THE BROKEN BELT: METEORITE CONCENTRATIONS ON STRANDED ICE. R. P. Harvey, Department of Geological Sciences, Case Western Reserve University, Cleveland OH 44106-7216 (rph@cwru.edu)

Introduction: Since the first Antarctic meteorite concentrations were discovered more than 25 years ago, many theories regarding the role of iceflow in the production of meteorite concentrations have been put forward, and most agree on the basic principles [1-3]. These models suggest that as the East Antarctic icesheet flows toward the margins of the continent, meteorites randomly located within the volume of ice are transported toward the icesheet margin. Where mountains or subsurface obstructions block glacial flow, diversion of ice around or over an obstruction reduces horizontal ice movement rates adjacent to the barriers and creates a vertical (upward) component of movement. If local mechanisms for ice loss (ablation) exist at such sites, an equilibrium surface will develop according to the balance between ice supply and loss, and the cargo of meteorites is exhumed on a blue ice surface. The result is a conceptual "conveyor belt" bringing meteorite-bearing volumes of ice from the interior of the continent to stagnant or slow-moving surfaces where ice is then lost and a precious cargo is left as a lag deposit. Cassidy et al. [4] provides an excellent overview of how this model has been adapted to several Antarctic stranding surfaces.

Conveyor Belt Models: This "conveyor-belt" model actually incorporates two distinct meteorite concentration mechanisms, both of which reduce the volume of the ice substrate. Continued precipitation gradually compresses surface snow into ice at depth; typically this transition occurs at about 50 meters [5]. Conversion of snow to ice typically reduces the vertical dimension of a given stratigraphic sequence by a factor of 10x or more. As a result, a volume of deep glacial ice represents a much larger accumulation time than the same volume of surface snow, and thus contains a concentrated meteorite sample. Simple delivery of surface snows from one site to another does not concentrate meteorites; but the delivery of deep glacial ice through upward movement by the "conveyor-belt" models is a true concentration mechanism.

Ablation: The second concentration process implicit in "conveyor-belt" models is a continuation of the theme of reducing ice volume , but taken to the extreme through physical loss of ice. In principle, the simple loss of ice through ablation should be enough to produce a meteorite concentration regardless of iceflow or volumetric conversion of snow to ice [6]. As ablation removes surface snow and ice it leaves behind any meteorites those layers contained; over time continued ablation will therefore remove many layers and leave a surface with meteorites representing all the years of accumulation the lost layers represent.

The possibility that ablation can act as the sole or dominant process behind meteorite concentrations has been discounted by some authors, who note that the number of specimens recovered from some icefields far exceeds any reasonable estimates based on known influx or ablation rates [e.g., 4] In addition, the ice movement aspects of the "conveyor belt" model have been of more frequent interest to glaciologists because of their relevance to larger scale studies, while the local nature of ablation limits its possible significance on the scale of the icesheet [7,8]. But within combined models, the perception that ablation is less important than ice movement seems to be changing. Recent studies of the occurrence of meteorite concentrations at the Lewis Cliff Ice Tongue and Frontier Mountains icefields show that ice movement rates are very low where concentrations are highest, suggesting "conveyor belt" delivery is currently a very minor component [9,10]. This makes sense given well-documented climatic changes that have drastically reduced the thickness of the East Antarctic icesheet, particularly at its margins, since the last glacial highstand roughly 20,000 years ago [11]. The deflation of the ice sheet surface and redirection of iceflow resulting from climate change may be directly responsible for the meteorite concentrations we see today; while the widely held "conveyor belt" model may be, in fact, inactive.

Updating the "conveyor belt" models requires paying attention to these important constraints:

Meteorite-bearing blue ice fields are sites of confined, highly localized ablation embedded deep within the accumulation zone, far from its margins or terminus. This is unequivocal evidence that they deviate substantially from the generic icesheet-scale mechanisms portrayed by early "conveyor-belt" models, where large-scale directional flow from interior accumulation regions to distal ablation regions is the norm. Individual meteorite stranding surfaces are places where small-scale geography and microclimate factors have driven ablation and iceflow rates away from regional norms, and regional considerations are of baseline value only. Understanding a specific meteorite concentration thus requires an understanding of bedrock geometry, iceflow rates, ablation rates and other factors that may be entirely unique to this individual site, while subsets of this data may prove inadequate or misleading.

Reduction of icesheet volume is a key factor. If a penultimate broad scale phenomena is to be invoked as a driving force behind meteorite concentrations, climate change may be a better choice than ice sheet dynamics. All meteorite stranding surfaces seem to share a basic trait- ice loss by ablation exceeds ice input by horizontal flow. But rather than treat these two mechanisms as distinct, they should be considered as closely linked symptoms of the broad deflation of the East Antarctic icesheet surface since the last glacial highstand (about 18,000 years ago). A correlary to this consideration is that most meteorite stranding surfaces are currently far from equilibrium; they are a response to continuing reduction in ice sheet volume rather than a response to stable conditions. Models for most individual meteorite stranding surfaces must be consistent with continual ice volume loss and surface deflation over the past 20,000 years, and episodic ice loss and gain over the past several million years.

“Stranded” ice instead of "conveyor belts". Many meteorite-bearing blue ice areas contain regions where horizontal iceflow rates are phenomenally low. Such sites represent an endmember in the continuum of iceflow conditions, places where horizontal outflow has essentially ceased and inward iceflow velocities are orders of magnitude slower that that seen on the larger regional scale. The most recognizable of these sites are in downhill settings, resembling a shallowly sloping alpine glacier flowing downhill from snowfields adjacent to the polar plateau with constrictions at their sides and significant morainal development at their terminus. Others are more subtle and offer no immediately obvious clues to their existence; stranded ice may be separated from moving ice only by a shear zone and may be expressed at the surface as a blue ice valley within a larger ablating area. Such sites presumably were well-supplied with incoming ice in the past , but continual reorganization of iceflow since the last glacial highstand has eventually cut off their source. By definition, such sites are no longer a part of local icestreams; therefore derailing any significant “conveyor belt” meteorite delivery process. With losses from ablation and sublimation exceeding the rate of inflow, ongoing loss of ice volume and surface deflation are the driving force behind any meteorite concentrations that might be present. Unfortunately, stranded ice sites can only be distinguished by high-resolution, long-term studies of ice movement and bedrock topography; only rarely are they visible in photographs as regions of crossing streamlines (Fig. 1). However, the mechanism has previously been proposed for sections of one important icefield (The Allan Hills Main Icefield) and suggested for another (the Lewis Cliff Ice Tongue) [12,13,4]. Meteorites with terrestrial ages exceeding 3 million years (roughly two orders of magnitude older than the mean terrestrial age for Antarctic meteorites) have been recovered from the periphery of the Allan Hills and Lewis Cliff sites, strengthening the suggestion that these sites contain stranded ice. That such old ice exists is not in question- stranded ice in the Dry Valleys of McMurdo Sound with ages approaching 8 million years are known [14]. These ice bodies represent stranded ice, formerly a part of a major drainage system, that are nearly 20x older than the oldest ice in the currently flowing parts of the icesheet [15].

Figure 1. Contrast-enhanced aerial photograph of stranded ice near Coalsack Bluff in the Walcott Névé, Transantarctic Mountains, East Antarctica. Cross-cutting stream lines indicate shear between faster moving ice on the left and slower, stranded ice on the right.

The result is a concept of meteorite stranding surfaces as ephemeral products of local and relatively short-lived glacial phenomena. The icefields we see today, therefore, are likely to be a mixture of sites, some of which were “flushed” by increased iceflow during the last glacial highstand, and others where flushing was incomplete or minimal [4]. For meteorite stranding surfaces, the result may be a very complex stratigraphy; with many ages of ice welded together and meteorites with terrestrial ages from a series of intervals including, but not necessarily limited to, the modern deflationary period. The full complexity that such behavior implies, however, is only now beginning to be grasped.

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