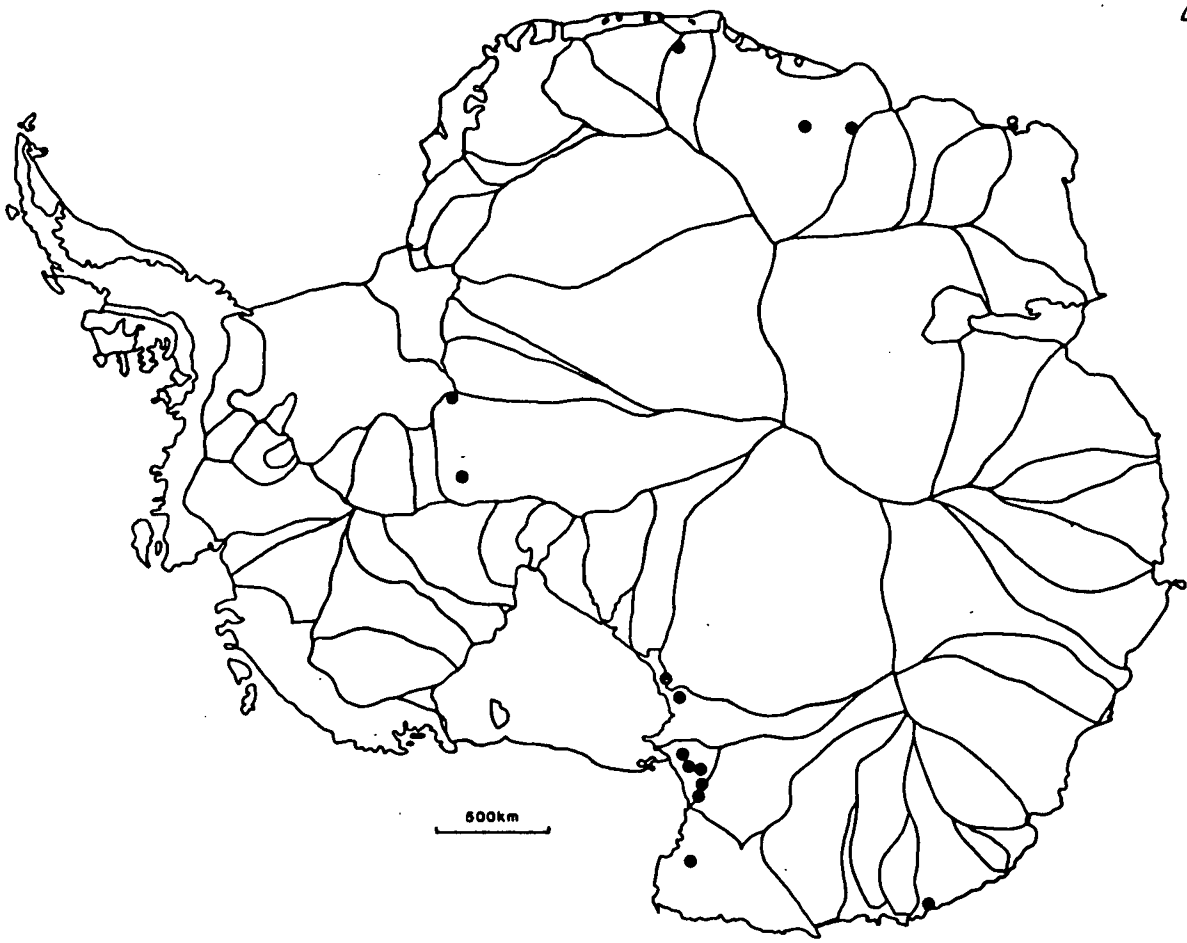

Figure 1 Principal ice drainage basin in Antarctica and location of meteorite accumulation areas.

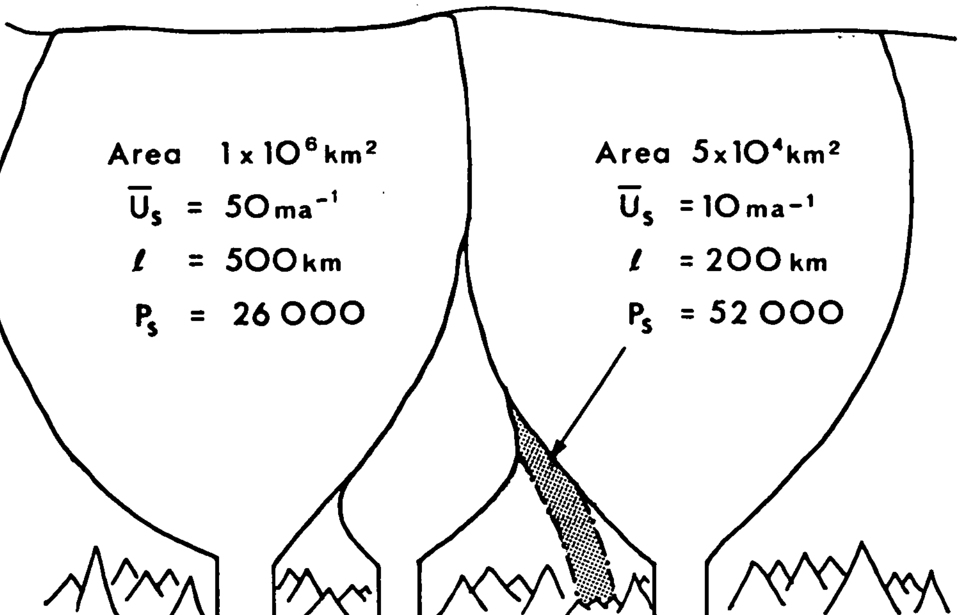

Figure 2 Comparison of steady-state meteorite populations (P_s) for a large ice sheet basin draining through an outlet glacier and a small inter-outlet basin. $\bar{U}_s$ = average ice velocity; l = flowline length.

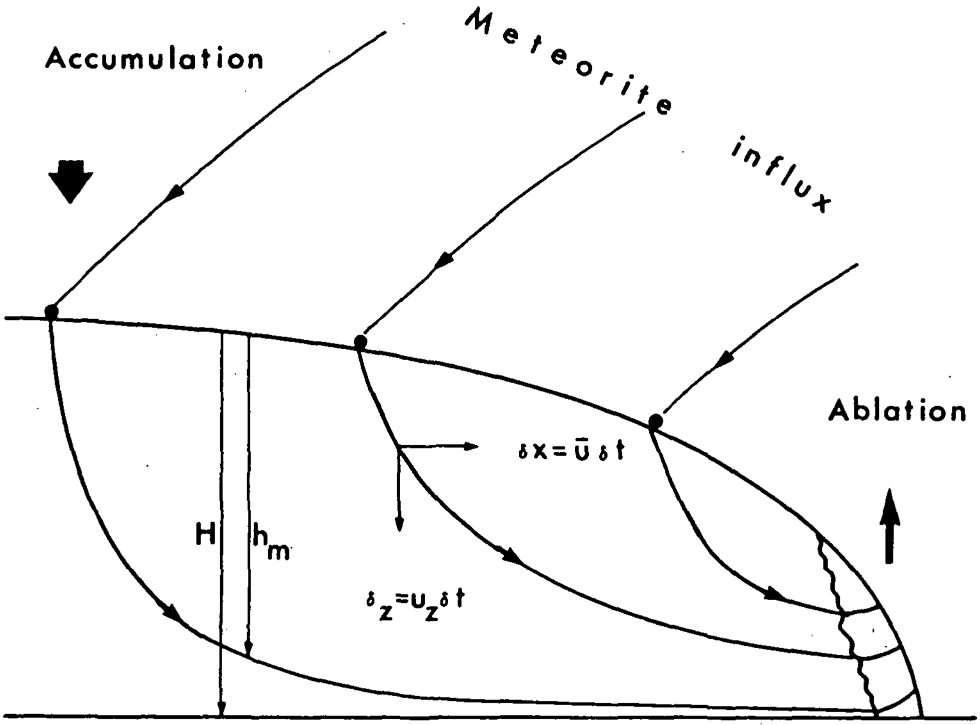

Figure 3 Vertical and horizontal motions in an cie sheet (see text).

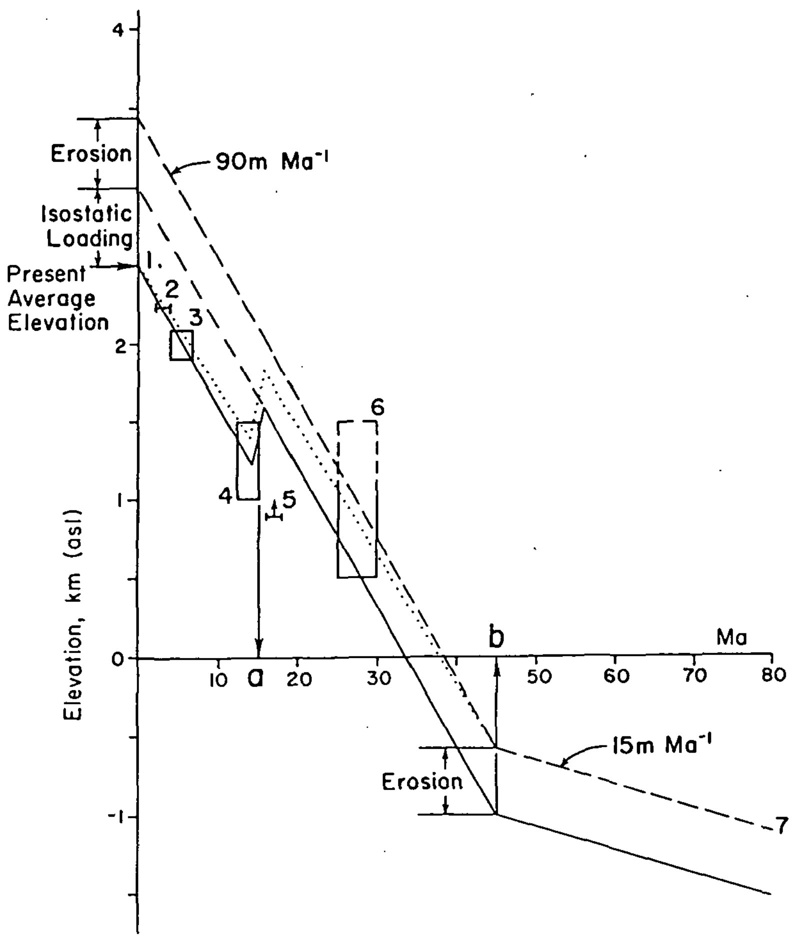

Figure 4 Uplift curve for the Transantarctic Mountains established from a variety of sources (from Smith and Drewry, 1984).

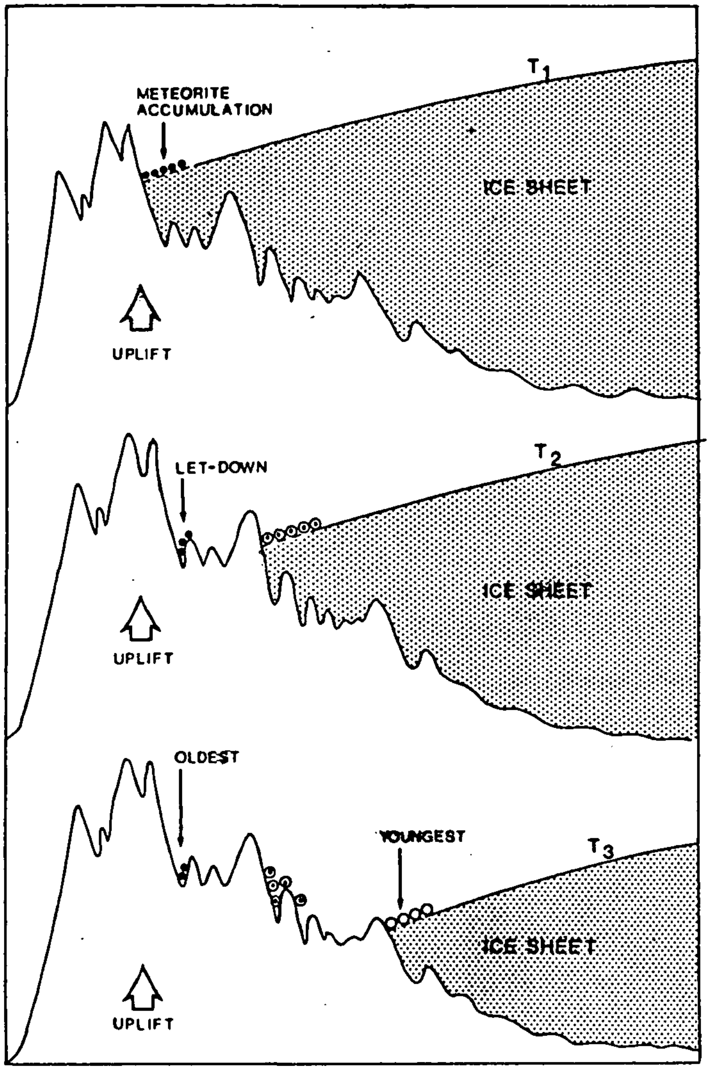

Figure 5 Cartoon depicting the effect of tectonic uplift on meteorite accumulations on the inland flank of the Transantarctic Mountains.