The Collection and Analysis of Freshly Fallen Hailstones[1]

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ABSTRACT

Attempts have been made to obtain samples of freshly fallen hailstones from severe storms in Oklahoma with the purpose of studying the nature and extent of spongy ice within natural hail. Interception by automobile of radar echoes with $Z_e > 10^6$ mm^6 m^{-3} has been found to provide a workable technique for collecting large hailstones as they fall to the ground. Observations suggest that the regions of highest reflectivity were associated more closely with the falls of large hail than with the accompanying heavy rain.

Immediate sectioning of the freshly fallen hailstones revealed the presence of thin shells of spongy ice in many of the larger stones. Calorimetric analyses gave liquid water contents of up to 12±4% of the mass of the stones. Some of the hailstones were aspherical owing to preferential melting of the regions of spongy ice during fall. In the case of hailstones that were stored at sub-freezing temperatures, spongy ice shells could often still be identified from the presence of millimeter size cavities embedded within ice composed of large crystals.

1. Introduction

A hailstone grows by accreting supercooled cloud droplets. The latent heat released as the droplets freeze raises the mean temperature of the hailstone surface toward 0C and, as pointed out by Ludlam (1958), there is a critical rate of accretion above which not all of the accreted water can be frozen immediately. Laboratory studies first conducted by List (1961a) showed that much of this unfrozen water may be retained to give a spongy ice-water mixture. Weickmann (1953) has, in fact, recounted a number of observations of liquid water within natural hailstones. Several authors have also described observations of natural hailstones which apparently have been sufficiently spongy to splash, or otherwise disintegrate, upon hitting the ground (Vittori, 1960; Donaldson *et al.*, 1965; Carte, 1966). All of these observations of liquid water within natural hailstones have been qualitative. More recently, Gitlin *et al.* (1966) have reported some first attempts at quantitative measurement of the liquid water content of freshly fallen hailstones. However, there have as yet been no detailed descriptions of hailstone structure in which the distribution of spongy ice has been known. As List (1961b) has lamented, detailed examinations of hailstone structure have been carried out only for hailstones that have been stored at sub-freezing temperatures. Therefore, with this in mind, a project was organized in 1966 under the auspices of the National Severe Storms Laboratory (NSSL), to collect and analyze the internal structure of freshly fallen hailstones.

Because it was desirable to catch the largest hailstones and because the chance of large hail falling at a fixed point is remote, even in Oklahoma, it was decided to attempt to obtain the hailstones using mobile hail collectors. However, getting an observer and his equipment beneath the core of a severe hailstorm is a major undertaking in itself, requiring the timely identification of a hailstorm that is likely to be persistently intense and the accurate prediction of its movement, especially when it is at long range. Therefore, the present paper is written in two parts, the first being concerned with the practical problem of identifying and intercepting a hailstorm and the second with the analysis of the stones themselves, especially in regard to the distribution of spongy ice related to other aspects of hailstone structure.

2. Collection of freshly fallen hailstones

Hailstorms were intercepted using two and sometimes three station wagons equipped with cold-storage facilities. They were directed toward suspected hailstorms on the basis of WSR-57 radar data obtained at Norman, Okla. This 10-cm radar was scanned mainly at 0° elevation and contours of storm reflectivity at 5-db intervals were obtained over successive 2-min periods using the NSSL Weather Radar Signal Integrator described by Lhermitte and Kessler (1965). According to Ward *et al.* (1965), most hail reports in Oklahoma are associated with echoes (at 10 cm wavelength) whose equivalent reflectivity factor Z_e is about 10^6 mm^6 m^{-3}; most echoes

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TABLE 1. Summary of hailstorms during the project, 21 April–20 May 1966.

Date	Approx. time (CST)	Approx. range (km)	Interception attempted	Large hail collected	Remarks
17 April	2100	170	Yes	No	Hail localized. Lack of suitable roads in the area.
28 April	2200	150	No	—	Small hail only up to ¾ inch.
1 May	2200	40	No	—	Small hail only.
15 May	2200	150	Yes	No	Hail ceased prior to interception.
16 May	2200	170	Yes	Yes	See text.
17 May	2200	20	Yes	No	Only very small amounts of hail fell.
20 May	2000	40	Yes	Yes	See text.

where $Z_e \geq 10^5$ probably contain some significant hail. The largest hail is generally associated with the highest reflectivity. Accordingly, the hail wagons were directed toward centers of high reflectivity. Communications were solely by roadside telephones. Once in the vicinity of a suspected hailstorm the mobile observers were guided by their own visual observations.

All hailstorms known to have occurred within 185 km (100 n mi) of Norman during the period of the project, between 21 April and 20 May 1966, are listed in Table 1. Unfortunately, May 1966 turned out to be the driest May on record throughout the state of Oklahoma. Most hail fell after sunset, adding to the difficulties of collection. Freshly fallen large hail was collected on two occasions. The hailstorm on 20 May, near El Reno, was intercepted fairly easily, mainly because it occurred at close range and began during daylight. The hailstorm on 16 May, on the other hand, was intercepted at night near Tonkawa at a range of 170 km, after a 2-hr journey.

a. Interception of the El Reno hailstorm.

A hail wagon left NSSL at 1830 CST on 20 May following the appearance of radar echo with $Z_e > 10^5$, to the west of Oklahoma City. At 1900 reports were received that hail had fallen at Mustang, 30 km northwest of the laboratory. From this time the storm was followed visually. At 1945, observations from Highway 92 about 6 km north of its intersection with Highway 152 showed a very intense region of precipitation (Fig. 1). This precipitation area was approached from the east along Highway 40. Very heavy rain was encountered at first, then small hail 1.0 cm in diameter and, finally, as the car penetrated the edge of the storm, the

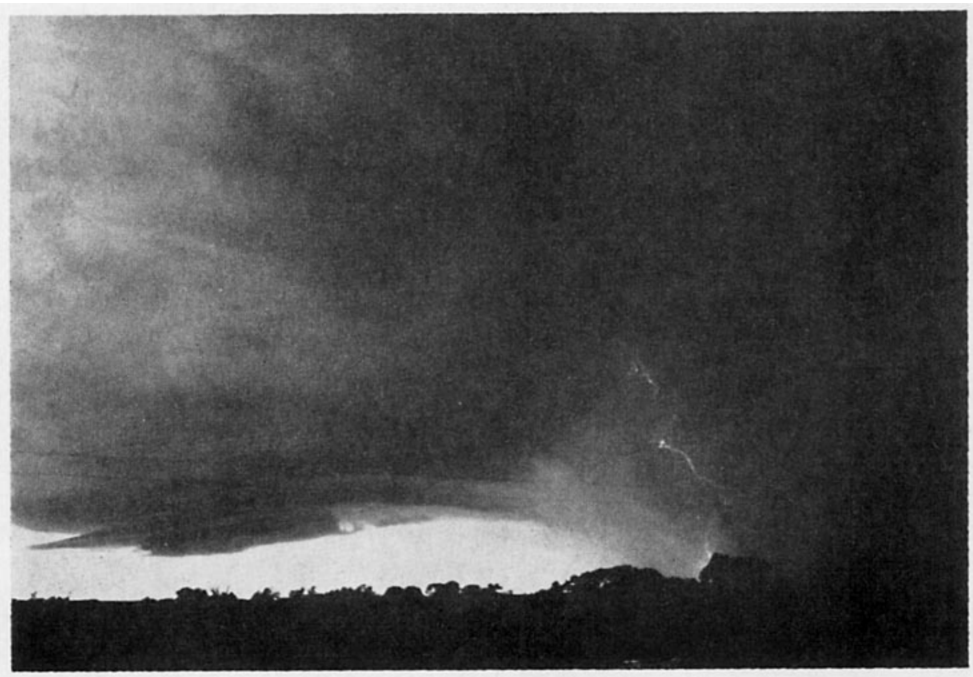

FIG. 1. View to the WNW at 1945 CST, 20 May 1967, of the hailshaft which was giving egg size hailstones at El Reno, about 15 km away. The sky was clear to the left of the photograph. Note the lenticular form of the low-level cloud.

TABLE 2. The interception of the Tonkawa hailstorm of 16 May 1966.

Time (CST)	Information obtained from the WSR-57 radar at Norman	Instruction given to the mobile observer
1745	Line of radar echoes beginning to develop in NW Oklahoma and SW Kansas.	Standby at Norman; observer will have to attempt to intercept these at long range if no significant echoes develop soon at closer range.
1950	One of the storm cells (A) in the line just reaching a Z_e of 10^5. Storm A is at a range of 200 km toward 345° from Norman.	Observer sent northward along fast Interstate Highway 35. Told to telephone back in 1 hr.
2050	Storm A, with large area of $Z_e=10^5$, traveling to right of winds. It is evidently an SR storm (Browning, 1964).	Observer advised to continue northward, in anticipation that Storm A will persist with the same direction of travel. Told to telephone back in ½ hr.
2135	Storm A, still with large area of $Z_e=10^5$, maintaining roughly constant speed and direction to right of winds. Extrapolating its motion, the reflectivity core should cross Highway 35 at 2200.	Observer advised to continue north to location shown in Figs. 2 and 3 and to await passage of Storm A overhead.
2206	Mobile observer encounters falling hail up to walnut size at location shown in Figs. 2 and 3.	

largest hail with a maximum diameter of about 4 cm. This was encountered about 8 km east of El Reno at 2015. The hail ceased at 2020 leaving a clear sky to the west as the hailstorm moved away toward the east.

b. Interception of the Tonkawa hailstorm.

The way in which the region of large hail was identified and intercepted in the Tonkawa storm on 16 May is summarized in Table 2.

In order to clarify what it was that permitted the region of large hail in the Tonkawa storm to be identified and intercepted at so long a range, it is worthwhile looking at the behavior of this storm in more detail. During the afternoon of 16 May a dry line was oriented NNE/SSW in western Oklahoma and a surface low was situated in the Oklahoma Panhandle. After 1745 CST showers developed quickly along a 250-km length of this line; most were small and short-lived, but the northernmost two, which were located close to the surface low, developed into active storms. At 1930 several cells were in existence, the strongest radar echo being centered about 210 km NNW of Norman. As shown by Fig. 2 most of these cells traveled toward the ENE at about 55 km hr^{-1}. The 1800 rawin ascents at Dodge City (about 200 km WNW of storm) and Oklahoma City (about 200 km SSE) showed that this corresponded to the direction of the wind in the middle troposphere. The maximum Z_e of most of the cells at 0° elevation remained less than 10^5. However, by 2000, one of them (labeled A in Fig. 2) was exceeding a Z_e of 10^5 and a little later, another (labeled B) also began to exceed this level. Both storms were later shown to have contained hail. The time-integrated extent of echo with $Z_e > 10^5$ is indicated by the hatched areas in Fig. 2. (An error in the radar display gives rise to an uncertainty of about 3 km in the absolute position of the echo paths.) Storm B remained intense for only about 1 hr and never traveled significantly to the right of the winds. Storm A, on the other hand, remained intense for over 2½ hr and, although it redeveloped twice and was evidently not in a perfectly steady state, it traveled at a fairly uniform velocity to the right of the winds at all levels throughout this period. Storm A, therefore, fell into the category of the SR local storm (Browning, 1964). The persistence and relative steadiness of SR storms render them more predictable than most storm cells, and this, of course, was a great asset when it came to attempting to intercept Storm A.

Although the regions of hail in Storms A and B were successfully identified using the reflectivity criterion of Ward *et al.* (1965), it will be recalled that this criterion was obtained on the basis of statistics from a rather sparse network of hail observations. In order to investigate the closeness of the relationship between hailsize and reflectivity on small space and time scales during the lifetime of individual hailstorms, a fairly detailed post-storm survey was made of the distribution of hail size from Storms A and B. Most of the information was gleaned from ordinary householders by means of a house-to-house survey. The area affected by the storms consisted of farming communities and because of their dependence on the weather, most persons interviewed were able to give detailed and consistent accounts of the storms. Information on maximum hailsize was asked for in terms of easily visualized size categories (pea, grape, walnut and golfball) and the resulting distribution is shown in Fig. 3. Many persons also measured rainfall totals using simple gages. Despite the often poor exposure of these gages, Fig. 4 shows that con-

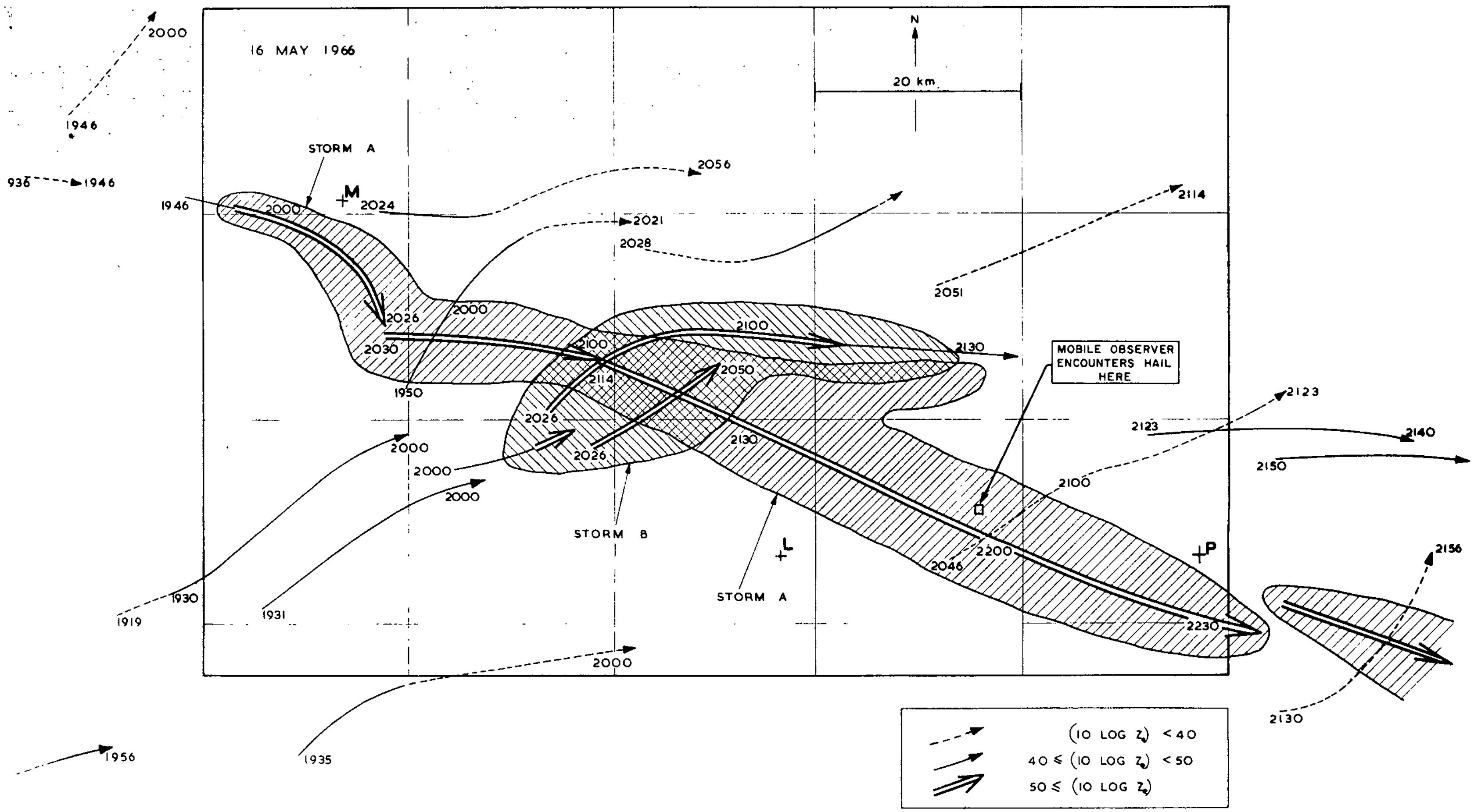

FIG. 2. Tracks of storm cells in NW Oklahoma, 16 May 1966. Dashed, solid and double lines indicate the tracks of cells of various intensities as specified in the key. The time integrated extent of echo for which $Z_e > 10^5$ mm^6 m^{-3} is shown hatched. Times in CST are indicated along the echo tracks. The heavy rectangular frame corresponds to the area in Figs. 3–5. The background grid divides the area into 20-km squares. The locations of Manchester (M), Lamont (L) and Ponca City (P) are shown.

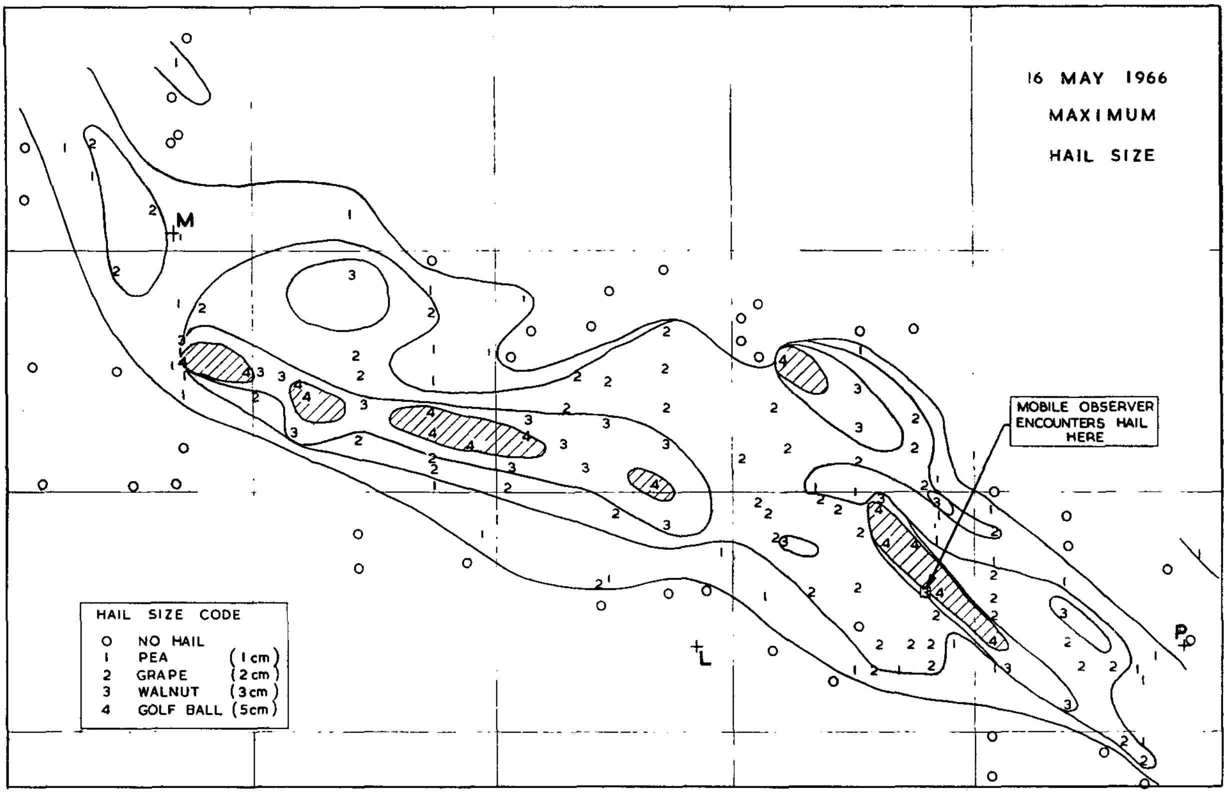

FIG. 3. Maximum hail size, 16 May 1966. Individual observations are plotted according to the indicated code and areas receiving golfball size hail are hatched.

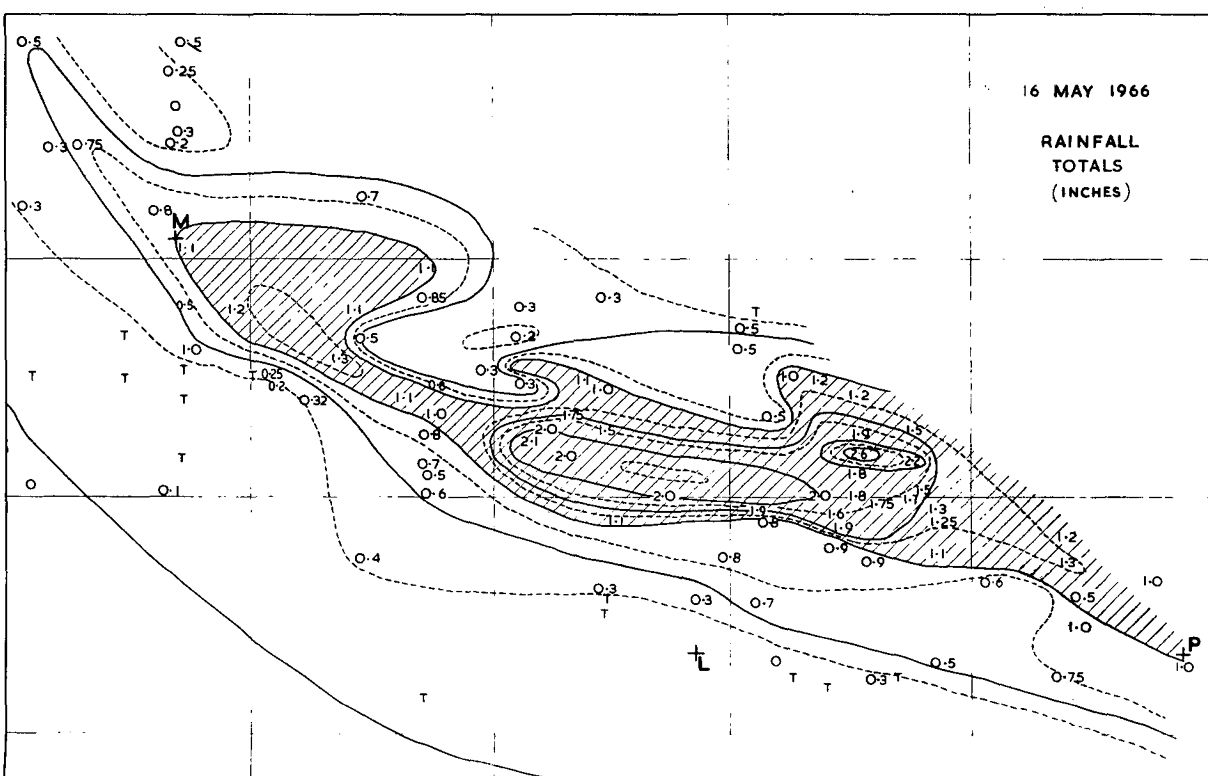

FIG. 4. Rainfall totals, 16 May 1966. Isohyets are drawn at 0.25-inch intervals and areas with totals exceeding 1 inch are hatched.

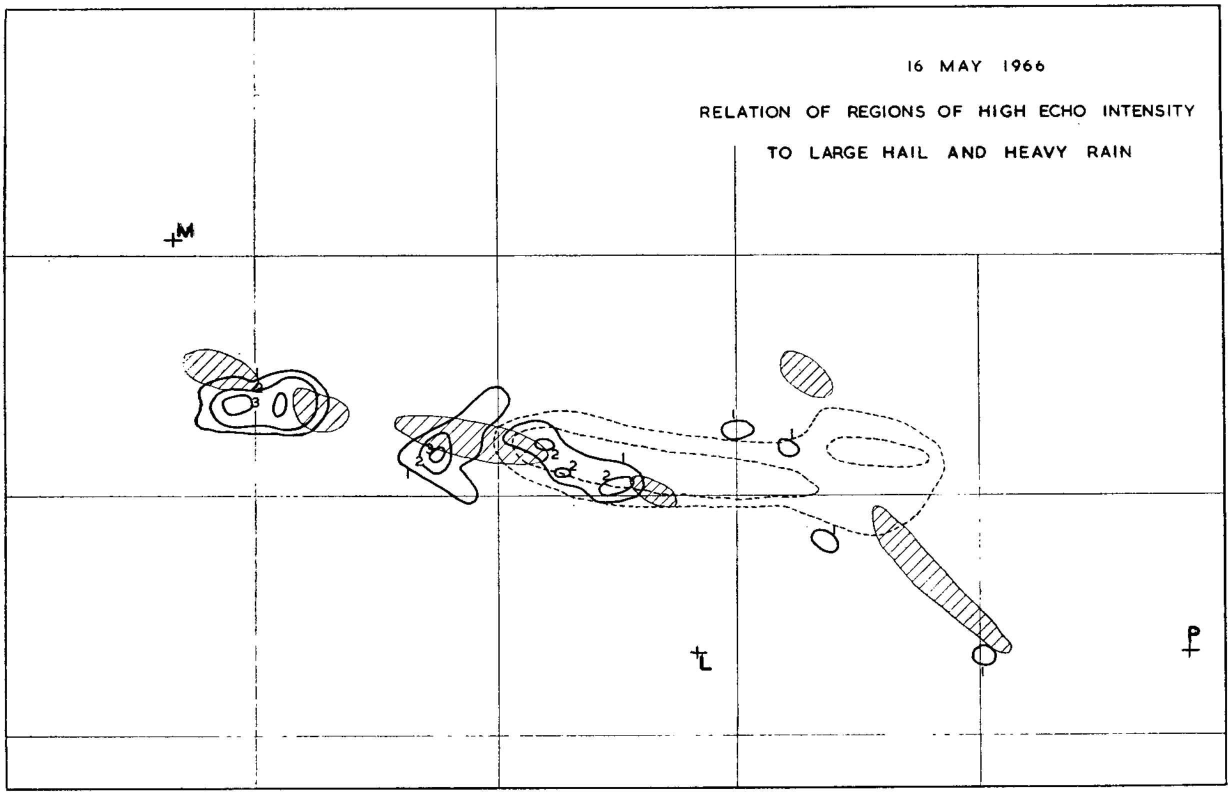

FIG. 5. Relationship of regions of high echo intensity to the surface distribution of large hail and heavy rainfall, 16 May 1966. The heavy contours indicate the number of 4-min periods for which $Z_e \geq 10^{6.5}$ mm^6 m^{-3}, the hatched areas denote the distribution of golfball size hailstones and the dotted contours are isohyets for 1.5 and 2 inches.

sistent isohyets could be drawn. A comparison of Figs. 3 and 4 with Fig. 2 shows that the tracks of those parts of the echoes for which $Z_e > 10^5$ are fairly closely related to the swath of hail and also heavy rain. Broadly speaking, on this occasion a Z_e of 10^5 was a good indication of grapesize hail and 1-inch rainfall, although there was a tendency for the axis of the heaviest rainfall to be displaced toward the left flank of the swath. This poses the question, however, as to whether the high reflectivity was due mainly to high concentrations of raindrops and small spongy hailstones or to smaller concentrations of large hailstones. Fig. 5 has been prepared in an attempt to shed some light on this problem. It shows that there is a fairly good relationship between regions of $Z_e > 10^{5.5}$ and golfball size hail (shown shaded). On the other hand, heavy rain (totals in excess of 1.5 and 2 inch are shown by dotted contours in Fig. 5.) is more poorly related to the regions of high reflectivity. Thus, there is evidence to support the view that the regions of high reflectivity were due to the presence of the large hail itself. (For technical reasons the absolute magnitude of reflectivity is thought to have been underestimated by several db.)

An equally close relationship of the highest reflectivity to regions of maximum hail size was found in another Oklahoma hailstorm (Browning, 1965, Fig. 3). In this case a WSR-57 value of Z_e of $10^{5.7}$ at a range of 40 km was found to be associated with 5- to 10-cm hail. There have been several more extensive statistical studies relating maximum hailsize to echo intensity, but these have not employed sufficiently dense networks of observations to ensure that the largest hailstones have been observed. Nevertheless, the present observations are in line with the statistics for Oklahoma hailstorms presented by Ward *et al.* (1965), which indicate that most echoes equal to or exceeding a Z_e of 10^5 probably contain some significant hail.

3. Structure and liquid water content of the hailstones

Stones falling from both the El Reno and Tonkawa storms were collected within 1 min of reaching the ground. Stones were stored in two ways, some in dry ice and some in individual polythene bags placed in the center of a large container of ice at 0C. Other stones were sliced in half immediately and tested for hardness by gently prodding with a pair of tweezers. On return to the laboratory each of the stones stored at 0C was weighed and its principal axes measured; it was then sliced in half with a sharp razor blade. One half of each stone was melted in a calorimeter to give its liquid con-

Table 3. Distribution of spongy ice within the Tonkawa hailstones.

Stone	Mass (gm)	Principal axes (cm)	Liquid water content (%)	Diameter of soft ice shell (cm)	Thickness of bubble shell (cm)	Structure of bubble shell in frozen section
1	6.5	2.6, 2.6, 2.6	3±5	0.9	0.2	Opaque; maximum diameter of bubbles 200 μ.
2	6.2	2.6, 2.6, 2.6	5±3	—	—	Other half of stone lost.
19	15.5	4.6, 3.4, 2.7	4±4	1.0	0.2	Clear ice and bubbles 100 μ in diameter; a cavity 500 μ×0.3 cm long.
20	8.8	3.6, 2.7, 2.4	12±4	1.1	—	Other half of stone lost.
24	6.8	2.7, 2.4, 1.9	9±6	0.8	0.3	Numerous bubbles, 200 μ in diameter.

tent; the other half was frozen, sectioned at 0.3-cm intervals and examined in ordinary and polarized light.

For the calorimetric measurement, one of three different sized aluminum calorimeters was selected depending on the mass of the stone. It was filled with water to a level such that the stone would be almost immersed. Water and calorimeter were then heated to a temperature above ambient equal to that (as shown by a rough calculation) which the hailstone, as it melted, would cool water and calorimeter below ambient. This procedure minimized heat leak errors.

a. Hailstones from the Tonkawa Storm.

Thirty two stones were collected and sectioned, their mass distribution being as follows:

Weight (gm)	0–2	2–4	4–6	6–8	8–10	15
Number	10	13	3	3	2	1

Stones lighter than 6 gm were invariably hard throughout. The heavier stones (5 in all) contained a soft inner shell having a mean diameter of 0.9±0.1 cm and a thickness of 0.2±0.1 cm. Ice within this shell was made up of a mixture of fine crystals and liquid; it had the consistency of spongy ice grown in the laboratory. A section through one of these stones made after it had completely frozen is shown in Fig. 6. The soft shell was associated with the ring of bubbles at 0.9 cm diameter. Had this shell been completely liquid it would have given a mean liquid content of about 5%. In fact, the calorimetric measurements gave a mean liquid content of 4%, which corresponded to the limits of accuracy of the calorimetric measurements for this stone. The distribution of spongy ice within this and four other stones from the Tonkawa storm is summarized in Table 3. Two of these stones had high liquid contents suggesting that the liquid was distributed in a shell of greater dimensions than the associated bubble ring distinguishable in the thin sections. From a comparison of the position of the soft shell before the half stone was frozen and the subsequent thin section, it was found that the soft shell was contained within a much thicker shell (about 0.8 cm) of relatively clear ice composed of large crystals whose long axes (0.3–0.8 cm) were oriented approximately radially. These large crystals evidently formed, at least in part, by the solidification of the soft shell so that the fine crystals first observed were probably in the form of regions of parallel dendritic planes which froze together to give crystals much larger than the individual dendrites. One stone also contained a large cavity (Fig. 6a) within the soft ice shell. The outer surface of all stones examined was quite smooth, without any holes or cracks.

b. Hailstones from the El Reno storm.

About 100 stones were sliced open within 1 min of falling. Stones lighter than 4 gm (2 cm in diameter) were invariably hard throughout. All larger stones (30 in all) contained a soft inner shell at a diameter of about

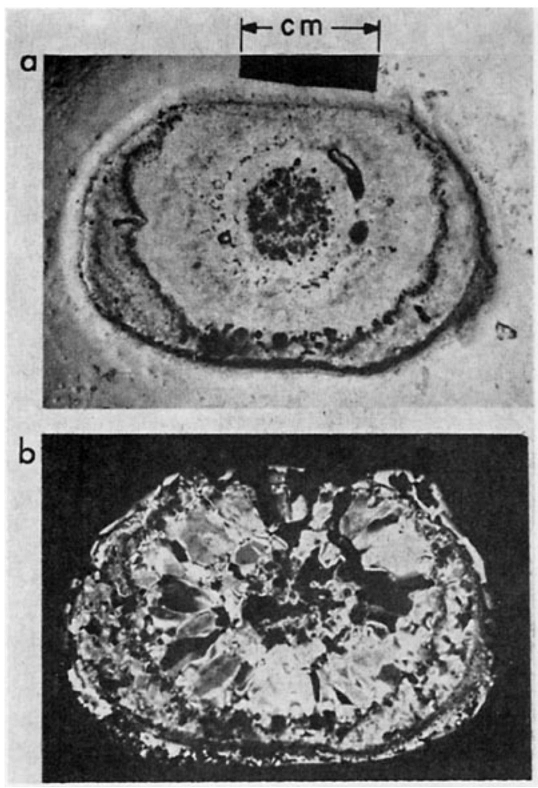

Fig. 6. Stone 19 (section 1) from the Tonkawa storm in white light, a., polarized light, b. This stone contained a soft shell, 1.0 cm in diameter, concentric with the stone center, visible in the frozen section as a ring of bubbles. Note also the large cavity.

1.0 cm, apparently containing spongy ice. No calorimetric measurements were made; however, 22 of the larger stones were preserved in dry ice and subsequently sectioned. These stones were very uniform in structure. Each had an opaque inner core diameter 0.7±0.1 cm composed of small crystals. This core was surrounded by a thick clear shell of diameter 2.0 cm composed of large crystals with the long axis oriented radially; this was in turn surrounded by a 0.2 cm thick opaque layer of small crystals, whose shape was convoluted.

Fourteen of the twenty-two sectioned stones contained large cavities, up to several millimeters across which were situated just outside the central core within the large crystal shell (Figs. 7, 8). The cavities were not completely empty when the stone was first sectioned, but contained a network of delicate crystals; these broke during sectioning. Cavities did not extend completely around the central core, but typically covered about $\frac{3}{4}$ of its area, lying on an approximately spherical shell. The diameter of the shells containing the cavities varied between 0.8 and 1.2 cm, corresponding to the diameter of the soft shells observed in the stones that were sliced open immediately after falling. One stone (Fig. 7) showed evidence of the formation of several distinct layers of cavities.

Unlike stones from the Tonkawa storm, 10 El Reno stones had marked re-entrant cavities (Fig. 8). These cavities occurred on only one side of the stone and were most extensive within the soft shell. As shown in Fig. 8a the partial loss of the outer shells of ice left the hard central core exposed. The external form was otherwise unrelated to crystal or bubble structure.

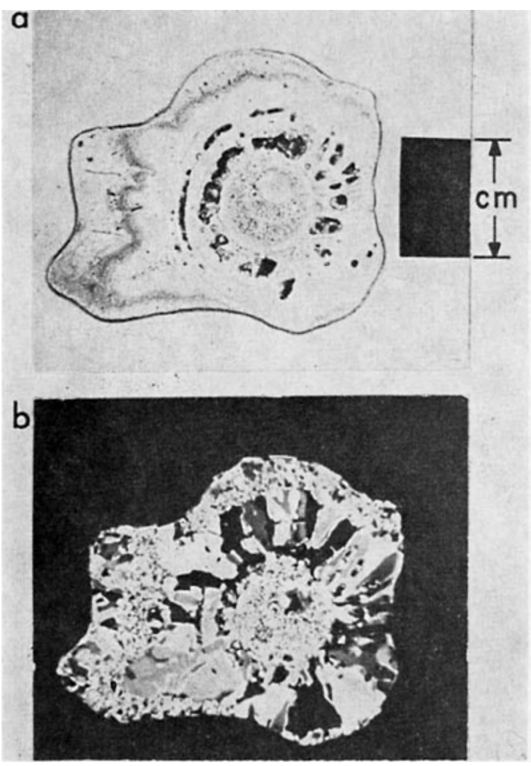

FIG. 7. Stone 3 (section 3) from the El Reno storm in white light, a., polarized light, b. An inner core is surrounded by a large-crystal layer of clear ice containing layers of cavities, suggesting that the stone grew spongily while rotating freely. (Note that the inner core contains an embryo composed of four crystals.)

c. Interpretation of cavities.

Although the initial conical core which could be detected in one-third of the hailstones must have fallen without tumbling, the presence of growth layers which completely surrounded the stones suggested that random tumbling began once the core had grown to about 0.8 cm diameter. The large internal cavities found in most of the larger stones are similar to those found in accreted ice grown spongily in wind tunnels and are to be attributed to displacement of liquid water by air (List, 1961b). The pressure difference between front and back of the stone will be of order ρV^2 (ρ, air density; V, stone terminal fall speed) which is of the same order as the hydrostatic pressure of water in the stone and can lead to displacement of liquid water. The asymmetry in the distribution of the cavities implies that the stone rotation rate was small during the time of the displacement. The detailed distribution of the cavities will depend on the detailed motion of the stone and the crystallographic texture of the sponge.

The presence of liquid water or air cavities within a stone enables those parts to melt more quickly as the stone falls into an environment above 0C [see also Browning and Beimers (1967)]. This is thought to have led to the shape of the stone in Fig. 8a, where ablation has taken place primarily between the hard outer shell and the hard central core. Since many stones were aspherical, a possible interpretation is that, once melting of the outer shell begins, the stone orients itself so that the same edge faces the air flow and continues melting, thus tending to further increase its asymmetry and orientational stability.

4. Conclusions

Problems associated with the identification and interception of hailstorms have been considered with particular emphasis on the Tonkawa hailstorm of 16 May 1966. The successful interception of large hail on this occasion can be attributed to 1) the correct and early identification of Storm A as the hailstorm of interest on the basis of the large area of radar echo with $Z_e > 10^6$ mm^6 m^{-3} and its anomalous motion to the right of the winds; and 2) the persistence and uniform velocity of Storm A, a feature of many SR storms. If Storm A had been a short-lived hailstorm like Storm B, there would have been no chance of intercepting it at so long a range in view of the 2-hr road journey involved.

Although the reflectivity values were probably underestimated on this occasion, it is noteworthy that the occurrences of $Z_e > 10^{5.5}$ mm^6 m^{-3} along the path of the

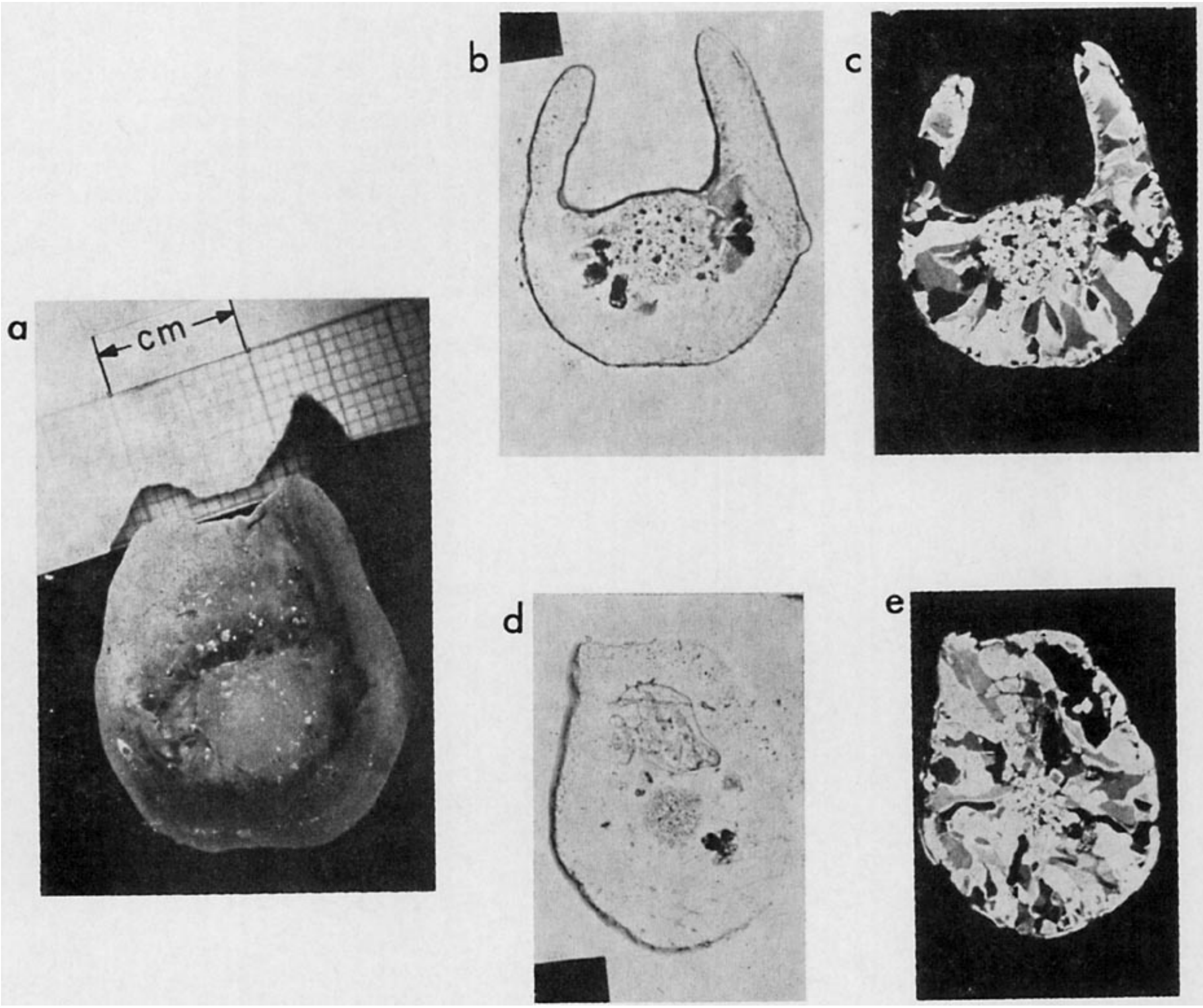

FIG. 8. Stone 1 (sections 1 and 2) from the El Reno storm. Fig. 8a shows a general view, Figs. 8b and 8c a section (in white and polarized light, respectively) through the hailstone center, and Figs. 8d and 8e (in white and polarized light, respectively) a parallel section that intersects the edge of the opaque ice core. This stone shows some characteristics of the stone in Fig. 7, but has melted considerably during fall. Melting has occurred preferentially in the region of the soft spongy ice shell, associated in this case with large cavities.

Tonkawa hailstorm were closely associated with the bursts of largest hail, suggesting that high reflectivity was due to the large hail itself.

Hailstones were collected and examined within 1 min of falling from both the Tonkawa and El Reno storms. The presence of spongy ice within some of the stones was inferred from calorimetric measurements which indicated liquid water contents of up to $12\pm4\%$. The spongy ice was found to be associated with thin shells of soft ice. After the stones had been frozen entirely, these shells were found to be recognizable from the presence of a shell of air bubbles up to 200 μ diameter and of large air cavities embedded in ice which contained large crystals whose long axes were orientated radially. The external shape of some hailstones was aspherical due to melting during fall. The melting was most pronounced in the region of the spongy shell.

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