1974Metic...9..223N

THE LOCATION OF METEORITE IMPACTS BY SEISMIC METHODS

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Photographic methods for the location of meteorite falls are restricted to hours of darkness and limited by weather conditions, resulting in a low detection rate. The importance of rapid recovery of newly-fallen meteorites leads to the consideration of seismic methods for the location of impact points. The purpose of this paper is to discuss the degree to which seismic networks can augment the detection of meteorites by conventional means. Factors involved in the generation of seismic waves are considered. The present sophistication of experimental and computational techniques in seismology should enable a microearthquake detection network to locate within 2 km the impacts of larger meteorites. The detection limits are determined by meteorite size and the configuration and instrumentation of the seismograph network.

DETECTION OF METEORITES

Rapid recovery of meteorites is necessary if the short half-life radioactivity due to cosmic rays is to be studied (Anon. 1962), and also to avoid organic contamination of the meteorite material.

When a meteorite enters the atmosphere, surface heating and ablation occur, causing the luminous phenomenon. Photographic observation is possible during ablation, but when the velocity has been reduced by atmospheric drag to below approximately 3 km s^{-1}, the meteorite ceases to be luminous (McCrosky and Ceplecha, 1968). Ideally it should be possible to extrapolate the observed part of the flight path to the impact point. However, beyond the luminous path trajectory determination becomes difficult, as the falling meteorite is subject to poorly-known wind fields. The resulting uncertainty in locating the impact point is of the order of 1 km (McCrosky and Ceplecha, 1968).

Photographic methods are currently in use to expedite recovery operations (*e.g,* Ceplecha and Rajchl, 1965; McCrosky and Boeschenstein,

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1965; McCrosky and Ceplecha, 1968; Anon., 1970). However, the operation of an optical network is limited to the hours of darkness. In practice only about one third of the night is sufficiently clear of cloud for useful photographic observations (*i.e.* an average of 3.5 hours per 10.5-hour night). In addition, the rate of meteorite influx varies throughout the day, and during the night is only about half the 24-hourly rate. Thus only 7% of all meteorite falls in the vicinity of an optical network will be detected (McCrosky and Ceplecha, 1968). (More optimistic estimates suggest a detection rate of up to 15%). Hence it is useful to consider supplementary methods of locating meteorites. Seismic studies offer the possibility of direct observation of the impacts of larger meteorites, and therefore may aid in their location.

RATES AND VELOCITIES OF IMPACTS

The rate of meteorite influx on earth has been the subject of a number of studies (*e.g.* Hawkins, 1960; Brown, 1960; Millard, 1963; McCrosky, 1968), summarized by Dohnanyi (1972).

From statistics on recovered meteorites, Hawkins has obtained the following relation between the numbers and masses of meteorites at the earth's surface:

$$\log_{10} N(m) = -\log_{10} m - 18.20$$

where $N(m)$ is the number of meteorites with mass equal to or greater than m kg reaching the surface per square meter per second. This implies that for an area of 1.7×10^6 km^2 (corresponding to the optical "Prairie network" (McCrosky and Ceplecha, 1968), one meteorite of mass 10 kg or greater will impact on average every 3.5 months. If the detection efficiency of the photographic network is 15%, one meteorite of this mass should be observed over the network every 2.0 years.

The velocity and mass of a meteorite at impact are determined by the initial mass, speed and angle of approach, and also the density of the body and whether or not it fragments during descent (Heide, 1964). Although the range of possible velocities of incoming meteorites is between 11 and 70 km s^{-1} (Krinov, 1960), the majority of initial velocities are below 25 km s^{-1} (McCrosky, 1970), with a mean of 16.5 km s^{-1} (Whipple and Hughes, 1955).

Generally, the greater the initial mass of the meteorite, the closer the final velocity and mass will be to their pre-atmospheric (cosmic) values. Heide's (1964) calculations indicate that, despite air drag, meteorites with final masses of greater than 10^4 kg will retain part of their cosmic velocity.

Smaller meteorites, given that some mass survives ablation, will be slowed to their terminal fall speed, typically 100 to 200 m s^{-1} (Heide, 1964), and at impact will be travelling almost vertically (Krinov, 1960).

During descent meteorites are subject to considerable stress from air drag (Krinov, 1966), which frequently causes fragmentation. This effect is strongly dependent on mass, and approximately 70% of meteorites with final mass around 100 kg will break up before impact (Hellyer, 1969). The terminal speed of a falling body increases with its mass, so that if a large meteorite breaks up during descent, the individual fragments will be decelerated more by air drag than the original body would have been had it remained whole. After fragmentation, the Sikhote-Alin meteorite impacted at only 500 to 600 m s^{-1}, although the total mass reaching ground level was of the order of 10^5 kg (Fessenkov, 1955).

IMPACT PHENOMENA

The effects of meteorite impacts at different velocities have been calculated by Stanyukovich (1950) (reported by Krinov [1961]). For impacts at velocities up to 100 m s^{-1}, a meteorite will remain intact and will form a pit of roughly the same size as itself in soft ground, while an impact on rock will cause breakage of both the meteorite and ground. At velocities above 100 m s^{-1} but below 3 km s^{-1} both ground and meteorite are shattered, fragments of ground and meteorite are ejected, and a crater is formed with dimensions greater than the meteorite. Craters of this type vary from two meters to several tens of meters across. For impacts at velocities above 3 km s^{-1}, corresponding to giant meteorites, there is sufficient kinetic energy to vaporize the meteorite and surrounding ground. These craters produced are similar to surface nuclear explosion craters and are typically more than 100 meters in diameter (Krinov, 1960).

Thus, with the exception of rare giant meteorites, the craters produced are relatively small. In the absence of eyewitness observations of the impact, the crater will be difficult to locate. If photographic records of the meteorite fall are available, the impact area should be sufficiently small to be covered by ground search parties (McCrosky, 1970). With less accurate impact information, such as visual observations, aerial search methods can be used to find craters, but even if the impact point is known to within a few km, these may not be successful (Halliday and Blackwell, 1971).

SEISMIC DETECTION OF METEORITES

The difficulty in locating meteorite impacts leads to the investigation of methods to complement optical observations. Seismic techniques permit direct determination of the impact coordinates for larger meteorites, for which the ground body wave energies of the impact may be comparable with those from small earthquakes.

Apollo lunar seismic experiments have detected meteoroid impacts on the surface of the moon. Due to the absence of mass ablation and air drag, the kinetic energy flux of meteoroids hitting the moon is significantly greater than that on the earth. The high impact velocities and high seismometer gains used permit the detection of meteoroids of mass 1 g or less near the seismometer (Latham *et. al.* 1969). The situation on earth differs considerably from that on the moon, due to the lower flux and the generally much lower kinetic energies of meteorites of a given mass. As a result, and also due to the sparse coverage of the earth's surface by high sensitivity seismographs, few meteorite impacts have been identified so far on terrestrial seismic records.

In 1908 the Tunguska, Siberia, meteorite (possibly a comet) exploded above ground with an energy of about 10^{16} Joule (Krinov, 1963). The seismic wave induced in the ground was recorded at Irkutsk, at a distance of 893 km, on a primitive seismograph.

The Sikhote-Alin meteorite landed 375 km north of Vladivostok in 1947, forming craters varying in diameter from 0.5 to 28 m. Aerial detonations of the meteorite were heard up to 400 km away, but the impact was not detected seismically at Vladivostok, probably due to low seismograph sensitivity.

Near Revelstoke, British Columbia, a meteorite detonated at 30 km altitude in 1965. Seismic waves due to the air blast were recorded at four seismograph stations in western Canada and the U.S. (Folinsbee *et al.*, 1967). The Vilna, Alberta, meteorite of 1967 also detonated at 30 km and seismic records of the air blast were obtained at Edmonton, 155 km away (Folinsbee *et al.*, 1969). The latter authors state that "it is clear that the seismograph network in western Canada can be of considerable use in predicting the end points of detonating bolides, and might supplement the proposed camera network in locating meteorites."

The only actual meteorite impact to be recorded seismically occurred near Prince George, British Columbia, in August 1969 (Halliday and Blackwell, 1971). The impact was recorded on four seismographs, at distances up to 500 km. Although approximate epicentral distances were determined from the records, it appears that a full numerical analysis of available data was not carried out to determine accurately the impact location. An accurate solution (± 2 km) may not have been possible from the configuration and instrumentation of the seismograph stations then operating (Milke *et al.*, 1970) as the epicentral distances were of the order of several hundred kilometers. The inaccuracies in the impact coordinates and the mountainous terrain were responsible for the failure to recover the meteorite (Halliday and Blackwell, 1971).

IMPACT EFFICIENCIES AND THE PRINCE GEORGE METEORITE

The fraction of kinetic energy converted to seismic energy in a meteorite impact is not known accurately, but is an important factor to be considered in detection by seismic methods. The conversion efficiency should depend on the cratering mechanism, which is determined primarily by the impact velocity. Nuclear explosion data and seismic sounding experiments provide useful information on the subject. In the case of air-coupled seismic waves from aerial detonations, the fraction of the explosion energy converted to seismic energy (or "seismic efficiency") is probably the same as for nuclear air blasts, *i.e.* about 0.001% (Griggs and Press, 1961). For the impacts of giant meteorites it is reasonable to assume efficiences comparable with surface nuclear blasts, as the craters originate in a similar manner in explosions of comparable energies. Laboratory experiments involving bodies impacting at cosmic speeds (1 to 7 $\mathrm{km\ s^{-1}}$) yielded energy conversion efficiencies of 0.006%. The impacts were found to be similar in effect to shallow explosions (McGarr and Latham, 1969). This is similar to the value obtained for the seismic efficiency of surface nuclear explosions, *i.e.* ~ 0.01% (Griggs and Press, 1961).

For the impacts of smaller meteorites, which involve much lower impact speeds, the seismic efficiency may be still higher, possibly up to 10% (after Neitzel, 1958). The seismic energy generated in a meteorite impact is, of course, spread over a range of frequencies. The frequency distribution of the seismic energy may not fall entirely within the bandwidth of the seismometer. This "mismatch" between the two frequency bands will reduce further the effective seismic efficiency of the impact. It is probable, then, that the impacts of small meteorites produce seismic energy with an efficiency of the order of 1%.

Analysis of the seismic records of the Prince George meteorite impact yielded a seismic energy of 10^9 Joule (Halliday and Blackwell, 1971), which was assumed to be the impact kinetic energy of the meteorite. The foregoing discussions of seismic efficiencies, however, suggest that the meteorite kinetic energy may in fact have been ~ 10^{11} Joule. This increase in actual impact energy necessitates a re-evaluation of the mass and velocity of the meteorite at impact. An upper limit of 3 $\mathrm{km\ s^{-1}}$ can be placed on the final speed, as the body ceased to be luminous before impact (McCrosky, 1970). Reasonable estimates of mass and speed at impact would be 2×10^5 kg and 1 $\mathrm{km\ s^{-1}}$ respectively, assuming a seismic energy of 10^9 Joule and a seismic efficiency of 1%. It is possible that there are errors of up to one order of magnitude in both the seismic efficiency and energy. For a maximum possible seismic efficiency of 10% and a seismic energy of 10^8 Joule, the impact mass and velocity become 1.2×10^3 kg and 400 $\mathrm{m\ s^{-1}}$ respectively. These values are the same as those originally obtained by Halliday and Blackwell (1971), and are lower limits. The upper limits should be ~ 2×10^6 kg and ~ 3 $\mathrm{km\ s^{-1}}$.

SEISMIC CONSIDERATIONS

The seismic network on which the Prince George meteorite impact was detected was far from ideal for the purpose, both in station locations and sensitivity. However, permanent networks of high-gain seismographs for microearthquake observation may be of use in detecting meteorites, if the seismic energies are similar to those of small earthquakes. The Large Aperture Seismic Arrays, located for example in Montana, U.S.A., Yellowknife, Canada and Northern Territory, Australia should also be suitable.

The practical operational limit for seismographs is governed by background noise, which is generally due to weather conditions and human activity (Donn, 1966; Douze, 1967). However, local earthquake source spectra tend to peak in a different frequency range from that of natural microseismic noise (Brune and Oliver, 1959; Mason, 1957; De Noyer, 1964). Observation of the Prince George meteorite suggests that for large meteorites at least, much of the impact seismic energy may be in the frequency range normally observed from local earthquakes. Hence most microseismic noise can be filtered out of any recording, and favourable sites for seismometers will also enchance the signal-to-noise ratio (*e.g.* Robertson, 1965; Hirono *et al.*, 1968). Local earthquake studies by one of the authors (I.C.F.S.) indicate that it is possible to detect easily seismic sources of 10^4 Joule at 100 km. Fitch (1969) detected sources as small as 3×10^2 Joule at 40 km distance.

Seismic events are usually located by least squares methods, using arrival times at three or more stations (*e.g.* Bolt, 1960). Since the impact is a surface event, the three unknown parameters in the calculation are the two coordinates and the origin time. Ideally the event should occur within the boundaries of the detecting network. A local network (covering a few hundred kilometers square) may be calibrated using artificial seismic sources (*e.g.* explosions), to allow for lateral variations in crustal structure when locating events. An alternative would be to drop large masses from an airplane over the array. This would serve both to calibrate the array and to determine the impact seismic efficiency experimentally.

Apart from the number of local stations recording the event, the location accuracy also will be influenced by the precision with which seismic phases are recorded and identified at each station. Use of seismographs more than a few hundred kilometers from the event may increase the errors in location, due to poorer readings and lack of weight given to nearby records. It should be appreciated that the standard errors of least squares calculations are a measure of the mathematical goodness-of-fit of data to a particular model, and do not necessarily indicate the accuracy of the final answer. Both network calibration and experience of data analysis are important in obtaining optimum results. A least squares solution may also be obtained with only two stations, if it is possible to remove the ambiguity in epicenter location through other observations.

It should be possible to derive the impact coordinates to an accuracy of 1 km (certainly 5 km), using optimum methods of calculation (*e.g.* James *et al.*, 1969), depending on the quality and quantity of data analysed.

The detectability should be independent of azimuth for most impacting meteorites, as the near vertical incidence (Krinov, 1960) implies that the radiation patterns for seismic waves would have little azimuthal variation.

The spacing of seismograph stations, as well as their gain, will determine the minimum impact energy for which a least squares location is possible. For seismographs in favourable (low noise) locations operating at high gain ($> 10^6$), a spacing of up to 100 km between stations should enable events of seismic energy greater than 10^4 Joule to be located within 2 km, provided the event occurs within the array area.

This energy corresponds to the impact of a 50 kg meteorite at 200 m s^{-1}, assuming an impact seismic efficiency of 1%. Using Hawkins' relation, meteorites of this mass or greater can be expected at a rate of 1 per 2.5 years per 10^6 km^2. If 50% of such meteorites impact without breaking up beforehand (and therefore slow down below 200 m s^{-1}), the useful detection rate of meteorites by seismic methods would be of the order of 1 per 5 years per 10^6 km^2.

SUMMARY

The efficiency with which kinetic energy is converted to seismic energy in a meteorite impact is an important factor in any determination of meteorite mass from seismic records. The conversion process is most efficient for low velocity impacts (< 3 km s^{-1}), ~ 1%. For the explosive impact of giant meteorites, the efficiency is ~ 0.01%, and for air explosions, ~ 0.001%.

Over an area of 10^6 km^2, the incidence of detectable meteorite impacts may be sufficiently great to consider the use of seismic methods as an aid to the recovery of meteorites. Although not effective for smaller meteorites ($m < 50$ kg) except for aerial detonation detection, the instrumentation can be used 24 hours a day in all weather, compared with the low utilization of optical means of detection. As any seismic impact identification relies on confirmation by visual sighting of the meteorite, seismology may be regarded in general as a supplement to other methods of locating meteorite falls.

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Manuscript received 8/9/74.