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THE ST-ROBERT BOLIDE OF JUNE 14, 1994[1]

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(Received October 2, 1996; revised October 30, 1997)

ABSTRACT. The fall of the two tonne St-Robert bolide was widely seen and heard by witnesses on the ground and satellite systems in Earth orbit. The St-Robert fireball can be classified as ablation group I with a single fragmentation (IF) and strength group "d" (disruption at ~9 × 10^5 Pa) according to the system of Ceplecha *et al.* (1993). Its terminal disruption was characteristic of fireballs of that group and low entry velocity (< 15 km s^{-1}). The fragmentation event yielded an estimated 200 meteorites with masses in excess of 0.055 kg that fell in a strewn field measuring 8 km × 3.5 km. Plunge pits formed in the clay-rich soils of the region have depths proportional to the momenta per cross sectional area of the falling meteorites. Cosmogenic radionuclide results suggest that the meteoroid had a single stage exposure history and was significantly nonspherical. A tentative detection of the bolide by a seismograph allows provisional calibration of seismic observations of bolides using the satellite-derived energy and mass estimates. The value of the satellite and seismograph observations of the St-Robert fireball is enhanced because the bolide was typical of slow fireballs and was caused by the most common type of meteorite to fall (H5 chondrite).

RÉSUMÉ. La chute du bolide de deux tonnes de Saint-Robert a été aperçue et entendue par un grand nombre de témoins sur la Terre et par des satellites en orbite autour de la planète. Le bolide de Saint-Robert se classe dans le groupe I d'ablation, avec une seule instance de fragmentation (IF), et dans le groupe "d" de force (perturbation à ~9 ×10^5 Pa) selon le système de Ceplecha *et al.* (1993). Sa perturbation finale est caractéristique de boules de feu de ce groupe, ainsi que du groupe de pénétration de l'atmosphère à base vitesse (< 15 km s^{-1}). L'évènement de fragmentation a produit quelques deux cent météorites de masse de plus de 0.055 kg, qui se sont éparpillés sur un étendu de terrain de 8 km × 3.5 km. Les trous, creusés dans le sol riche en argile du terrain de la chute, ont une profondeur proportionnelle à la quantité de mouvement par section efficace des météorites en chute. Les résultats d'analyse des radionucléides cosmogéniques suggèrent que le météorite a eu une seule étape d'exposition et qu'il était notamment non-sphérique. Une tentative de détection du bolide par seismographe permet un étallonage provisoire des observations seismiques de bolides, en utilisant les données d'énergie et de masse provenant de satellites. La valeur des observations fournies par les satellites et les seismographes du bolide de Saint-Robert s'accroit parce que ce bolide est typique des boules de feu lentes et est le résultat de météorites les plus communs à atteindre la Terre (chondrite H5).

"Over Québec we beheld a great Ball of fire, which illuminated the night almost with the splendour of day — had not our pleasure in beholding it been mingled with fear, caused by its emission of sparks in all directions. This same Meteor appeared over Montreal, but seemed to issue from the Moon's bosom, with a noise like that of Cannon or Thunder; and, after travelling three leagues in the air, it finally vanished behind the great mountain whose name that Island bears."

— *from* The Jesuit Relations and Allied Documents, *volume XLVIII, describing an exploding fireball seen from southern Québec in the autumn of 1662.*

1. INTRODUCTION

As with inhabitants in all areas of the Earth's surface, observers in southern Québec see brilliant fireballs at a rate of a few per year. The frontispiece gives a description of an exploding fireball (bolide) seen from Montreal and Québec City in the fall of 1662. Three hundred and thirty-two years later a similar event occurred, a few moments after 8:02 p.m. EDT on June 14, 1994, as a two-tonne rocky asteroidal fragment entered Earth's atmosphere over the Canada-United States border travelling NNE at a velocity of ~13 km s^{-1}. The resulting daylight fireball was widely seen from the provinces of Quebec and Ontario and the states of New Hampshire, Vermont and New York at distances up to ~500 km (Brown *et al.* 1996). The rock fragmented spectacularly ~50 km northeast of downtown Montreal at an altitude of ~36 km; hundreds of fragments from

1 Based upon a research paper presented at the 1995 meeting of the Meteorite and Impacts Advisory Committee • Comité Consultatif sur les Météorites et les Impacts to the Canadian Space Agency, held in October, 1995, in Saint Hubert, Québec.

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the explosion fell in the parishes of St-Robert and St-Aimé located between the Richelieu and Yamaska rivers in the St. Lawrence Lowlands ~15 km southeast of the St. Lawrence River. Most local residents saw the fireball or heard the terminal explosion; the entire metropolitan area of Montreal was shaken by the blast. Some observers in the immediate fall area subsequently heard rocky fragments from the bolide falling to, and striking, the ground.

The first known meteorite recovery occurred 5 to 10 minutes after the event when Stephane Forcier removed a 2.297 kg meteoritic stone from a 25 cm-deep plunge pit in a field near his parents' house (located three kilometres east of the village of St-Robert). The stone was reportedly cool to the touch when first recovered, which probably represented a relic of the cold of space. Over the next three months at least an additional nineteen stones of 0.055 to 6.552 kg mass were found in the region, establishing approximate limits to the strewn field of the St-Robert meteorite fall.

Providentially, the fireball's terminal burst was recorded by satellites maintained by the U.S. Department of Defense, which allowed calibration of their observations with eyewitness accounts of the fireball and studies of the recovered meteorites (Brown *et al.* 1996). Although ground-based camera networks have accumulated many data giving insight into the characteristics of meteors and fireballs, including meteoroid orbits, they have been responsible for the recovery of only three freshly fallen meteorites (Ceplecha 1961; McCrosky *et al.* 1971; Halliday *et al.* 1978). The most common recovery circumstance for a fresh fall involves a meteorite falling to the ground within sight or hearing of a person, or within locales frequented by residents of a region; both circumstances occurred with the St-Robert fall. In only one case of such a fall has enough information serendipitously been available to determine accurately the prefall orbit for the meteorite (Brown *et al.* 1994). Continuous global satellite observations allow the possibility of recovering many meteorites from future falls, which will usually be events of larger size than previously available for investigation (*e.g.* Tagliaferri *et al.* 1994). Although the St-Robert object measured only ~2 tonnes and was ~1 m across, for example, it is nearly equivalent to the largest fireball previously observed by camera networks, but is almost the smallest fall that may be detected by satellite systems. The entire observing history of the Canadian camera observing system, the Meteor Observation and Recovery Project, is equivalent to only 30 hours of continuous global coverage (I. Halliday, private communication). A few years of continuous satellite observation will record the entry of objects of interest to asteroid researchers (> 10 m diameter), bridging the gap between observations by meteor camera networks and telescopic search programs. For example, the satellite systems recorded a fireball on February 1, 1994 (McCord *et al.* 1995) caused by an object of ~500 tonnes and ~10 m diameter (Brown *et al.* 1996).

The St-Robert bolide was also possibly recorded by a seismograph, allowing derivation of tentative coupling parameters between bolide mass and energy as derived from satellite observations, and the seismic response to sound waves created by terminal fireball explosions. Such a capability is useful for meteorite recovery efforts, as seismic networks already have the capability to locate positions and altitudes of terminal bursts (*e.g.* Qamar 1995), and now will be able to constrain the size of events as well.

Here we discuss phenomena associated with the St-Robert bolide, the search and recovery effort (and missed opportunities), the density of the meteorite and a revised entry model, radioactive cosmogenic nuclide results and meteoroid size and shape, and finally derive calibration factors for satellite observations versus seismic response.

2. Fall Phenomena

Bright fireballs (or, strictly, any single point on a fireball trajectory) are visible to distances of ~700 km from the surface of the Earth in clear skies. That limit results from the curvature of the Earth's surface and restricted thickness of the Earth's atmosphere. Observers located at higher altitudes may see fireballs at even greater distances (Folinsbee *et al.* 1967). Fireballs owe their visibility to the prodigious amount of energy being released as light and heat, while the atmosphere attempts to rid the entering object of its cosmic velocity. For a meteoroid in the ~one-tonne class like the St-Robert object, ~10^{11} joules must be lost in ~10 seconds, leading to power dissipation rates of ~10^{10} watts of which ~10^{9} watts is radiation (for a typical luminous efficiency of order 10%, *e.g.* Halliday *et al.* 1981). Such objects are therefore "billion watt bulbs" high in the sky. Their power generation rate is comparable to that generated by the Space Shuttle on lift-off, or to Niagara Falls.

Fig. 1 — St-Robert meteorite No. 5. This unusual elongated meteorite is 20 cm long and has a mass of 1,500.7 g. It was found embedded its length in sandy tilled soil with the "spear point" shown at the left oriented downwards. Note the different ablation histories of the three visible surfaces: the facing surface records very broad regmaglypt development indicative of prolonged erosion, the top surface shows well formed centimetre-scale regmaglypts indicative of moderate erosion, the corner to the right retains most of its freshly broken character with only incipiently developed ablation. The surfaces presumably record three ablation periods separated by at least two sequential episodes of fragmentation during the terminal burst. The matching piece to the right side is not yet found.

Brown *et al.* (1996) describe the fireball, dark flight, and sound phenomena associated with the St-Robert fall. Of particular interest is the character of the near-complete terminal disruption/fragmentation of the meteoroid. Visual satellite sensors recorded a minimum of 0.4 seconds duration for the

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event, with peak intensity at 00:02:26 UT at an altitude of ~36 km. Eyewitnesses reported two to four puffs of "smoke" punctuating the end of the dust trail with numerous radiating "streamers." The dust was usually described as gray-white. The unsmoothed optical light curve of Brown *et al.* (their figure 2) may show multiple episodes of fragmentation with an initial brightest flash followed by a twin-peaked flash following ~0.45 to ~0.6 seconds delay. The existence of the latter twin-flash fragmentation event is supported by infrared observations, which record a source after the first flash. Some of the St-Robert meteorites clearly showed the effects of the multiple fragmentation episodes. The meteorite illustrated in figure 1, for example, shows three surfaces with distinctly different ablation histories, establishing at least two episodes of fragmentation.

Reports of sounds heard may also support multiple fragmentation episodes. Brown *et al.* (1996) noted that several witnesses located up to 30 km from the fall ellipse reported three or four bangs preceding or following the main detonation. Possible origins considered for the extra bangs were multiple fragmentation episodes or sonic booms associated with a few of the largest individual fragments of the meteorite. Difficulties exist with the sonic boom origin, and variations in the reported sounds with witness location tend to support origin from multiple fragmentation episodes. Brown *et al.* noted that the largest fragments would have reached subsonic speeds at altitudes of ~15 km, substantially below and northeast of the main disruption point. The distances between sonic boom generation and the terminal explosion would thus have been up to ~25 km, corresponding to time delays of ~70 seconds; such long delays between sound arrivals were never reported. For witnesses downrange along the fireball trajectory, the sonic booms should also have been of long duration (~10 seconds of supersonic travel during dark flight). The observers would also have been equidistant from the supersonic paths and therefore would not be able to distinguish distinct bangs. The sharper sounds reported are more characteristic of point sources as in the fragmentation episodes. Although sonic booms have been reported for similar distances from fragment fall paths — *e.g.* ~30 km in the case of the Abee meteorite — that non-exploding fireball (which dropped a single large meteorite) had associated sonic booms of up to one-minute duration described as a rumble or as distant artillery fire (Griffin *et al.* 1992). Some observers reported the rumble beginning with an explosion. As that 107-kg meteorite was much larger than the St-Robert meteorites and continued its supersonic flight closer to the ground, and as the associated sound was of longer duration and less punctuated than reported for the St-Robert bolide, we presume that the sounds reported from the latter originated in the explosions. A still larger object, the 1,770 kg Kirin meteorite (more often referred to as Jilin), had audible sonic booms for up to four to five minutes, together with the sharp sound of its terminal explosion (Joint Investigation Group of the Kirin Meteorite Shower, Academica Sinica, 1977).

Miroslaw Adamczewski was located northeast of Yamaska, for example, downrange at ~5 km past the trajectory projection and ~45 km distant from the terminal disruption (~28 km downrange in ground projection). He reported a loud bang ~5 seconds long. While going outside a barn to look for the source of the noise, and then, after an interval of ~5 seconds, hearing two more sharper bangs that were less intense than the first. With a fireball speed of 12.2 km s^{-1} at disruption according to the satellites' infrared observations (Brown *et al.* 1996), the recorded flashes should have produced detonations (in order of arrival) of 5 to 15 and ~10 seconds duration, respectively, with ~15 seconds separation for observers downrange of the trajectory. If the latter twin-peaked flash was part of an extended disruption that produced the loudest and longest detonation, the reported sounds are qualitatively like those predicted (if the initial largest flash produced two sounds — the first from the explosion and the second from its reverberation), although the separation and durations are not good timing matches. In contrast, Jacques Grenon, located southwest (uprange) of the fall ellipse and approximately underneath the end of the luminous flight path (~20 km closer to the ground projection of the terminal bursts), heard only 10 to 15 seconds of continuous rumbling. Such reports suggest that the observers' positions relative to the fireball trajectory are more important to the timing and separation of sounds heard than is proximity to the supersonic portion of the meteorites' dark flight. In the absence of instrumental recordings and a model of sound paths through the atmosphere, however, the variability in the proximal sound descriptions can only tentatively be ascribed to the detection of discrete fragmentation events.

FIG. 2 — Part of a photograph taken on his balcony by Andre Dubois, who later drew the path of the fireball as he had seen it come below his balcony roof to end near his wind chime. The bottom edge of the roof corresponds approximately to the upper edge of the photo. The image is distorted because a wide-angle lens was used so that the photograph dip angles are not quite true. From field measurements the slope of the fireball trajectory is 77° ± 1°. Note two diverging fragments which split from main fireball.

M. Adamczewski's near line-of-flight location also allowed a favourable angle to report that the fireball's dust trail exhibited spiralling more pronounced than that of the photographed Pasamonte fireball wake (Nininger 1972). Because he was

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alerted to the dust trail only by the sound arrival, high altitude wind shear may be responsible for some of the reported distortion. He described the terminal dust cloud as white, in contrast to the spiral of brown smoke that reflected the earlier part of the trajectory. The colour change may reflect different dust origins, the darker brown colour indicating fused and ablated material (similar to the dark fusion crust developed on the meteorites), and the white coloured "puffs" reflecting powdered meteoritic material. The St-Robert meteorite shows a light gray colour on unweathered broken surfaces.

Brown *et al.* (1996) commented on the difficulty of deriving the slope of the fireball trajectory from conflicting eyewitness accounts (averaging all visual data yields a slope of 20°, versus 58° from instrumental observations) as a result of a typical observer's tendency to report elevations that are too low. On the other hand, the fireball azimuth was relatively well determined at 202° ± 5°. As noted by Brown *et al.*, some observers can give reports of good accuracy. Andre Dubois, for example, saw (and heard) the fireball from his covered balcony in downtown Montreal. A day or two later he photographed his view and sketched the fireball trajectory upon an overlay, yielding an observation of remarkable accuracy (figure 2). He reported seeing the fireball come into view below the edge of his balcony roof at elevation 27° (048° azimuth true), to travel downwards to the north at an angle of 77°, and to end at an elevation of 16° (050°.5). When projected, the observations indicate a fireball slope of 63°.5 which is within compass measurement uncertainty (one degree) of the instrumentally-observed 58°. With the trajectory position (and orientation) determined by the position of the 6.5 kg fragment in the strewn field, the witnessed fireball passage over Beloeil, and a burst position and altitude as described by Brown *et al.*, it requires an altitude of 34° to view the terminal burst from such a position. M. Dubois therefore witnessed only that portion of the fireball resulting from the largest fragments that survived the disruption event, establishing that the fireball persisted to lower elevations than recorded by satellite observations. With the trajectory as determined above, the bearings intersect the trajectory downrange of the terminal burst at elevations of approximately 27 km and 18 km altitude. The latter altitude for termination of visible flight is in good agreement with the theoretical entry model of Brown *et al.*, which places the passage through the visible limit at 4 km s^{-1} at 20 km altitude. The fireball was observed to split off two diverging pieces before the largest central piece extinguished in the sky, roughly consistent with the recovery of four large pieces of the meteorite. Eyewitness observations having several constraints/references on azimuth and elevation, plus their quick recording from the observer's position, are the next best record to photographic or other instrumental recordings of fireballs, and are often necessary to augment instrumental records when they do exist.

The fireball was presumably a type I event according to the classification of Ceplecha & McCrosky (1976), by virtue of its origin as the fall of a chondritic stone. Ceplecha *et al.* (1993) studied Prairie Network (PN) fireballs and found that type I fireballs exhibited three kinds of fragmentation behaviour in almost equal proportions: no fragmentation, a single episode, or multiple episodes of fragmentation. St-Robert is in the single fragmentation episode category (class IF), although the fragmentation event lasted ~0.6 seconds according to the satellite optical light sensors, and probably had more than one closely-spaced but distinct episodes. The revised entry model presented below shows mass loss at the terminal disruption to be ~98% (~1450 kg out of ~1480 kg). That compares with the range of observed mass loss fractions for Type I fireballs shown in figure 3. Reported mass loss fractions in fireballs observed by the Prairie Network showed two maxima in their distribution: a range of 50% to 70% broadly centred at 60%, and a tight peak at 95% to 99% fragmentation. The St-Robert fireball plots in the latter category. The terminal disruption occurred when the bolide was experiencing a dynamic pressure of ~9×10^5 Pa (Brown *et al.* 1996), at the high end of the range observed for PN fragmenting fireballs (Ceplecha *et al.* 1993), corresponding to strength class "d."

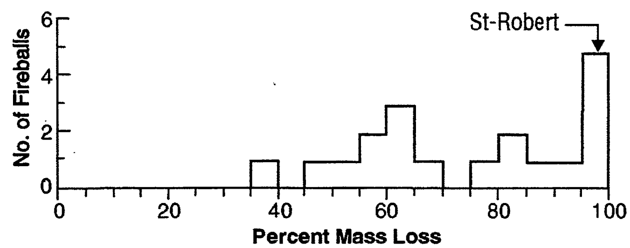

FIG. 3 — Proportional magnitudes of fragmentation events for 19 fireballs that experienced a single fragmentation episode, as observed by the Prairie Network (modified from figure 13 of Ceplecha *et al.* 1993). The St-Robert bolide at ~98% disruption plots in the 95–99% disruption increment, the most common behaviour exhibited for Type I fireballs.

The resulting implication for meteorite recovery is that all of the surviving individual fragments will be much smaller than the original meteoroid. The category of ~60% fragmentation corresponds to breaking the original meteoroid roughly in half, with some accompanying small fragments. In cases like that, recovered meteorites can sometimes be placed so as to reconstruct the original meteoroid, as in the example of the St. Severin fall; not much of the meteoroid is finely crushed. In the case of near total disruption, and particularly in the case of St-Robert, such a reconstruction is probably not possible even if all of the sizeable material on the ground was found, as so much of the bolide mass was pulverized. It is possible that some volume within the original meteoroid was more completely preserved, but none of the fragments recovered to date show any obvious matching surfaces. After all cosmic ray exposure tests are done, it will be interesting to revisit the question to see if individuals showing similar exposure histories may be conterminous in any way. A demonstration of matching would enable some insights into which portions of the bolide were most susceptible to crushing in the disruption event, and the extent to which the terminal disruption, and subsequent luminous and dark flight, can separate pieces previously in contact.

The fragmentation history of the St-Robert bolide was typical of its velocity and class. For meteoroids that exhibited single episodes of fragmentation (class IF) and had velocities of less

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than 15 km s^{-1}, Ceplecha *et al.* (1993) report that the fragmentation always occurred in the last second of visible flight. Higher velocity IF fireballs always displayed fragmentation during the first half of their trajectory. The similarity in behaviour is interesting in that the St-Robert bolide was more than 10 times as massive as the mass range typically observed by the Prairie Network, which suggests that such a fragmentation characteristic may be extrapolated to even larger sizes of meteoroids.

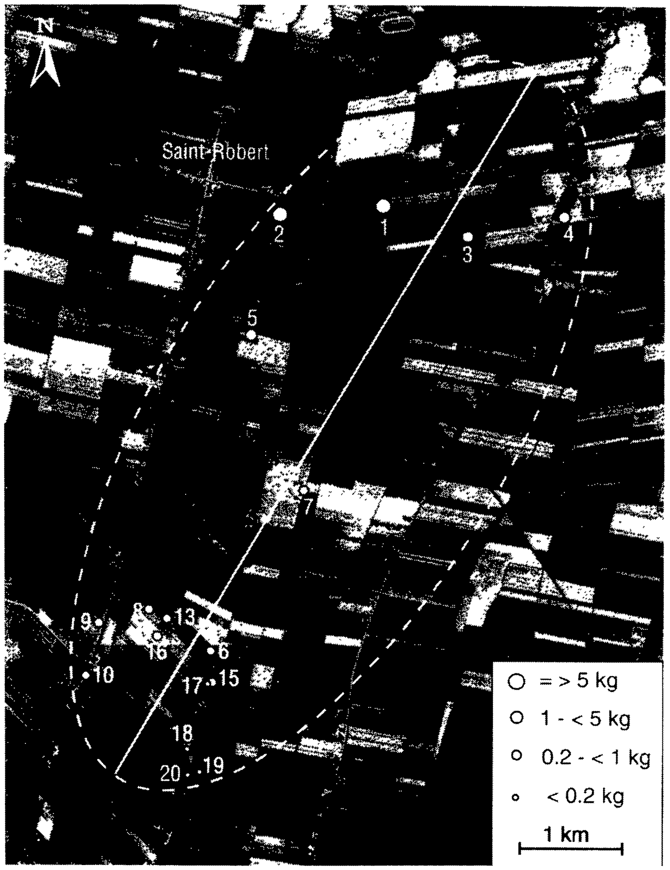

FIG. 4 — Strewn field of the St-Robert fall. Inconveniently for field-work and for portraying the strewn field, the fall area straddled the boundary of two 1:50,000 scale topographic map sheets — 31 H/15 Saint-Guillaume-D'Upton and 31 H/14 Verchères — near their northern boundary. The most recent series of ~1:50,000 air photos covering the area had been taken on August 22, 1984. Field checking revealed that only minor changes in land usage had occurred between that date and that of the meteorite fall, so a georeferenced mosaic based on four photographs, and corrected to the topographic maps, was constructed by D. Niehaus. Meteorite masses are indicated by sized dots as indicated in the legend.

3. Strewn Field and Meteorite Recovery

A well-mapped meteorite fall strewn field constrains the bolide's trajectory and size (*e.g.* Brown *et al.* 1996). The known distribution of meteorite recoveries is also the most useful guide to future search efforts. Figure 4 illustrates the strewn field of the St-Robert meteorite fall as known to date. The long axis of the observed strewn field ellipse (8 × 3.5 km) is oriented along an azimuth of ~210°, which is within uncertainty of the value of 202° derived for the fireball trajectory from eyewitness accounts (Brown *et al.* 1996). The down-range separation of fragments of varying masses corresponds well with the results of dark flight modelling. From a combination of the results from an entry model (as revised below) and dark flight calculations, a fall path for a 5 kg fragment from the terminal burst to ground contact can be constructed, as portrayed in figure 5. The computed path, with ~23 km horizontal displacement, compares to the down range horizontal distance of ~17 km to ~19 km between the observed burst point (as determined by eyewitnesses and satellite observations, respectively) and the recovery locations of the large meteorites; it is within the uncertainty of ±5 km for the location of the terminal burst for both methods.

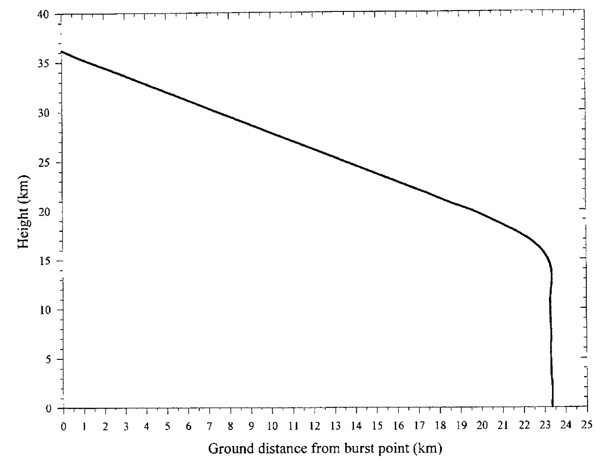

FIG. 5 — Lateral view of the fall path of the 5-kg St-Robert meteorite after terminal disruption. Note that the terminal near-vertical fall is distorted by opposing upper wind currents. Horizontal exaggeration of 2.25 times.

The distribution of meteorite recoveries was strongly influenced by land usage. Most pieces were found in yards (including one fragment that struck a shed), on roads, or in fields near homes — the places where people most often go. The remainder were found in fields in the course of cultivation or during dedicated searching. Fortunately, most of the fall area is agricultural land, which leads to fair opportunities for recoveries; forested land is restricted primarily to the west side of the ellipse. The fall showed pairings of recovered meteorites in three cases. That is similar to the pairing observed in the Bruderheim strewn field (Folinsbee & Bayrock 1961). It is not known if the pairings reflect chance juxtaposition or some effect associated with dark flight.

Most local residents had an awareness of the meteorite fall through media reports and educational programs, which resulted in recovery of half of the meteorites. The other half were discovered during dedicated searches of the region by residents and groups organized by the Meteorites and Impacts Advisory Committee (MIAC — the group in Canada charged with the recovery of meteorites) to the Canadian Space Agency. The most productive searcher was P. Sasseville, who found seven of the known specimens, followed by J. Hanes with three specimens and G. Jarret with two specimens; all others had single

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recoveries only. Figure 6 illustrates the date of meteorite recoveries relative to the time of fall. Meteorites were much easier to find at early times before vegetation growth and washed soil covered specimens and closed the shallow pits that they had often formed. Because the meteorites often did lie in shallow pits, and many such pits dug by small animals are found in the fields, P. Sasseville invented the technique of using a modified ski pole to check holes in the ground, a technique subsequently adopted by most searchers.

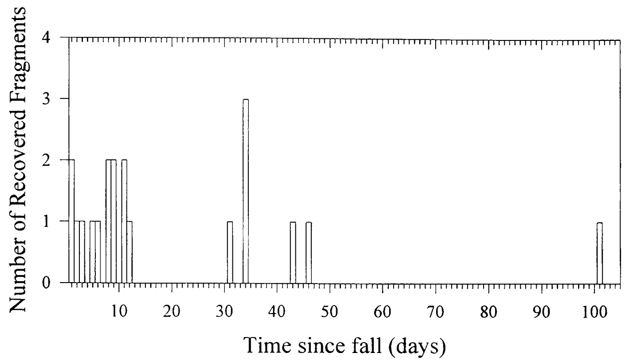

FIG. 6 — Distribution of recovered fragments as a function of time after fall of the St-Robert meteorite.

Most meteorites were recovered in the first two weeks subsequent to the fall, and no meteorites have been found since the first season, although Brown *et al.* (1996) calculate that more than 200 individual fragments > 0.055 kg fell in the region and remain unrecovered. Searchers from MIAC were active in the area days after the fall and intermittently through the 1994 season. More effort should have been concentrated in the first two weeks (an hour searching then having an advantage over a day searching after two months), and a continuous presence should have been maintained to take advantage of search opportunities as they appeared. For example, on the 34th day after the fall three meteorites were recovered when a hay field was cut for the first time since the fall.

The masses of the largest individual fragments to fall in a meteorite strewn field are the most useful data provided because fragmentation of the meteoroid typically follows power law relations (*e.g.* Fujiwara *et al*; Jenniskens *et al.* 1994). Estimates of the total fall mass on the ground may therefore be made using only knowledge of the largest masses. The power-law character of fragmentation relations also results in much of the mass in a fall occurring in the few largest pieces. If larger meteorite fragments exist, they will probably have travelled farther to the northeast of the meteorite recoveries, as outlined in figure 6. The dark flight model predicts that a 20 kg fragment will fly only ~1.5 km farther downrange than a 5 kg fragment. The area outlined in figure 7 for further searches extends ~3 times this distance from the ~5 kg pieces, so that any larger fragments (of expected sizes based on the mass distribution of meteorites recovered to date) are expected to have fallen within such an area.

The area outlined in figure 7 for further searches has been searched from the air 16 days after the fall at ~200 m altitude without success. Twenty-kilogram meteorites would be ~25 cm in diameter, and the tops of their plunge pits would probably be similar in size. High contrast objects of similar size, such as sea gulls, were easily visible in the fields during the aerial search. However, dark holes would have had less contrast as the shade of crops lowered contrast for dark objects, and the crops could have directly obscured plunge pits. One 3.708 kg meteorite was subsequently recovered from the search area, indicating that the aerial search was not able to find smaller plunge pits, although it is not known if tilling may have obscured the pit between the time of fall and the aerial search. Serendipitously, the fall area was photographed from the air with infrared sensitive film at a scale of ~1:15,000 on the morning of June 18, 1994, less than four days after the fall. Stereoscopic inspection of the air photos, which have a resolution of ~0.5 m, has not revealed any obvious plunge pits, including those of the known meteorites, with the exception of the first meteorite recovered on the Forcier farm. Its plunge pit is obvious from the path beaten in the grass to and around the pit by interested persons. Ground searches of the area outlined in figure 7 may still be practical, as larger meteorites may have made sizeable pits that could potentially endure longer than one growing season in untilled areas. Potential searchers should bear in mind that plunge pits of larger fragments will probably exceed 0.5 m in depth, and might be inclined towards the NNE.

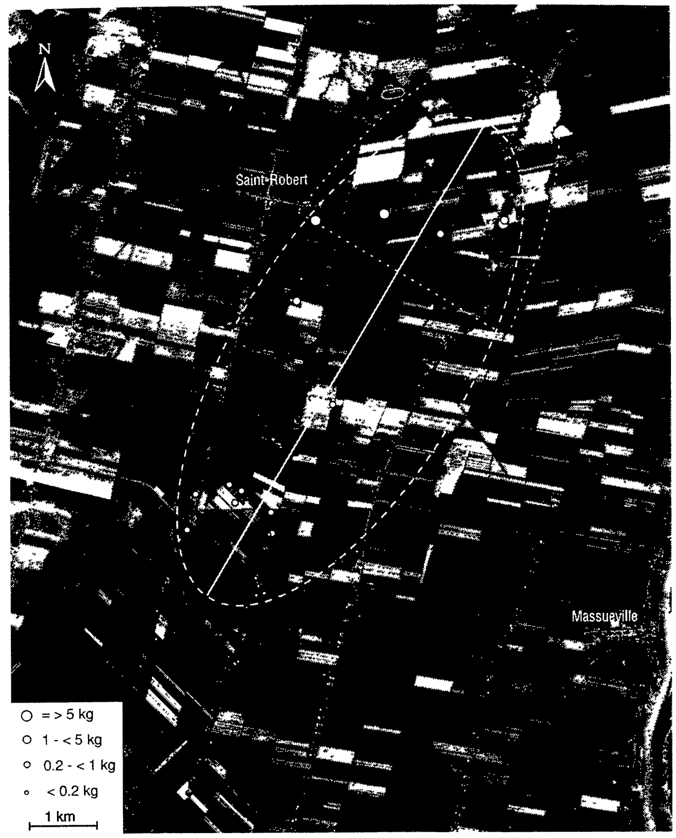

FIG. 7 — Recommended area for future ground-based meteorite searches (area outlined at head of fall ellipse by short dashes).

4. Plunge Pit Formation

The St-Robert meteorites that fell in fields and lawns made

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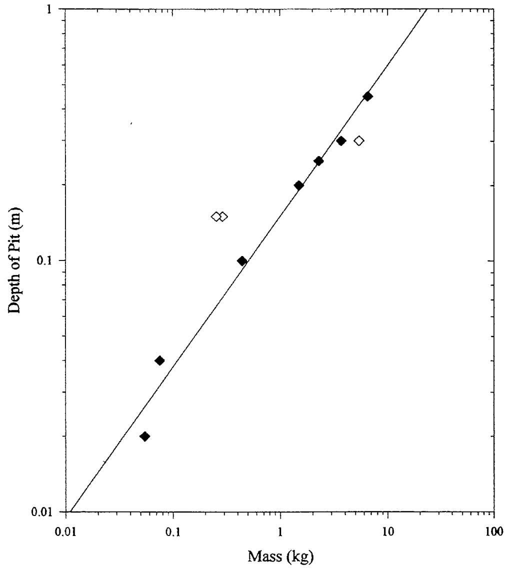

FIG. 8 — Plunge pit depth versus meteorite mass for St-Robert meteorites that did not fall on artificial or sandy surfaces, and where accurate measurements of pit depth were taken. The open points represent depths considered questionable or non-representative; the No. 2 fragment depth was never measured in the field, but was reported approximately by the finder, M. Laliberté. The pits associated with Nos. 15 and 16 were developed in a soft black humus soil and water saturated clay, respectively.

plunge pits by compacting and pushing the soil aside. In no case was soil observed to have been blown out of the holes, and the pit diameters were only as large as the meteorites. The pits of the eleven meteorite fragments that fell on typical soils of the region (developed by agriculture in glacial marine clays to sandy clays) define a consistent relationship (figure 8). The data for all pits yield a log-log relationship of the form:

$$\log D = -0.782 + 0.51 \log M \ ,$$

where D is the depth in metres and M is the mass in kilograms.

It is assumed that all meteorite fragments have reached their terminal velocity by the time they reach the ground. From that condition we may equate the drag force to gravity to yield:

$$V_t \;=\; \sqrt{\frac{2 M g}{A \rho_a}} \tag{1}$$

for the terminal velocity V_t, where g is the local gravitational acceleration, A is the cross-sectional area of the meteorite fragment, and ρ_a is the density of the atmosphere at ground level. On the basis of elementary considerations for momentum transfer between the impacting meteorite fragment and the displaced soil, we expect that the penetration depth will be proportional to the fragment's momentum per unit cross-sectional area. Hence, for a spherical body we have that:

$$D \propto \frac{p}{A} \propto C\left(\frac{m}{A}\right)^{\frac{3}{2}} \propto C r^{\frac{3}{2}} \propto C m^{\frac{1}{2}}, \tag{2}$$

where p is the momentum of the meteorite, C is a constant, and r is the equivalent radius for a spherical body of mass m. If pit depth is therefore regarded as reflecting momentum per unit area, the dependence should be proportional to $m^{1/2}$. A similar dependence was found for the Mbale meteorite plunge pits by Jenniskens *et. al.* (1994). The Abee (107 kg) and Jilin (1,770 kg) meteorites impacted in crudely similar soils/substrates and have pit depths that fit the $m^{1/2}$ dependence (1.8 m calculated versus 1.5 m observed, and 7.5 m calculated versus 6 m observed, respectively), so the empirical relationship appears to extrapolate upwards across two additional mass decades reasonably well.

The dark flight model of Brown *et al.* (1996), revised for the measured St-Robert densities, predicts that the ~5 kg pieces fell with terminal velocities of ~70 m s^{-1}. Whether that is consistent with the strength properties of the soils pitted by the meteorites remains an interesting question. Low velocities are certainly consistent with the descriptions of witnesses to the fall who heard the whistling sounds of the fragments for several seconds. They are also required by the lag between the arrival of the sound associated with the terminal burst and the meteorites' arrivals. Mme. Forcier, for example, was outside near the north side of her home when she heard the thunder-like explosion sounds from the terminal disruption. Her son Stephane then arrived from bicycling to ask if she had also heard the explosions. While they talked they next heard the whistling sounds of fragment No. 4 falling to the ground (seen as a shadow passing through the sky), followed by the ground contact "thud." The duration between the arrival of the "thunder" and the fall of the meteorite was estimated by Mme. Forcier to be roughly one minute. Based upon her position and the location of the terminal burst at 36 km altitude at 45°.83 N, 73°.07 W, the arrival of the sound would have taken 121 seconds if one adopts a sound speed of 330 m s^{-1}. The entry model and dark flight calculations yield a meteorite travel time of 190 seconds and a terminal velocity of 60 m s^{-1} for the same fragment. The ~70 second delay is in good agreement with observation, and requires that much of the dark flight had to be at a fraction of sound speed. Another possible plunge pit was later found nearby, but no other fragment was seen or heard to fall.

The pit formation subjected the largest fragments to the greatest stresses that they experienced during their fall. The dark flight calculations indicate a ground contact velocity of ~70 m s^{-1} for the 6.552 kg fragment, roughly corresponding to a kinetic energy of ~16,000 J. That equals the work done in producing the plunge pit. For uniform deceleration and braking forces, the average deceleration is ~550 g produced by a resistance of ~35,000 N. The average pressure experienced by the meteorite was ~6.0 MPa. The values are probably lower limits for force and stress, since the quantities were probably non-uniform during deceleration. Pit formation stresses of such a magnitude were not able to crush the meteorites, which is consistent with measured crushing stresses of 2 to 50 MPa for chondritic meteorites (Bronsthen 1981). However, the stresses exceed, by an order of magnitude, the ~0.9 MPa which caused the fragmentation of the bolide at ~36 km altitude. The characteristic of meteoroids that causes them to fragment at pressures much lower than their material strengths remains a subject for speculation. The stresses are also larger than the ~2.5 MPa maximum dynamic stresses experienced by the largest fragments during deceleration after the disruption events.

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TABLE I

RECOVERY DATES, MASSES AND LOCATIONS OF INDIVIDUAL METEORITES RECOVERED FROM ST-ROBERT FALL

Fragment Number	Date Recovered	Mass (g)	Location Latitude	Longitude	Comments
1	June 17, 1994	6552	45° 58' 07"N	72° 58' 41"W	In 45 cm-deep pit. Chipped on impact.
2	June 16, 1994	5438	45° 58' 07"N	72° 59' 24"W	In 30 cm-deep pit.
3	Sept. 13, 1994	3708	45° 58' 02"N	72° 58' 03"W	In 30 cm-deep pit. Weathered and muddy.
4	June 14, 1994	2297	45° 58' 08"N	72° 57' 19"W	In 25 cm-deep pit. Three corners chipped.
5	June 22, 1994	1500.7	45° 57' 31"N	72° 59' 46"W	In 20 cm-deep pit. Angular.
6	June 19, 1994	755	45° 55' 56"N	73° 00' 04"W	Found on path. 6 cm-deep pit.
7	June 22, 1994	701	45° 56' 40"N	72° 59' 21"W	Found on road. Chipped by lawnmower?
8	June 23, 1994	644	45° 56' 00"N	73° 00' 30"W	Embedded.
9	June 20, 1994	598	45° 55' 53"N	73° 00' 55"W	Embedded in lawn. Oriented specimen.
10	June 23, 1994	533	45° 55' 38"N	73° 01' 09"W	Found 12 cm from paved road.
11	~July 19, 1994	516.96			Embedded in ground. Broken in two.
12	~July 19, 1994	459.12			Embedded.
13	~July 16, 1994	442.88	45° 55' 55"N	73° 00' 27"W	In 10 cm pit. Cut overhead pine needles and branches.
14	~July 19, 1994	323.6			Embedded?
15	June 26, 1994	290.44	45° 55' 35"N	73° 00' 06"W	In 15 cm-deep pit in very soft lawn.
16	July 30, 1994	253.75	45° 56' 19"N	73° 00' 31"W	In 15 cm-deep pit covered with maggots in wet clay.
17	July 23, 1994	158.5	45° 55' 34"N	73° 00' 07"W	Embedded in stony lawn. Chipped on bottom.
18	June 15, 1994	80.52	45° 55' 14"N	73° 00' 18"W	Hit roof of shed. Chipped.
19	June 25, 1994	75.64	45° 55' 05"N	73° 00' 18"W	Embedded 4 cm.
20	June 25, 1994	54.68	45° 55' 07"N	73° 00' 13"W	Quarter of broken individual. Embedded 2 cm.
1a	June 20, 1994	19.9			End piece from no. 1
1b	June 17, 1994	9.1			Chip from no. 1.
17a	July 24, 1994	0.23			Chip from no. 17.
4a,b,c,d	June 15, 1994	~1.5			Chips from no. 4.
4e	June 18, 1994	~0.1			Chip from no. 4.

Note. Some recovery dates are not exactly known and recovery locations for three individuals are poorly known (and not shown). Early recovery of additional meteorites is rumoured, but no recoveries have apparently been made in the three summers since the summer of 1994, which suggests that few additional meteorites will be found. (Updated from Table 3 of Brown *et al.* 1996.)

5. METEORITE DENSITY

Densities were determined for three St-Robert samples in order to provide an accurate density for the entry and dark flight modelling, as shown in Table II. The method used was Archimedean. The resultant average density of 3.40 g cm^{-3} compares favourably with the mean of 3.43 g cm^{-3} determined by Gorshkov *et al.* (1972) for nineteen H5 chondrites. Such close agreement to the mean density is somewhat fortuitous as densities range from 3.27 to 3.67 g cm^{-3} for the forty-two H chondrites (metamorphic grades 4 to 6) that were measured by them. Much of the variability in chondrite densities is the result of varying porosities. We did not wish to soak the meteorites to determine their porosities since that might have encouraged alteration (immersion times were less than one minute), so our densities are bulk densities (meteorite plus porosity). From changes in the weight of individual No. 16 after it air dried (it had been collected from a possibly water-saturated environment), we set a lower limit of ~3% porosity for the specimen. Yomogida & Matsui (1983), however, reported that using water as a soaking fluid yielded densities several percent smaller (*i.e.* a factor of ~2 in porosity) than was the case using helium gas as a saturating medium or measuring density on a finely crushed meteorite. The porosity is therefore probably higher in the St-Robert meteorites; Yomogida & Matsui report porosities of 5.0% and 6.1% for two H5 chondrites with intrinsic densities of 3.81 g cm^{-3} and 3.82 g cm^{-3}, respectively. If we adopt the same intrinsic density for the St-Robert bolide, since similar values were also determined by Hutchinson *et al.* (1977) for H5 chondrites, the resulting porosities must be about 10%. That is plausible since Hutchinson *et al.* found porosities as high as 14% in one H5 chondrite. Significant porosities are also consistent with the ease with which the St-Robert meteorites may be chipped.

St. Robert has been classified as a monomict breccia H5 chondrite (Wilson, 1994) and an ordinary H5 chondrite (Lecheminant and Herd, 1996). The meteorite is distinctly brecciated with a light-dark texture reflecting a medium gray, finer grained matrix enclosing coarser grained, light gray clasts. The meteorite preferentially fractures along the matrix-clasts contacts.

TABLE II

DENSITY DETERMINATIONS FOR THREE ST-ROBERT METEORITES

Fragment Number	Mass (g)	Density (g cm^{-3})
15	290.44	3.40
17	158.5	3.33
16	253.75	3.47

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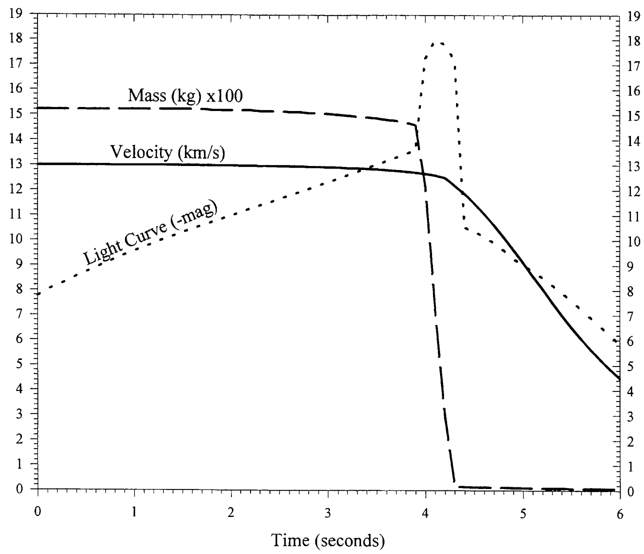

FIG. 9 — Results of a revised entry model. Bolide mass, visual magnitude, and velocity are shown versus time. Note that the model fragmentation event (actually a series of events) dominates fireball brightness and marks an inflection in the velocity curve, resulting from a radical change in the size of the largest object. Several hundred kilograms of fragments with masses in excess of 0.05 kg also survived the terminal disruption event and are not shown here in the mass curve. Subsequent dark flight calculations begin with the end of this model output, *i.e.* at an altitude of 20 km and velocity of 4 km s^{-1}. The solid line represents velocity, and the ordinate for the curve reads km s^{-1}. The dashed curve represents mass, and the ordinate should be multiplied by 100 to give mass in kilograms. The dotted curve represents a theoretical light curve, and the ordinate should read negative magnitude for this plot (adjusted for an observation distance of 100 km).

6. Theoretical Entry Model

The entry model of Brown *et al.* (1996) was rerun using the measured density for the meteoroid of 3.4 g cm^{-3}, instead of 3.8 g cm^{-3}, and an ablation coefficient of 0.011 s^2 km^{-2} from Ceplecha *et al.* (1993), instead of 0.02 s^2 km^{-2}. The salient difference in the revised entry model (figure 9) is that the initial mass drops by a minor amount from 1600 kg to 1520 kg, mostly because of the change in ablation coefficient. The model is therefore not particularly sensitive to factor-of-two variations in the ablation coefficient at typical chondritic values or 10% variations in density (for the observed low entry velocity for St-Robert). Note that we assume that a fraction of the disrupted bolide continued as sizeable fragments, which suggests that the mass estimate derived from the entry model for the pre-atmospheric meteoroid (based primarily on the quantity of mass consumption necessary to make the terminal flash) is a lower limit. If ~100 kg of meteorites fell in the strewn field (Brown *et al.* 1996), for example, the mass surviving the terminal disruption would be 2 to 3 times that amount in order to allow for ablation losses from the fragments after the disruption event. That increases the initial mass estimate to 1700–1800 kg. The model defines the largest surviving individual as the largest meteorite found (~6.5 kg), but is subject to revision with new discoveries. As minor fragmentation may also have occurred in the early part of the meteoroid's flight, the pre-atmospheric mass may have been as large as ~2,000 kg, which is consistent with all independent mass constraints (Brown *et al.* 1996). The mass estimate will probably be changed significantly only if future cosmogenic nuclide or track research indicates a larger mass, or if much larger St-Robert meteorites are found.

Although the fragmentation event dominates the dynamics of the fireball flight, it does not drastically change the amount of mass that reaches the ground. That may be seen by running the entry model for the same initial conditions but with no fragmentation assumed. In this case 237 kg is calculated to reach the ground, as opposed to the ~100 kg estimated to have fallen (Brown *et al.* 1996). Most of the meteoroid mass has still been lost in the no-fragmentation case, because substantial ablation is required to slow a meteoroid of this mass.

An energy of 10^{11} J is associated with deceleration of the St-Robert bolide, as derived from the estimates for velocity and initial mass. It compares favourably with the energy estimate made by Nemtchinov (1995) based upon the observed satellite light curve and hydrocode simulations, within the framework of an ablating piston model of 2.8×10^{11} J.

7. Radioactive Cosmogenic Nuclides

Arrangements were made to begin radiation counts for the St-Robert meteorites soon after the fall (68 hours), enabling detection of radioactive nuclides with half lives as short as 15 hours (^{24}Na). Counting efforts have continued, and 16 of the 20 specimens have been surveyed to date; Table III presents results including some activities revised from those reported by Brown *et al.* (1996). Note that a misleading picture of nuclide activity would have been obtained if radiation counting had ended with the first three individuals. Subsequent counts extended the range of observed activities for most cosmogenic radionuclides detected. The St-Robert bolide is now one of the most extensively surveyed meteorite falls, and the effort continues while the ^{22}Na activity is at detectable levels. Although a complete assessment of the data awaits determination of relevant elemental concentrations in the meteorites and reference to a cosmic ray flux model through the last solar maximum, some implications from the data are already apparent. While the counting results set only a lower limit on the exposure age of the meteorite of ~2×10^6 yr (^{26}Al activity levels appear to be in equilibrium with the cosmic ray flux, which implies a meteoroid exposure age in excess of 3 times the ^{26}Al half-life, or 7×10^5 yr), the cosmogenic nuclide activities also constrain the type of exposure history as well as the size and shape of the meteorite.

Figure 10 shows a plot of ^{22}Na versus ^{26}Al activities, together with modelled activities from Bhandari *et al.* (1993). The data and model results can show a straight-line relation (in single stage exposure cases) because both isotopes are spallogenic and derived from several target elements. The observed ^{22}Na/^{26}Al isotope ratios (1.24 to 1.70) are also relatively constant compared to many meteorites (Evans *et al.* 1982). The variation in the ^{22}Na/^{26}Al ratio between other meteorites has been attributed to variations in radiation hardness, but in the St-Robert meteorites the apparent variations all lie within two sigma of the counting uncertainties, so no significant differences exist.

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TABLE III

COUNTING RESULTS FOR RADIOACTIVE COSMOGENIC NUCLIDES IN SIXTEEN ST-ROBERT METEORITES

Sample	Mass (kg)	Analysis Date	^{60}Co $t_{1/2}$ = 5.3a	^{22}Na 2.6a	^{26}Al 700ka	^{54}Mn 312d	^{48}V 16d	^{46}Sc 84d	^{56}Co 77d	^{24}Na 15h
4	2.287	June 17, 1994	15.3 ±1.5	^{L}72.8 ±7.3	^{L}50.1 ±2.5	129.2 ±32	11.5 ±2.9	^{H}10.7 ±2.8	^{L}3.6 ±0.9	60.1 ±15.0
9	0.598	June 30, 1994	11.9 ±1.2	83.7 ±8.4	58.7 ±2.9	134.3 ±34	11.7 ±2.9	10.1 ±2.5	^{H}8.2 ±2.0	
6	0.755	July 16, 1994	8.7 ±0.9	74.0 ±7.4	59.7 ±3.0	^{L}119.0 ±30	^{L}7.2 ±1.8	6.4 ±1.6	6.6 ±1.7	
20	0.055	Sept. 24, 1994	15.6 ±1.6	107.1 ±11	70.2 ±3.5	167.8 ±42		4.8 ±1.2		
19	0.076	Sept. 25, 1994	^{L}3.5 ±0.4	100.7 ±10	61.0 ±3.0	148.5 ±37		^{L}0.5 ±0.1		
15	0.290	Sept. 21, 1994	37.8 ±3.8	110.1 ±11	^{H}83.4 ±4.2	151.7 ±38		7.7 ±1.9		
17	0.159	Sept. 23, 1994	53.1 ±5.3	121.1 ±12	70.9 ±3.5	^{H}176.2 ±44	^{H}61.9 ±16	5.8 ±1.4		
16	0.254	Sept. 22, 1994	24.1 ±2.4	103.7 ±10.4	67.7 ±3.4	153 ±38		8.6 ±2.2		
11	0.0448	Mar. 11, 1996	^{H}66.0 ±6.6	^{H}130.1 ±13	81.2 ±4.1					
12	0.4581	Feb. 16, 1996	5.1 ±0.5	72.8 ±7.3	57.0 ±2.8					
14	0.3224	Feb. 14, 1996	17.0 ±1.7	89.3 ±8.9	61.5 ±3.1					
7	0.1052	Feb. 23, 1996	16.2 ±1.6	95.4 ±9.5	54.9 ±2.7					
10	0.2541	Mar. 14, 1996	8.4 ±0.8	90.1 ±9.0	58.4 ±2.9					
13	0.4421	Feb. 25, 1996	17.3 ±1.7	83.3 ±8.3	63.6 ±3.2					
8	0.6358	Oct. 25, 1996	19.1 ±1.9	82.0 ±8.2	55.9 ±2.8					
5	1.4988	Oct. 31, 1996	37.2 ±3.7	90.6 ±9.1	63.4 ±3.2					

Note. All activities corrected to time of fall, 00:02 UT, June 15, and are in units of decays per minute per kilogram (dpm kg^{-1}). The highest and the lowest values in each column are tagged with the letters H and L respectively.

The data follow the relationship

$$^{22}\text{Na} = 1.54\ ^{26}\text{Al} - 3.55\ \ .$$

For the 50 cm-radius model of Bhandari *et al.* (1993), the ^{22}Na/^{26}Al ratio varies between 1.86 and 1.74 from the surface to the centre, respectively. Their model results compare with observed activity ratios of 1.66 ±0.28 dpm in seven chondrites that fell at times in the solar cycle that were similar to or slightly later than was the case for the St-Robert meteorite (Evans *et al.* 1982). For St-Robert the activity line is offset from the model results by an intercept value of ~23 dpm for ^{22}Na. Alternatively, increasing the ^{22}Na activity by ~20% also produces good agreement with a slope of 1.84. The latter is the more physically realistic approach, as solar maximum can reduce the cosmic ray flux by factors of 2.5 to 3. Evans *et al.* (1982) calculate that the ^{22}Na/^{26}Al ratio can change by ~1.5 times over the solar cycle, so that the relative depletion of ^{22}Na in St-Robert is very probably attributable to the solar maximum of 1991. Note that St-Robert had a pre-atmospheric orbit of very low inclination, less than or equal to 1° (Brown *et al.* 1996), so that activity in the meteorite reflects the maximum possible modulation by the solar wind for an orbit of that eccentricity and size. The well-behaved correlation between ^{26}Al (half-life $t_{1/2}$ of 7×10^5 yr) and ^{22}Na (half-life $t_{1/2}$ of 2.6 yr) activities indicates a single episode exposure history or a second exposure stage longer than 2–3 × 10^6 yr, since the St-Robert meteoroid was excavated from its parent body.

Figure 11 shows a plot of ^{60}Co versus ^{26}Al activities together with model results for ^{26}Al from Bhandari *et al.* (1993) and for ^{60}Co from Spergel *et al.* (1987). ^{60}Co is produced by neutron capture on ^{59}Co; its activity is more depth-dependent than for the spallogenic nuclides, and its concentration must be normalized to the elemental cobalt abundance. As Brown *et al.* (1996) discuss, the highest observed ^{60}Co activity in the St-Robert meteorites can set a lower limit on the mass of the pre-atmospheric meteoroid by assuming it is a central piece. They used the model results of Eberhardt *et al.* (1963), but Bhandari *et al.* have noted that better model parameters require adjustments to that model. As the Co concentration in the St-Robert meteorites is still unknown and the ^{60}Co activities are also depressed by the pre-fall solar maximum (the half-life for ^{60}Co is 5.3 yr), the lower limit remains a reasonable provisional estimate. The estimated lower limit for the mass is also

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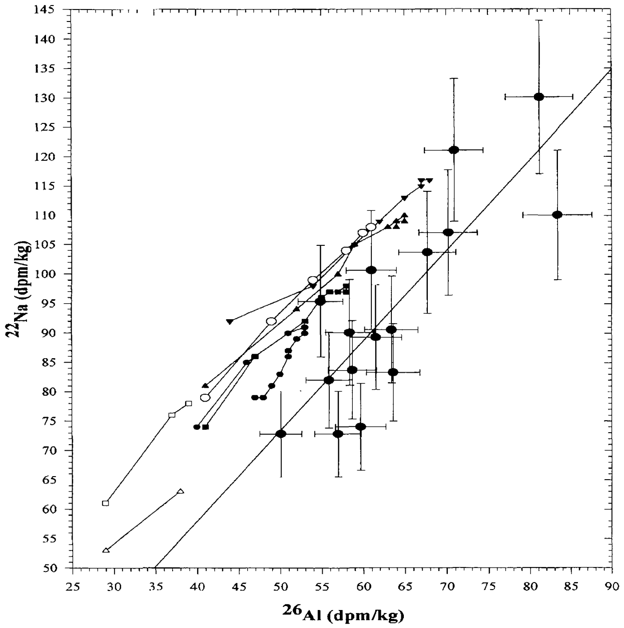

FIG. 10 — ^{26}Al versus ^{22}Na activity for sixteen individual St-Robert meteorites plotted as solid dots, with counting uncertainties indicated. The curves with differing symbols represent the theoretical activities for different sized bodies (open triangles, radius equals 5 cm; solid squares, 10 cm; open circles, 25 cm; solid inverted triangles, 50 cm; small solid triangles, 65 cm; small solid squares, 85 cm; small solid circles, 100 cm) as a function of depth, as reported by Bhandari *et al.* (1993). The ^{22}Na values have larger associated uncertainties beyond considerations of counting statistics because fewer mock-up calibrations have been done for the isotope.

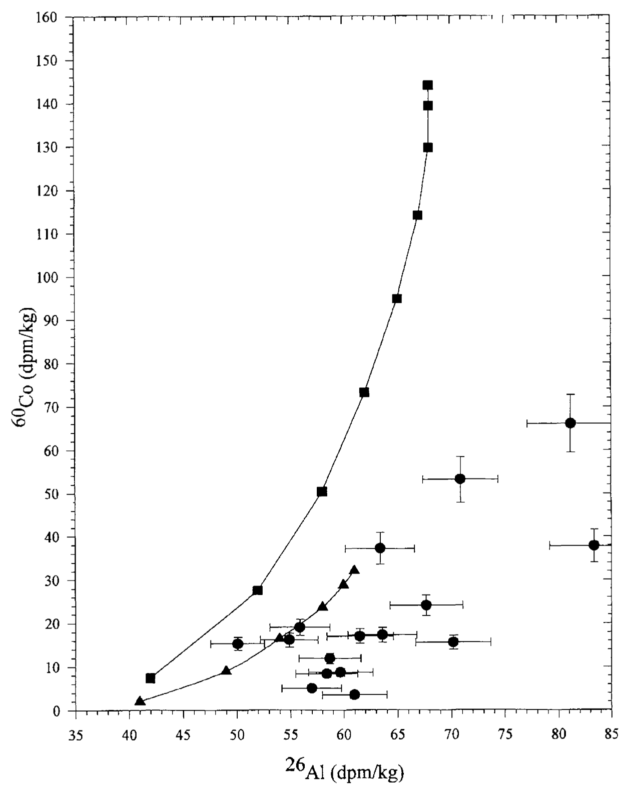

FIG. 11 — ^{26}Al versus ^{60}Co activity for sixteen individual St-Robert meteorites. The curves represent predicted activities with depth for bodies of 28 cm and 42 cm radius (triangles and squares, respectively). Note that the St-Robert meteorites plot significantly below the curves.

consistent with the ^{22}Na and ^{26}Al activities, which require an object with a radius between ~35 cm and ~65 cm to produce the high activities observed in the St-Robert meteorites (Bhandari *et al.* 1993). Figure 11 shows that, if the ^{60}Co activities were increased by even 50%, the observed data would not agree with model curves for spherical bodies. A spherical St-Robert meteoroid would have a radius of ~50 cm (1,780 kg for a density of 3.4 g cm^{-3}). The five individual St-Robert meteorites that have nearly identical activities between 15.3 and 17.3 dpm (Nos. 4, 7, 13, 14, 20) also have ^{26}Al activities ranging form 50.1 dpm to 70.2 dpm, a statistically significant difference at 3 sigma. Activities in ^{22}Na for the five meteorites correlate with the ^{26}Al activities. The lack of correlation between the spallogenic and neutron-activated nuclides indicates that they had different activity/concentration gradients in the meteoroid, which is not the case in a homogenous spherical body. The St-Robert meteoroid may thus have been distinctly non-spherical.

8. SEISMIC RESPONSE AND CALIBRATION PARAMETERS

Initially no fireball-related seismic signal was believed detected, as the reported 3.8 magnitude earthquake associated with the fireball had been established as a media hoax (Wetmiller *et al.* 1994). With a precise time (00:00:26 UT) and location (36 km altitude at 45°.83 N and 73°.07 W) for the terminal burst, however, a possible seismic signal was found. The closest station of the Eastern Canada Telemetered Network (ECTN) maintained by the Geological Survey of Canada is MNT located northwest of downtown Montreal. Brown *et al.* describe the potential seismic signal in detail. Since the station saves data only when triggered by events on the seismic network, and since the bolide did not trigger the network, it is fortunate that any data are available. The raw data showed no obvious signal; it was only after computing an expected arrival time of 00:00:54 UT based upon a sound velocity of 0.330 km s^{-1}, the fastest observed arrival for bolide-induced atmospherically transmitted sound (Ben-Menahem 1975; Cumming 1989), that a potential signal was noted commencing near the end of the seismic record at 00:00:56 UT. Filtering the data to look for energy at 8–12 Hz — the sound frequencies found by Qamar (1995) for another bolide terminal disruption at similar altitude — enhanced the signal-to-noise ratio. The peak ground motion recorded was 4 nm at 10 Hz. Unfortunately, the record truncates after only two seconds of signal, leaving much of the signal character uncertain; its origin as cultural noise remains a possibility. No other seismic network records were found, although two more distant stations had recorded data across the corresponding arrival times.

The recorded ground motion indicates a coupling of the air waves' energy to the ground with an efficiency of ~10^{-7} (Brown *et al.* 1996). That value compares with a coupling efficiency of ~10^{-5} for energy deposited to the ground immediately below the terminal explosion associated with the June 30, 1908, Tunguska bolide (Ben-Menahem 1975). That explosion — the magnitude of the Tunguska explosion was ~3 × 10^{16} J — was lower in the atmosphere and may have involved a more efficient mechanism for transferring energy to the ground (some directionality of the

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bolide energy was transferred), so the smaller derived coupling parameter for St-Robert seems plausible.

We regard the signal as provisional barring confirmation with a second sound recording. We note a substantial lost opportunity; although aware of the potential of security camera systems to record fireballs, at the time of the fall we were not aware that some security camera systems also record sound. The explosions were probably recorded on hundreds of security systems in the Montreal metropolitan area. In the case of the bolide of November 21, 1995, in Colorado, such a recording was made serendipitously (J. Murphy, private communication). The video-tapes made by security systems are typically saved for only one week or one month before overtaping. Any single recording with a calibrated time base would have been sufficient to confirm or deny the validity of the seismic signal, and would have been of intrinsic research interest. Three such recordings, if widely spaced about the burst point, would have allowed an independent determination of the location of the terminal burst that would likely have exceeded the accuracy of the data available. All future investigators of bolides audible in populated areas should immediately attempt to locate such security camera sound recordings.

The potential recording of the seismic signal of the St-Robert terminal burst offers a calibration for seismic signals of bolides. We derive in Table IV empirical calibration factors using the maximum ground displacement (4 nm), equivalent to a maximum velocity (251 nm s^{-1}) recorded at the MNT relative to the energy released (1.3×10^{11} J) and the mass consumed (1450 kg) in the terminal burst. For meaningful calculations of the energies and masses of other bolides, the altitude and distance of the terminal burst must be the same or correctable, and if bolide mass is desired then entry velocity must also be the same or accounted for in an energy-based comparison. Such requirements for valid comparisons may seem so restrictive that the potential calibration of the relations is of limited use. However, for the events of interest, fireball characteristics ameliorate variation in entry velocities and burst altitudes, and variation in distance to a recording seismograph station may be compensated for by calculation.

TABLE IV

PROVISIONAL CALIBRATION PARAMETERS BETWEEN BOLIDE MASS AND ENERGY AND GROUND MOTION CAUSED BY THE ATMOSPHERIC SOUND WAVE

	Mass (kg) versus Ground Motion	Energy (J) versus Ground Motion
Mass and energy versus displacement (nm)	360 kg nm^{-1}	3.3×10^{10} J nm^{-1}
Mass and energy versus velocity (nm s^{-1})	5.8 kg s nm^{-1}	5.2×10^{8} J s nm^{-1}

Note. The calibrations are most valid for H chondrite bolides with terminal bursts at 12.2 km s^{-1} at 35 km altitudes.

First, for distances in excess of 300 km, sound intensity declines inversely with distance; for closer distances it varies inversely as the distance squared (ReVelle 1995). Most bolide seismic records will fall in the latter category when adjusted to a ground distance of 58 km. Second, meteoroids tend to disrupt terminally over a relatively small range of altitudes because of the exponential increase in atmospheric density, particularly for fireballs of the same type. Most of the potential meteorite-dropping fireballs will be of Type I (chondrites) or Type II (carbonaceous chondrites) in the Ceplecha & McCrosky (1976) scheme. The St-Robert calibration will be most reliable when applied to the former at altitudes comparable to 35 km. Third, fireballs which suffer a single terminal disruption (the event that is most likely to produce an explosion large enough to be detected by a seismograph) typically have velocities of less than 15 km s^{-1} (Ceplecha *et al.* 1993), as noted above. That class amounts to 37% of all well-recorded Prairie Network fireballs and 63% of all types of fragmenting fireballs. Since it originated from an H5 chondrite, the St-Robert bolide represents the most common type of sizeable meteoritic material observed to fall, which increases its value as a calibration standard.

As an example of the potential usefulness of seismic records in assessing bolide size, we consider the daylight fireball of January 25, 1989 (Pugh 1990; Qamar 1995). That fireball travelled across the state of Washington at ~12:51 PST and was described as approaching the Sun in brightness; it cast shadows in broad daylight. The fireball ended with two large successive explosions that were recorded by the Pacific Northwest Seismograph Network (PNSN), including numerous seismic stations deployed near Mount St. Helens. Qamar (1995) was able to determine the locations, altitudes and burst times of the explosions with accuracies only exceeded by data from camera networks. Knowledge of the origin locations and altitudes for the explosions allows calculation from the seismic response of the energy dissipated and mass disrupted. The validity of the estimates is favoured by the fact that the burst altitudes are 35.1 ±1.0 km and 30.4 ±0.7 km, similar to that of the St-Robert terminal disruption. The velocity of the January 25, 1989, meteoroid is also constrained to be close to that of the St-Robert bolide according to its orbital parameters, which are based on the fireball trajectory derived from seismic solutions (155° azimuth, 34° elevation). Orbits intersecting the asteroid belt have a permitted velocity range of 14–16 km s^{-1}, which compares with the preferred estimate of 13.0 km s^{-1} for St-Robert (Brown *et al.* 1996). The 8–12 Hz frequencies recorded for the seismic signals are the same, as noted above. Use of the data recorded at the RVW station of the PNSN eliminates any need to correct for distance, since the ground distance to the bursts is nearly identical (~58 km). With maximum ground motions of 3,500 nm s^{-1} and 1,800 nm s^{-1} at RVW for the successive explosions, the disruptions released 1.8×10^{12} J and 9.5×10^{11} J of energy and consumed 20 tonnes and 10 tonnes of bolide, respectively. The calculation serves to establish that the January 25, 1989, fireball corresponded to the entry of an object ~15 times more massive than the St-Robert meteoroid (~30 tonnes), and was approximately a magnitude –17 fireball with –21

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terminal flares. Our instrumentally-based mass and energy estimates are useful for calibration of the witness reports for the event (which include a range of phenomena, including anomalous sounds), and for estimation of recovery opportunities for meteorites or meteoritic dust. The greatest use of seismic observation calibrations, however, will be realized if similar estimates can be applied to future falls with consequent optimal recovery possibilities. The example of the January 25, 1989, fireball also shows that seismic networks can locate and assess bolide characteristics to an accuracy useful for meteorite recovery efforts.

9. Conclusions

The fall of the St-Robert meteorite has provided a calibration standard on several levels. The terminal disruption of the meteoroid as observed by eyewitnesses and satellites suggests that it was a typical Ceplecha Type I fireball that experienced a single episode of fragmentation (IF) near the end of its luminous trajectory. That is very similar to the behaviour of PN bolides of much smaller mass, and suggests uniformity in structural characteristics over several decades in mass for such fireballs.

The multiple detonations heard by eyewitnesses may be the result of point source explosions associated with ablational break-up of the body. A definitive answer to the question of the origin of such multiple sounds can only be made when instrumental records of the sound waves from a fireball can be analyzed in association with dynamical information from the bolide.

A re-analysis of the theoretical entry model using more accurate parameters for the ablation coefficient and bulk density of the meteoroid suggests a revised estimate for the pre-atmospheric mass of 1520 kg, very similar to the 1600 kg initial mass found by Brown *et al.* (1996). If fragmentation earlier in the trajectory is taken into account, a final initial mass estimate of ~2000 kg fits all available information best.

The apparent distribution of plunge pit depths with meteorite mass is in accord with a dependence of the form $D \propto M^{1/2}$, which suggests that plunge pit formation is proportional to momentum per unit frontal area.

The extensive survey of short-lived cosmogenic radionuclides in the St-Robert meteorites has provided an effective check on the validity of numerical models of meteoroid irradiation, and suggests that the St-Robert meteoroid was non-spherical. More importantly, the results also provide unequivocal constraints on the pre-atmospheric mass of the meteoroid.

Use of the possible seismic signal of the ground-coupled air wave from the shock of the terminal disruption of the St-Robert meteoroid through the atmosphere yields an approximate coupling coefficient of 10^{-7} (representing the fraction of initial energy transferred to ground motion). Our tentative calibration of seismograph networks' observations of ground motion induced by bolides may be tested with additional observations, and its dependence on energy, distance and burst altitude explored. As more seismic fireball events are observed, further refinement of the value and its dependence on energy, distance and burst altitude might be found.

We are very grateful to all of the residents of eastern Canada and the United States who described the St-Robert fireball, and to the residents of the parishes of St-Robert and St-Aimé who granted permission to search their farms, described their discoveries of meteorites, and lent specimens for measurement/photography. We are particularly grateful to the individuals and institutions who lent their meteorites for gamma ray counting: S. Forcier, J. Vanier, P. Sasseville, J.–G. Berger, M.–C. Roussel, G. Jarret, S. Legrand, M. Bouchard and l'Université de Montréal, M. Higgins and l'Université de Québec á Chicoutimi, A. Lèvesque and l'Université Laval, P. Lacombe and the Planetarium de Montréal, F. Wicks and the Royal Ontario Museum, and the Musée de la Civilisation du Québec. R. K. Herd quickly transported 3 meteorites to counting facilities early in the investigation. Computer code for modelling was kindly provided by Z. Ceplecha. D. Niehaus made the corrected air photo mosaic for figures 4 and 7; A. Rafeek provided drafting services. Many other individuals and institutions aided the St-Robert investigation and field searches as previously acknowledged in Brown *et al.* (1996). Funding for this research, as provided by the Canadian Space Agency via the Meteorites and Impacts Advisory Committee, was indispensable. JW's work was supported by NASA contract NASW-4841. This is GSC contribution number 1996390 and LANL contribution number LA-UR-97-3447.

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