PERSPECTIVES: PLANETARY SCIENCE

A Meteorite Falls on Ice

Jeffrey N. Grossman

Most meteorites that reach Earth's surface are pieces of asteroids and are older than any native rock on our planet. Meteorites thus provide a glimpse into the first few tens of millions of years of the solar system's history. The most primitive meteorites are made up of materials that contain the clearest accounts of the solar system's most ancient events, mixed up with exotic "presolar" grains that formed in other stars before the beginning of our 4.56-billion-year local history. Among these primitive meteorites, the CI carbonaceous chondrites hold a special place because they have nearly the same composition as the sun's photosphere (ignoring H and He) (*1*) and have experienced little thermal processing since the earliest history of the solar system.

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The more pristine meteoritic material of this type we can analyze, the better we will understand how our solar system formed and how the remnants of others came to be incorporated into it. It turns out, however, that CI chondrites and similar meteorites are rather elusive. The recent witnessed fall of the Tagish Lake meteorite (see the figure), the first analysis of which is reported by Brown *et al.* on page 320 of this issue (*2*), represents a unique opportunity to study such a meteorite in detail.

CI chondrites probably derive from so-called C asteroids (*3*). Astronomical observations show that such asteroids are relatively common in the outer parts of the asteroid belt (*4*, *5*). Nevertheless, it takes a series of lucky events to actually get a reasonable amount of this most primitive asteroid material to the laboratory in pristine condition. Over the last two centuries, only five of the nearly 1000 meteorites recovered from witnessed falls have been CI chondrites. Two 20th century falls in France, a 1911 fall in India, and a 1938 fall in Tanzania yielded a total of around 20 kg of material, but time and antiquated curation techniques have severely degraded these samples, especially for the analysis of low-temperature and organic components. In 1965, a CI chondrite fall was accompanied by a spectacular fireball over British Columbia, but only ~1 g of material was recovered (*6*).

The search for already fallen meteorites is even less promising. Of the >20,000 meteorites found on Earth whose fall was not witnessed, only two fragments of CI chondrites, totaling no more than about 15 g, have been identified, both in the Antarctic.

One likely reason why the fall and recovery of CI chondrites are so rare in proportion to the likely abundance of C asteroids is the inherent structural weakness of C asteroid materials (*7*). In contrast to the other stony meteorites, which have physical properties akin to terrestrial rocks, a reasonably close physical analog to CI chondrites would be dried mud. When a CI meteoroid enters Earth's atmosphere, it is much less likely to produce a fall of stones than a tougher object of similar size (*8*). The inherent weakness of CI source material means that what would otherwise be an annual event only occurs about once every 40 years. Furthermore, once CI chondrite fragments hit the ground, they are difficult to recognize—CI meteorites cannot be found with a metal detector—and disintegrate rapidly.

Witnessing the fall. The Tagish Lake meteorite left a widely visible contrail, aiding discovery of the meteorite fragments.

The recovery of the Tagish Lake (British Columbia, Canada) meteorite is therefore of particular importance. The meteorite fell on 18 January 2000 and was recovered 7 to 8 days later. Brown *et al.* (*2*) show that the meteorite is closely related to the CI chondrites and speculate that it may in some respects be even more primitive.

The Tagish Lake meteorite's recovery took an unprecedented run of good fortune. First of all, it is fortunate that the meteorite fell when and where it did. The fall happened in the middle of winter in a cold climate, mostly over a frozen lake, where the black stones could be easily recognized. If the conditions had been humid or wet, the meteorite would likely have degraded even in the few days before the first stones were collected. In fact, a large amount of Tagish Lake material collected months after the fall had undergone a few freeze/thaw cycles (the objects melted their way down into the lake ice) and had already mostly turned to mud. This fate also befell material from the 1965 Revelstoke CI chondrite fall, all of which was collected after several weeks on lake ice. Although some of the Tagish Lake meteorite's strewn field likely included forest, virtually no material could be recovered in the following spring or summer.

Most fortunate of all were the actions of Jim Brook, who found the first stones a few days after they fell. Brook had heard that it would be a good idea not to handle the meteorites and to keep them frozen. When he found the meteorite, he diligently collected about 1 kg in plastic bags and kept them in his freezer. These specimens have not warmed above 0°C since they hit the frozen lake. This is almost certainly the first time any fresh meteorite has received such treatment, and it could not have happened to a better sample. Tagish Lake now proves to be a highly primitive, volatile-rich, carbonaceous chondrite. The low temperatures seem to have hindered the loss of volatiles from the meteorites. The stones give off a strong sulfur odor when warmed to room temperature, as some of the volatile compounds evaporate (*9*).

In addition to the good luck of recovering such a large, pristine mass of a primitive meteorite, the fall of the Tagish Lake meteorite was widely enough witnessed to allow the calculation of an orbit for the original meteoroid, which has never before been done for a carbonaceous chondrite.

Future studies of this meteorite will be numerous and no doubt fascinating. Of particular interest will be results on the nature of the organic components that are preserved so well in the Tagish Lake meteorite. This provides a unique opportunity to expand our knowledge of the nature and origin of organic matter that may have accreted on early Earth and played a role in the origin of life. The carbon and

The author is at the U.S. Geological Survey, Reston, VA 20192, USA. E-mail: jgrossman@usgs.gov

nitrogen isotope results reported by Brown *et al.* also hint at a great abundance of interstellar grains in the Tagish Lake meteorite, which will likely spur a flurry of studies of those components. Petrologists and cosmochemists will be interested in this meteorite because it seems to have some chemical and textural properties transitional between highly primitive CI chondrites and the more processed CM group and may shed light on problems such as chondrule and refractory-inclusion formation and chemical fractionations in the solar nebula.

It seems likely that the Tagish Lake meteorite will be the most important recovered fall since the Allende (Mexico) and Murchison (Australia) events, both in 1969, touched off a revolution in our understanding of meteorites and what they tell us about the early solar system.

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PERSPECTIVES: PALEOCLIMATE

The Younger Dryas: Cold, Cold Everywhere?

Donald T. Rodbell

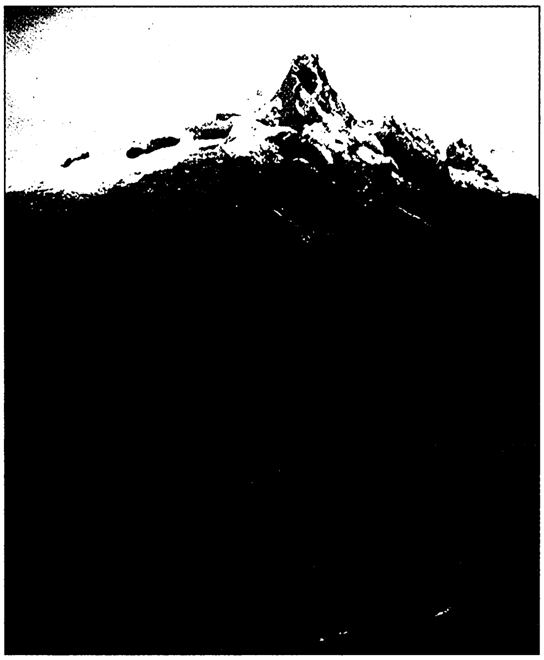
During the Younger Dryas (YD) period, climatic conditions returned to near full glacial conditions for about 1000 years, midway through the transition from the last glacial period to the present interglacial. This event has fascinated Earth scientists because it demonstrates a relatively recent instability in regional and possibly global climate. Evidence for this event was first documented in glacial deposits and pollen records from Scandinavia (*1*), which revealed a reexpansion of ice and a brief return of *Dryas octopetala*, a cold-tolerant flower, to the landscape. Subsequent marine and ice-core evidence has demonstrated a YD cooling in and around much of the North Atlantic (*2*).

On page 325 of this issue, Bennett *et al.* (*3*) report results of a study of fossil pollen grains preserved in lake sediments in maritime southern Chile that indicate that no such cooling took place in that region nor, they assert, elsewhere in the Southern Hemisphere. These conclusions are sure to generate passionate discussion among paleoclimatologists. Numerous workers have endeavored to document the global extent of the YD cooling, and few climate records have produced more conflicting results than those from South America.

Most evidence for the YD comes from regions in and around the North Atlantic, and this has led to speculation that its origin lies in the North Atlantic Ocean. One leading hypothesis (*4*) holds that the event was a climatic accident driven by an abrupt change in the flow of the melt water from the waning ice sheet that covered much of North America during the glacial period. According to this hypothesis, the melt water first took a route through the Mississippi River, but this changed to one that carried melt water to the North Atlantic, thereby upsetting the salinity balance of the North Atlantic so much that it briefly shut down the ocean circulation patterns that moderate regional climate. In the last decade, it has become clear (*5*) that the YD was but one of a series of millennial-scale cold snaps that punctuated the climate of the North Atlantic region over at least the past 50,000 years or so. YD-like events are thus far more common than previously appreciated, but both their cause and their geographic extent remain elusive.

If we knew to what extent these rapid climatic oscillations were felt in regions far from the North Atlantic, this may help to identify oceanic and atmospheric teleconnections that linked regional climates during glacial-interglacial cycles. Of the many cold snaps, the YD is most likely to be recorded in mid- and low-latitude lakes and glacial deposits because most lakes were formed during the last deglaciation and deposits from older glacial advances are commonly obliterated by subsequent advances. One exception is found in the Chilean Andes, about 300 km north of the area studied by Bennett *et al.* (*3*), where glaciers advanced in near lockstep with the predecessor cold snaps of the YD in the North Atlantic region, and another in New Zealand, where a similar pattern of glacial advance includes an advance contemporaneous with the onset of the YD in the North Atlantic (*6*). Synchroneity does not necessarily reflect a common cause, however, and climate change during the YD in some areas far from the North Atlantic has been very different from the cooling that occurred around the North Atlantic (*7*).

Many proxy climate indicators from both South and North America reveal climatic reversals of some kind during the last glacial-interglacial transition. Some of these appear to fit neatly into the North Atlantic climate template, but in many cases, dating is insufficient to rigorously



Traces of millennial-scale climatic change. Regional climate history can be inferred from proxy climate indicators such as the age of glacial landforms. Features such as the small moraine ridge (above) that crosses part of a valley floor in the Cordillera Blanca in the northern Peruvian Andes indicate that many glaciated regions of the world experienced unstable climatic conditions throughout the last deglaciation, but the evidence for a YD cooling in the Southern Hemisphere remains equivocal.

The author is in the Geology Department, Union College, Schenectady, NY 12308–2311, USA. E-mail: rodbelld@union.edu