ANALYSIS OF HAILSTONES

from

Northeastern Colorado, 1962

by

Ron R. Robinson

May, 1963

CER63RRR38

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DEFINITION OF TERMS

Cold box	Small portable refrigerator
Cooperators	People who collect and report hail
Density	Ratio of weight of ice to the same volume of water, diemensionless
Dry growth rings	Rings of ice made up of small ice crystals
Ice crystal ratio	Volume of small ice crystals in a hailstone divided by the volume of large ice crystals in the hailstone
Large ice crystals	0.3 to ∞ cm in length dimensions
Large hailstones	Hailstones with diameter > 3 cm
Max Z values	Max reflectivity
Medium hailstones	Hailstones with diameter from 1.5 + to 3 cm
Small ice crystal ratio	A ratio from 0.0 to 1
Small ice crystal	0.0 to 0.3 cm in length dimension
Large ice crystal ratios	A ratio from 1 to ∞
Tilt	Angle of thunderstorm core from the vertical
Wet growth rings	Ice rings made up of large ice crystals

I. INTRODUCTION

A large number of hailstones were collected in Northeastern Colorado during the summer of 1962. Certain measurements were made on these stones for the purpose of determining their physical characteristics. Measurements were made of the following:

Density,

Ratio of small ice crystals to large ice crystals in individual hailstones,

Number of wet and dry growth rings,

Diameter of the hailstone or shape of stones,

Size of the embryo, and

Shape of the embryo.

The mean, standard deviation, variance and coefficient of variation of each of these parameters was computed for each sample. Simple correlation coefficients were computed between these parameters for individual stones. The data were analyzed to determine seasonal and geographical variation. The physical properties of hailstones were compared to the physical properties (Z values, cloud tops, tilt of core) of the storms from which they fell by computation of simple correlation coefficients.

II. PROCEDURES

A. Laboratory

1. Slicing process - while the slicing of hailstones for photographing is a tedious and exacting operation, with some practice it is possible to slice and photograph four stones per hour.

For slicing a hailstone an apparatus was used which contained two hot wires attached to an inclined plane (1)*. These two wires could be adjusted to cut any thickness desired. The hailstone was frozen to a brass cart, which was rolled down the inclined plane. The hot wires made contact with the hailstone, and were adjusted to cut a hail slice three millimeters thick. The hailstone slice was then polished on a damp chamois to a final thickness of one millimeter. The slice was then ready to be photographed for air bubble structure.

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* Numbers in parenthesis refer to appended references.

2. Photographing hailstone slices - Photographing a hailstone slice must be done at $0^{o}C$ or colder. To accomplish this, a photobox was mounted in a refrigerator. The photobox contains its own light source, cross-polarized lenses, and a roleflex camera mounted in the top. For black and white pictures the film used was Pan-X-125. In taking a picture of the air bubble structure, only one polarized lens was used. The hail slice (one millimeter thick) was placed in the photobox, and a time exposure of five seconds was taken. The hail slice was then removed and further polished to a thickness of one tenth of a millimeter. Again the hailstone was placed in the photobox with two polarized lenses crossed. For a picture of the crystal structure of the hail slice, the time exposure was eighteen seconds.

The cross polarized lenses let only the refracted light from the crystals pass through to the camera, thus giving a picture of the crystal structure to the hail slice.

For taking color photographs of the crystal structure of hailstone slices a 35 mm single lens reflex camera was used which contained a bellows attachment with a magnification of 2. 7. The bellows attachment made it possible to take detailed pictures of small hailstone slices. The photobox used for taking colored photographs was made of plexiglass. It has the dimensions of 6" x 6" x 12" (see Figure 1). For a light source, 700 watt photoflood light bulb was mounted in the base of the photobox. The hailstone slice was placed eight inches above the base of the photobox on a glass slide for photographing. One polarized lens was placed one inch above the glass slide which held the hailstone slice. The second polarized lens was placed 0. 25 inch above the first. These lenses were crossed to allow only light refracted from the crystals to enter the camera. The top of the photobox was left open to allow the 35 mm reflex camera, which was mounted on a tripod, to be focused on the hailstone slice. The lens setting and lens speeds were variable. They depend on the magnification, thickness of the hailstone slice and the power of the photoflood light in the photobox. The settings that we used were: Lens opening f/16, lens speed one-fourth second, type of film - Kodachrome II. The photoflood light could only be left burning for a few seconds, because the heat was produced tended to melt the hailstone slice. This prohibited time exposures of any length.

3. Density measurements - Several methods may be used for measuring the densities of hailstones. The method that we used was introduced to us by the late Dr. Lyle V. Andrews of Nebraska State Teachers' College. The materials needed were one gallon can, a gallon mixture of alcohol and water with the ratio of 25 percent alcohol to 75 percent water, ice, 250 milliliter flask, a bracket for holding the 250 milliliter flask, carbon tetrachloride (CCl_4) and paint thinner. The gallon can was used to hold the mixture of alcohol, water and ice. The 250 milliliter flask containing CCl_4 and paint thinner with a density of .855 was lowered into the solution of alcohol, water and ice. It was held in position by a four-pronged bracket. (See Figure 2). The mixture of alcohol and ice hold the 250 milliliter flask of CCl_4 and paint thinner just below $0^\circ C$; this allowed a hailstone to be placed into the solution of CCl_4 and paint thinner without melting. When a hailstone was placed into the 250 milliliter flask containing CCl_4 and paint thinner, it would either sink or float. If the hailstone floats, the density of the solution was decreased by adding paint thinner to the solution until the hailstone was suspended midway in the solution. If the hailstone sinks to the bottom of the solution of CCl_4 and paint thinner, then the density of the solution was increased by adding CCl_4 until the hailstone was suspended midway in the solution. Once the hailstone was suspended in the solution of CCl_4 and paint thinner, the density of the solution (and thus that of the stone) was measured with a hydrometer*. Once the density kit was in operation it took very little time to measure the densities of hailstones.

Density measurements were always made after all other physical operations were completed, since it is probably that soaking the hailstone in a solution of CCl_4 and paint thinner may change the inner structure of the stone.

B. Fieldwork

1. Collecting hailstones - The majority of hailstones collected during during the summer of 1962 were collected by cooperators in northeastern Colorado, and southwestern Nebraska. When it hailed the cooperators would collect a sample, store it in the refrigerator and mail a Report of Hail to Colorado State University. The hail samples would then be picked up and stored in a refrigerator.

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* Temperature corrections to be applied to the hydrometer readings are given in Figure 3.

A few hail samples were collected in cold boxes. These cold boxes consist of a small portable refrigerator with a canvas funnel mounted on top of the portable refrigerator in such a manner that the hailstones would fall inside the refrigerator. The advantage of catching hailstones in a cold box is that it allows for a more random sample. Cooperators tend to pick the largest and most unusual hailstones.

2. Slicing hailstones - Slicing hailstones in the field was similar to the operation performed in the laboratory. However, there were a few minor changes. For a power supply, six volts were obtained from a car battery. To freeze the hailstone to the brass cart, the brass cart was cooled with dry ice. Other than these changes, the slicing was done in the same manner as in the laboratory procedures.

3. Photographing hailstones - Due to the lack of a 110 volt power supply the photobox was mounted in a styrofoam ice chest filled with dry ice. A portable flash unit was used in place of the 110 volt photoflood light mounted in the base of the photobox. Other than these changes the procedures for taking black and white air bubble and crystal pictures was the same as the procedures used in the laboratory.

It was discovered that due to the time element in taking colored photographs (focusing, changing cameras, etc.) that it was difficult to take a colored picture, because the hailstone slice would start to melt.

4. Density measurements - Density measurements were made in the same manner as in the laboratory. Hailstones were used to cool the alcohol and water solution.

III. DATA ANALYSIS

A. Hailstone parameters

Nine different hailstone parameters were recorded from hailstones collected during the summer of 1962. These parameters are:

1. size,
2. shape,
3. density,
4. ratio of ice crystals (volume of small ice crystals/volume of large ice crystals,
5. number of wet growth rings,

6. number of dry growth rings,
7. radius of wet embryo,
8. radius of dry embryo, and
9. shape of the embryo.

1. Size - For the size of a hailstone, the diameter was measured and recorded in centimeters. If the hailstone was an ellipsoid or some odd shape, the greatest length of the hailstone was recorded.

2. Shape - The hailstone shapes were designated by five different classes, each class identified by a different number. These classes were: Spheroid = 1, ellipsoid = 2, saucer stone = 3, conical stone = 4, star stone = 5. The saucer stone was a hailstone which had a shape similar to that of a saucer, and generally had a dimple on one or both faces. The conical hailstone had the shape of a cone or a tear drop. The star hailstone had the same basic shape of the classical shapes plus very distinct icicle type projections on the surface.

3. Density - The density of the hailstones were measured with the density kit.

4. Ice crystal ratio - The ice crystal ratio was calculated from color slides of the hailstone slices when they were available, and from the black and white photos when the color slides were not available. When color slides were used, the volume of large ice crystals and small ice crystals was calculated by projecting the picture of a hailstone slice onto a circular grid. The assumption was made that every hailstone was made up of spherical or elliptical shells, consisting of either "small" or "large" ice crystals. With this assumption and using the grid to find the radius of the different ice crystal shells, the volume of shells composed of large and small ice crystals was calculated. The photograph of the hailstone slice was always centered on the grid at the embryo center, which is not necessarily the geometric center. An ice crystal was considered "small" if its length was less than . 3 cm and a "large" ice crystal was any crystal having a length greater than . 3 cm. If the shells of small and large ice crystals were elliptical, it was assumed that the shells were ellipsoids and the volume of the ellipsoids was calculated.

If there were no color slides available of a hailstone slice, a black and white crystal structure photo was used for calculating the volumes of "large" and "small" crystals. For black and white photos a plastic grid was used which contained fifteen circles with a common center. The grid was placed on the hail slice photograph and centered on the hailstone embryo. The radius of the circular shells of the small and large ice crystals was then calculated. Knowing the radius of each different shell the volume of the small and large ice crystal shells was calculated. The same assumptions were used that were used for calculating the volume of ice crystal shells using colored photos.

It was impossible to slice and photograph small hailstones, however, they were cut with a razor blade and the ice crystal ratio determined by approximating the volumes of small and large ice crystals by looking at the sliced hailstone through a magnifying glass. The density and size were measured.

The colored slides were much better for calculating the volume of ice crystal shells, since it was possible to obtain large magnification factors when the photographs were projected on a screen. For our calculations a magnification factor of twelve was used. It was also much easier to distinguish between small and large ice crystals when using color slides.

The ratio (volume of small crystals/volume of large crystals) was then determined for every hailstone analyzed after computations of the volumes of large and small crystals were completed.

5. Growth rings - From the colored slides and black and white photographs of the hailstone slices, the number of wet and dry growth rings was recorded. (Wet growth was assumed to consist of large ice crystals, and dry growth was assumed to consist of small ice crystals.)

6. Embryo diameter - From the colored photographs and the black and white photographs, the radius of the hailstone embryo was measured and it was determined whether the embryo consisted of large or small ice crystals. The shape of the embryo was recorded according to the category to which it belonged. These categories were the following: Spherical = 1, elliptical = 2 and conical = 3.

7. Amount of data - For every hail sample of large hailstones (hailstones with a diameter equal to or greater than 1.17 centimeters) ten hailstones were analyzed. If there were less than ten hailstones in the hail sample, then as many stones were analyzed as possible. There were very few samples that did not have ten hail stones analyzed.

For every hail sample of small hailstones (hailstones with a diameter less than 1.27 centimeters) five hailstones were analyzed.

A total of 610 hailstones were analyzed for density, size, and ice crystal ratio. Of these, 345 were also analyzed for number of wet and dry growth rings, shape of hailstone, radius of wet or dry hailstone embryo, and the shape of the embryo.

8. Accuracy of data - The density measurements can be measured accurately to $\pm .002$. The density of our solution of CCl_4 and paint thinner has been calibrated for different temperatures (See Figure 6).

The accuracy of our stone data is as follows: Hailstone size (diameter) $\pm$ 3 millimeters, density $\pm .002$, ratio of ice crystals $\pm .05$, radius of embryo $\pm .005$ centimeters.

B. Radar data

During the summer of 1962 the hail project obtained cloud data from three different radars: A three-centimeter PPI radar leased from and operated by Atmospheric Incorporated, Fresno, California, a CPS-9 radar equipped with a step-gain system and operated by the project at Lowry Air Force Base, Denver, Colorado, and the project's Navy model SO-12M/N 3 cm radar modified to give an RHI presentation. All the radars were equipped with 16 mm cameras for a continuous recording of scope presentation. The PPI and RHI radars operated at New Raymer, Colorado. With these three radars the paths of thunderstorm echoes were plotted across northeastern Colorado.

Each of these radars was calibrated to give reflectivity as a function of range and gain setting. With this calibration, an estimate could be made of reflectivity (Z values) values for each thunderstorm echo tracked. The radars also obtained information on the altitude of the cloud tops. Observations were made of the base and top of the echo. From these observations it was possible to calculate the amount of "tilt" from the vertical (2).

There were approximately 750 different thunderstorm echoes tracked during the summer of 1962. Of this number it was possible to positively identify 25 hail samples from 20 different thunderstorm echoes. From these 25 hail samples, 200 hailstones were analyzed.

In comparing a hail sample to a certain cloud echo, $\pm$ 30 minutes time difference was allowed between the time the hail sample was picked up by the cooperator and the time that the radar placed a thunderstorm echo over the location of the hail sample. This large tolerance in time was permited because of uncertainty in the accuracy of the reported times of hailfalls.

IV. RESULTS

A. Mean hailstone properties

1. Density - The mean density of hailstones analyzed was .888. The range was from .853 to .916. The hailstones with the lowest densities (densities around .853) were predominantly rime ice. (Small ice crystals surrounded by many air bubbles). The hailstones with the higher densities were almost completely composed of clear ice.

2. Size - The mean size (diameter) of the 610 hailstones analyzed was 1.83 centimeters.

The hailstones were separated into three different categories; small hailstones, medium hailstones and large hailstones. The frequency of occurrence of hailstones of each category is shown in Table 1. Table 1 shows that

Table 1. Frequency of occurrence of small, medium, and large hailstones.

Diameter	May	# Samples	June	# Samples	July	#Samples	Total Individual	Stones
Small (0-1.5 cm)	68%	15	57%	12	53%	26	47%	302
Medium (1.5-3.0 cm)	27%	6	19%	4	14%	7	21%	139
Large (> 3.0 cm)	5%	1	24%	5	33%	16	32%	208
Total		22		21		49		649

68 percent of the individual stones were small and medium size. However, these data are biased towards the occurrence of large hailstones, because the cooperators tend to collect the largest hailstones for a hail sample. It would be more correct to say that small and medium sized hailstones made up about 90 percent of the hailstones that fell in 1962.

3. Ice crystal ratio - The frequency of small ($r < 1$) and large ($r > 1$) ice crystal ratios was calculated. The results are shown in Table 2. As may be seen from Table 2, 46 percent of the hailstones had large ice crystal ratios, (hailstones containing a greater volume of small ice crystals) and 54 percent had small ice crystal ratios (hailstones containing greater volume of large ice crystals.

Table 2. Frequency of occurrence of small and large ice crystal ratios.

	Total		May		June		July	
		# Samples		# Samples		# Samples		# Samples
$r < 1$ (Greater volume of large crystals)	54%	341	63%	14	29%	6	61%	30
$r > 1$ (Greater volume of small crystals)	46%	293	37%	8	71%	15	39%	19
Total		634		22		21		49

4. Growth rings - The total volume of ice from the 610 hailstones that were analyzed was 13,382 cm^3. This volume was calculated by assuming each hailstone was a spheroid having a diameter equal to the greatest length. The corresponding volume of small ice crystals was 6,415 cm^3, and the volume of the large ice crystals was 6,967 cm^3. This indicates that during the summer there was a greater volume of hail formed from large ice crystals than from small ice crystals.

Analysis was made of 257 hailstones to determine the number of wet and dry growth rings. The average number for both wet and dry growth rings was found to be 1.3. This indicates that the mean hailstone for 1962 contained about one dry growth ring and one wet growth ring. However, there were many hailstones with 3 growth rings and a few that contained as many as 8 growth rings.

5. Embryo diameter - The mean embryo diameter for 257 hailstones analyzed was .08 centimeters. The range was from .01 to .16 centimeters.

6. Hailstone shape - Analysis of shape was made for 427 hailstones. The results are given in Table 3. Table 3 shows that the greatest number of hailstones were shaped as spheroids or ellipsoids*.

*The method for categorizing hailstones and hailstone embryos were discussed in the section on Data Analysis. It is sometimes difficult to distinguish the difference between a spheroid and an ellipsoid, therefore, the spheroids and ellipsoids should be considered as one shape. The other categories are very easily distinguishable from one another.

Table 3. Frequency of occurrence of different shapes of hailstones.

	Percent	Number of stones
Spheroids	56%	240
Ellipsoids	23%	96
Saucer	15%	66
Conical	3%	13
Star	3%	11
Total	100%	426

7. Embryo shape - Analysis of shape of embryo was made for 407 hailstones. The results are shown in Table 4. The "undetermined" shapes are the hailstones which had no distinguishable embryo. Table 4 shows that the majority of the hailstones embryos were shaped as spheroids or ellipsoids.

Table 4. Frequency of occurrence of embryo shape for 407 hailstones.

	Percent	Number of stones
Spheroids	68%	277
Ellipsoids	5%	19
Conical	5%	19
Undetermined	22%	92
Total	100	407

8. Type of embryo - The type of embryo (wet or dry) was analyzed from 326 hailstones. It was determined that the dry embryos appeared 54 percent of the time and the wet embryos 46 percent of the time.

9. Summary - From the foregoing calculations, the mean hailstone structure for the summer of 1962 can be summarized as follows:

Mean Hailstone Structure

Size (diameter)	=	1.83 cm
Shape	=	Spheroid or Ellipsoid
Density	=	.888
Ice crystal ratio	=	1 or less
Number of dry growth rings	=	1
Number of wet growth rings	=	1
Diameter of embryo	=	.08 cm
Shape of embryo	=	Spheroid or Ellipsoid

B. Hailstone parameter means and variability by months

The hailstone data were categorized by months. The mean and standard deviation of each parameter were computed by months, and comparisons were made between months. The results are shown in Table 5.

Table 5. Mean hailstone parameters ($\bar{x}$), standard deviations (s) and number of samples (N)

Parameter	May			June			July			Season		
	$\bar{x}$	s	N	$\bar{x}$	s	N	$\bar{x}$	s	N	$\bar{x}$	s	N
Density	.886	.015	145	.883	.014	107	.895	.012	358	.888	.014	257
Ice crystal ratio, r	38	24	145	4.8	8.8	107	4.6	30.6	358			
Stone dia., cm	1.4	.6	145	1.9	1.8	107	2.2	1.7	358	1.83	1.63	257
Embryo dia. (dry) cm	.06	.03	75	.06	.05	67	.08	.05	310			
Embryo dia. (wet) cm	.08	.03	75	.10	.05	67	.08	.05	310			

1. Density - From Table 5 it may be seen that the hailstones analyzed for the month of June had the lowest density and those analyzed for the month of July had the highest density. The difference between May and June (0. 003) is not considered significant, since it is of the same order as the accuracy of measurement.

2. Ice crystal ratio - If the density measurements are correct, one would expect that the ice crystal ratio of the hailstones for May and June would be larger than the ice crystal ratio of hailstones in July. The greater the amount of small ice crystals in a hailstone the less dense the hailstone becomes because the small ice crystals are surrounded by many more air bubbles than are the large ice crystals. From Table 5 it may be seen that May and June do have larger ice crystal ratios than July, which indicates that the hailstones in May and June had proportionally more small ice crystals than in July.

3. Size - Table 5 shows that the mean hailstone diameter was smallest in May (1. 4 cm) and largest in July (2. 2 cm). These data are consistent with the idea of thunderstorms in late June and early July having higher cloud tops and being more vigorous than the thunderstorms in May and early June. It seems reasonable to believe that the thunderstorms with high cloud tops and large vertical velocities produce the larger hailstones, since the hailstone will have farther to travel in the cloud, and must also obtain a greater mass to overcome the strong vertical current before falling to the ground.

Hailstone diameters were divided into three different size categories for May, June and July. The frequency of occurrence was then determined for each category for each month. (See Table 1.) From Table 1 it may be seen that May had the greatest frequency of small hail, and the lowest frequency for large hail. June had less small hail than May, and more large hail than May, and more large hail than May. July had the least amount of small hail and the greatest amount of large hail. These data also lends support to the idea that late June and early July are the months with the most vigorous thunderstorms.

4. Embryo diameter - From Table 5 it may be seen that the diameter of the wet and dry embryos are uniformly distributed for the three months.

C. Hailstone parameter means and variability by geographic areas

The hail network in northeastern Colorado was divided into four quadrants with the east, west and the north-south lines crossing at Sterling, Colorado.

(See Figure 4) The mean value and standard deviation of each hailstone parameter were then calculated for each quadrant. The results are given in Table 6.

Table 6. Mean hailstone parameters ($\bar{x}$), standard deviations (s), and number of samples (N) by quadrants from Sterling, Colorado

Parameter	Quadrant I (NE)			Quadrant II (NW)			Quadrant III (SW)			Quadrant IV (SE)		
	$\bar{x}$	s	N	$\bar{x}$	s	N	$\bar{x}$	s	N	$\bar{x}$	s	N
Dia., cm	2.6	1.6	135	1.8	1.4	230	1.2	1.6	140	2.3	2.0	165
Density	.893	.013	135	.891	.014	230	.889	.014	140	.892	.007	165
Wet embryo dia. cm	.03		110	.03		150	.04		100	.03		100
Dry embryo dia. cm	.03		110	.04		150	.04		100	.04		100

From Table 6 it may be seen that the eastern quadrants have the larger hailstones. This difference could be attributed to the fact that the thunderstorms form in the lee of the Rocky Mountains and move east. The maximum cloud tops are not attained until the thunderstorms are 50 to 60 miles east of the Rocky Mountains. This would put the thunderstorms just east of Sterling, Colorado at the time maximum cloud tops are attained, hence, the larger hailstones should fall in eastern Colorado.

The densities of hailstones vary little between quadrants.

There is no significant difference in the diameters of the embryos for the four different quadrants.

V. SIMPLE CORRELATIONS

A. Total analyzed hailstones

Using the 1620 IBM computer and the Esso Stepwise Multiple Linear Regression Analysis Program, simple correlations between hailstone size (diameter), density, ice crystal ratio, number of dry growth rings, number of wet growth rings, and diameter of embryo were made.* These correlations were first made for all hailstones analyzed. The results are given in Table 7.

Table 7. Simple correlation coefficients for all (257) hailstones.

	Diameter	Ratio	No. of wet growth rings	No. of dry growth rings	Diameter of embryo	Density
Diameter	1.00	0.02627-	0.14543*	0.25134**	0.05585-	0.04000
Ratio		1.00	0.12281-*	0.04515-	0.05239-	0.16427-**
No. of wet growth rings			1.00	0.28380**	0.09500-	0.07301
No. of dry growth rings				1.00	0.17875-**	0.01121
Diameter of embryo					1.00	0.07974-
Density						1.00

* indicates significance at the 5 percent level
**indicates significance at the 1 percent level

Looking at Table 7, we see that only two parameters (number of wet growth rings and the number of dry growth rings) have a significant correlation with hailstone diameter. There is significant negative correlation between ice crystal ratio rings and density. This result indicates that as the ice crystal ratio increases, the density of a hailstone decreases. This result is reasonable, since a large ice crystal ratio should mean that there are more small ice crystals than large ice crystals, and therefore, a lower density.

There is a significant positive correlation between the number of wet growth rings and the number of dry growth rings.

There is a significant negative correlation between the number of dry growth rings and the diameter of the embryo.

B. Hailstone parameter correlations by months

Correlations of each hailstone parameter with other parameters were made for each month separately. The number of observations for each month was as follows: May = 27, June = 50, July = 180. The results are given in Tables 8, 9 and 10.

Table 8. Simple correlation coefficients for May (27) hailstones.

	Diameter	Ratio	No. of wet growth rings	No. of dry growth rings	Diameter of embryo	Density
Diameter	1.00	0.43275*	0.20018	0.11517	0.17529	0.18642-
Ratio		1.00	0.21713-	0.07742	0.2273-	0.27348
No. of wet growth rings			1.00	0.34069*	0.31769-	0.29209
No. of dry growth rings				1.00	0.37300-	0.04677
Diameter of embryo					1.00	0.21989
Density						1.00

*indicates significance at the 5 percent level

Table 9. Simple correlation coefficients for June (50) hailstones.

	Diameter	Ratio	No. of wet growth rings	No. of dry growth rings	Diameter of embryo	Density
Diameter	1.00	0.17011	0.17705	0.34735*	0.03769	0.54907**
Ratio		1.00	0.20322-	0.21157	0.10346-	0.16104-
No. of wet growth rings			1.00	0.08115	0.16717-	0.09297-
No. of dry growth rings				1.00	0.45248-**	0.03266-
Diameter of embryo					1.00	0.30715-*
Density						1.00

* indicates significance at the 5 percent level
**indicates significance at the 1 percent level

Table 10. Simple correlation coefficients for July (180) hailstones.

	Diameter	Ratio	No. of wet growth rings	No. of dry growth rings	Diameter of embryo	Density
Diameter	1.00	0.06634-	0.17145*	0.20438**	0.10854-	0.24630**
Ratio		1.00	0.11306-	0.06806-	0.05628-	0.19626-**
No. of wet growth rings			1.00	0.36836**	0.05400-	0.05736
No. of dry growth rings				1.00	0.09343-	0.06774
Diameter of embryo					1.00	0.04137
Density						1.00

* indicates significance at the 5 percent level
**indicates significance at the 1 percent level

Looking at Tables 8, 9, and 10, it may be seen that eleven have significant correlations. These correlations are listed below:

May

Diameter vs ice crystal ratio

Number of wet growth rings vs number of dry growth rings

June

Diameter vs density

Diameter vs number of dry growth rings

Number of dry growth rings vs diameter of the embryo (negative)

Diameter of the embryo vs density (negative)

July

Diameter vs number of wet growth rings

Diameter vs number of dry growth rings

Diameter vs density

Ice crystal ratio vs density (negative)

Number of wet growth rings vs number of dry growth rings

C. Hailstone parameter correlations by geographic areas

The hailstone data were divided into four quadrants, depending on the area in which they fell. Correlations between each hailstone parameter was then made for each quadrant. The sample size for each quadrant was as follows: Quadrant I = 64, II = 69, III = 81, and IV = 34. The results are shown in Tables 11, 12, 13, and 14.

Table 11. Simple correlation coefficients for 64 hailstones in area I

	Diameter	Ratio	No. of wet growth rings	No. of dry growth rings	Diameter of embryo	Density
Diameter	1.00	0.13818	0.10160-	0.59547**	0.02964	0.57838-**
Ratio		1.00	0.38725-**	0.17775	0.04339-	0.25878-*
No. of wet growth rings			1.00	0.07936	0.32075-**	0.13363
No. of dry growth rings				1.00	0.33062-**	0.36154**
Diameter of embryo					1.00	0.22011-
Density						1.00

* indicates significance at the 5 percent level
**indicates significance at the 1 percent level

Table 12. Simple correlation coefficients for 69 hailstones in area II

	Diameter	Ratio	No. of wet growth rings	No. of dry growth rings	Diameter of embryo	Density
Diameter	1.00	0.06464	0.17322	0.03017	0.04265-	0.16965
Ratio		1.00	0.13890-	0.06679-	0.07253-	0.26487-*
No. of wet growth rings			1.00	0.23541*	0.12922-	0.15459
No. of dry growth rings				1.00	0.20748	0.31518**
Diameter of embryo					1.00	0.22341-
Density						1.00

* indicates significance at the 5 percent level
**indicates significance at the 1 percent level

Table 13. Simple correlation coefficients for 81 hailstones in area III

	Diameter	Ratio	No. of wet growth rings	No. of dry growth rings	Diameter of embryo	Density
Diameter	1.00	0.07568-	0.26636	0.11276	0.15108	0.29590**
Ratio		1.00	0.09708	0.06310-	0.06570-	0.18772-
No. of wet growth rings			1.00	0.32123**	0.00522	0.10121
No. of dry growth rings				1.00	0.15297	0.04912
Diameter of embryo					1.00	0.01416-
Density						1.00

* indicates significance at the 5 percent level
**indicates significance at the 1 percent level

Table 14. Simple correlation coefficients for 34 hailstones in area IV

	Diameter	Ratio	No. of wet growth rings	No. of dry growth rings	Diameter of embryo	Density
Diameter	1.00	0.10465-	0.22589	0.46395**	0.10409	0.20040
Ratio		1.00	0.30942-	0.28793-	0.16421	0.07641
No. of wet growth rings			1.00	0.50724**	0.09582	0.00267
No. of dry growth rings				1.00	0.02053-	0.01547-
Diameter of embryo					1.00	0.09769
Density						1.00

* indicates significance at the 5 percent level
**indicates significance at the 1 percent level

From Tables 11, 12, 13 and 14, it may be seen that the significant correlations were as follows:

Quadrant I

Diameter vs number of dry growth rings

Diameter vs density (negative)

Ratio vs number of wet growth rings (negative)

Wet growth rings vs diameter of embryo

Dry growth rings vs density

Dry growth rings vs diameter of embryo (negative)

Quadrant II

Ratio vs density (negative)

Number of wet growth rings vs number of dry growth rings

Number of dry growth rings vs density.

Quadrant III

Diameter vs density

Number of wet growth rings vs number of dry growth rings.

Quadrant IV

Diameter vs number of dry growth rings.

Number of wet growth rings vs number of dry growth rings.

VI. PREDICTION OF DENSITY FROM OTHER HAILSTONE PARAMETERS

A. Prediction equations by months

Using the Esso Stepwise Regression Program on the 1620 Computer, the hailstone density was computed as a function of the other hailstone parameters.

Using the density as the dependent variable, and the other five variables as independent variables, their program computes the variables, single or as a group, would be the best for predicting the density of a hailstone. This was done by computing the standard error of Y for each group of independent variables, and choosing the single or group of variables with the lowest standard error of Y .

$$Y = K + C_1 X_1 + C_2 X_3 + C_3 X_4 + C_5 X_5$$

where

Y = Density

X_1 = Hailstone diameter

X_2 = Ice crystal ratio

X_3 = Number of dry growth rings

X_4 = Number of wet growth rings

X_5 = Diameter of embryo.

The results of these computations are as follows:

May

$$Y = .889 - .007 X_1 + .001 X_4$$

June

$$Y = .905 - .004 X_1 + .008 X_5$$

July

$$Y = .89 + .002 X_1$$

B. Prediction equations by quadrants

Using the same procedure as described above for months, prediction equations for density were computed for each geographic area (See Figure 4). The results were as follows:

Quadrant I

$$Y = .913 - .004 X_1 - 0002 X_2 - .0004 X_3 - .0008 X_5$$

Quadrant II

$$Y = .889 + .003 X_1 - .00005 X_2$$

Quadrant III

$$Y = .889 + .0025 X_1 - .00005 X_2$$

Quadrant IV

$$Y = .898 - .0007 X_1$$

VII. ANALYSIS OF VARIANCE

A. F Tests

An analysis of variance was performed to determine if these were significant differences tin hailstone diameter between months. The results indicated highly significant differences (at the 1 percent level).

A similar computation indicated highly significant differences in hailstone density between months.

An analysis of variance was performed to determine whether significant differences existed between geographic areas for hailstone parameters of diameter and density. The results indicated highly significant differences for both parameters.

B. Students "t" tests

Students "t" tests were then applied to determine which of the above factors were significantly different when considered on an individual basis.

The results of this test applied to the parameter of hailstone diameter indicated that the only significant difference was between May vs June and July.

The results of the test applied to the hailstone density also indicated a significant difference between May vs June and July.

The student "t" test was applied to hailstone diameter for the four geographic areas shown in Figure 4. The results indicate significant differences in hailstone diameter between area I vs II, area II vs IV, and area III vs IV.

A similar computation for hailstone density indicates significant differences in mean hailstone densities between area I vs III, and area I vs IV.

VIII. CORRELATION BETWEEN HAILSTONE PARAMETERS AND THUNDERSTORM PARAMETERS

Hailstone parameters of diameter and density were plotted against corresponding thunderstorm parameters of radar tops, Z_{max}, and "tilt of echo. The results are given in Figures 5-10.

From Figure 5 it may be noted that there are no large hailstone diameters (greater than 3.5 centimeters) having radar echo tops below 45,000 feet. This scatter diagram indicates that high cloud tops do not mean that only large hailstones will form, but that it is necessary to have high cloud tops to have large hailstones.

Simple correlation coefficients were computed between each of the parameters listed above. The results are shown in Table 15.

Table 15. Simple correlation coefficients between hailstone

	Radar Tops		Z_{max}		Tilt	
	r	d.f.	r	d.f.	r	d.f.
Diameter	.06	22	.41	16	.13	13
Density	.17	22	.21	16	.47	13

None of the correlations were significant at the 5 percent level.

IX. SUMMARY AND CONCLUSIONS

During the summer of 1962 hail samples were collected. Eight hailstone parameters were determined. The mean and variance of each hailstone parameter was determined by various groupings. The simple correlation coefficients between the hailstone parameters were determined. An analysis of variance using the test was applied to determine significant differences of hailstone parameters between months and geographic areas.

The average hailstone for the summer of 1962 had the following mean parameters:

Size (diameter)	=	1.83 centimeters
Shape hailstone	=	Spheroid or Ellipsoid
Density	=	.888
Ice crystal ratio	=	1
Number of dry growth rings	=	1

Number of wet growth rings	=	1
Diameter of embryo	=	. 08 centimeters
Shape of embryo	=	Spheroid or Ellipsoid

On a seasonal basis, May had the lowest mean hailstone diameter and July had the largest. June had the least dense hailstones and July had the most dense hailstones. The other hailstone parameters; ice crystal ratio, embryo diameter, and the number of wet and dry growth rings, did not vary much.

The fact that the mean hailstone diameter was larger in June and July can be attributed to the fact that thunderstorms in late June and early July have, on the average, higher cloud tops and are more vigorous than the thunderstorms in May or early June. This would mean that a hailstone would have further to travel in a cloud and would have to develop a greater mass to overcome the stronger vertical velocities.

On a geographic basis the hailstones east of Sterling, Colorado, have a larger mean hailstone diameter than the hailstones west of Sterling. This is probably due to the fact that the majority of the thunderstorms form in the lee of the Rocky Mountains and move east. The max cloud tops are not reached until they approach the Sterling area. These thunderstorms would then be producing their largest hailstones, which would be falling in eastern Colorado. The other hailstone parameters did not vary significantly.

The standard deviation of the total analyzed hailstones was large. On a seasonal basis May had the lowest standard deviation for hailstone diameters while June and July had large standard deviations. This would indicate that in May the hailstones were mostly small, while in June and July the hailstones consisted of both small and large diameters. For density, May had the largest standard deviation, and June and July the lowest.

The Esso Stepwise Multiple Linear Regression Analysis was applied to various groups of data to give equations of the following form for predicting hailstone density, the following formula:

$$\text{Density} = K + C_1 X_1 + C_2 X_2 + C_3 X_3 + C_4 X_4 + C_5 X_5$$

An analysis of variance using the F test and students' t tests showed that there were significant seasonal and geographical differences in hailstone diameter and density.

The simple correlation coefficients between the physical properties of a hailstone and the radar properties of a thunderstorm failed to yield any significant results. This was probably due to small sample sizes and the methods used for determining from which thunderstorm a certain hail sample fell.

X. REFERENCES

1. Eaton, Larry. Hailstone Structure Studies, 1960-1961. Unpublished report, Civil Engineering Section, Colorado State University, 1962.

2. Schleusener, R. A., and J. D. Marwitz. Characteristics of Hailstones on the High Plains as Deduced from 3 cm Radar Observations. Proc. Ninth Weather Radar Conference, 1962.

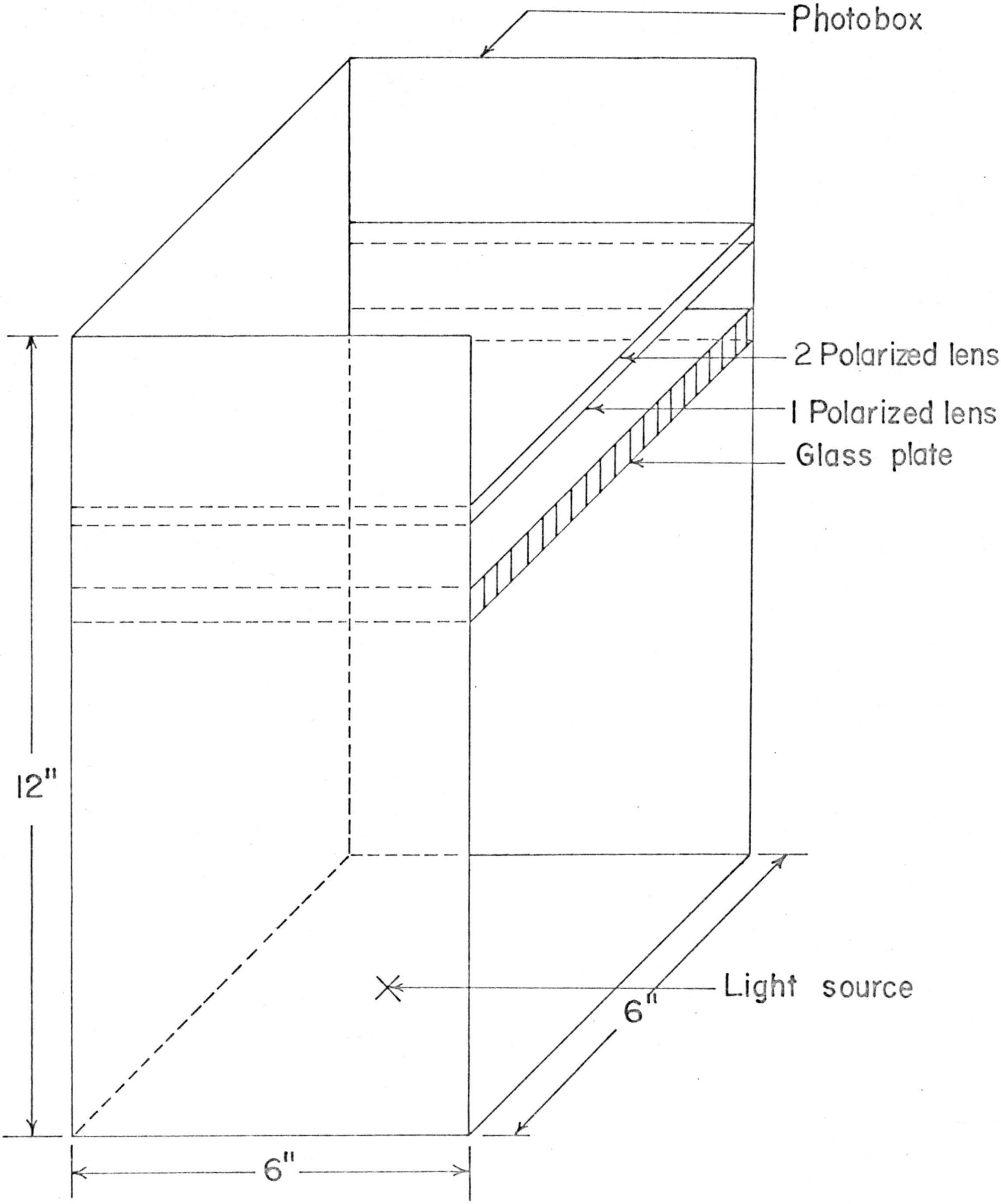

Fig. 1 Photobox

½ Scale

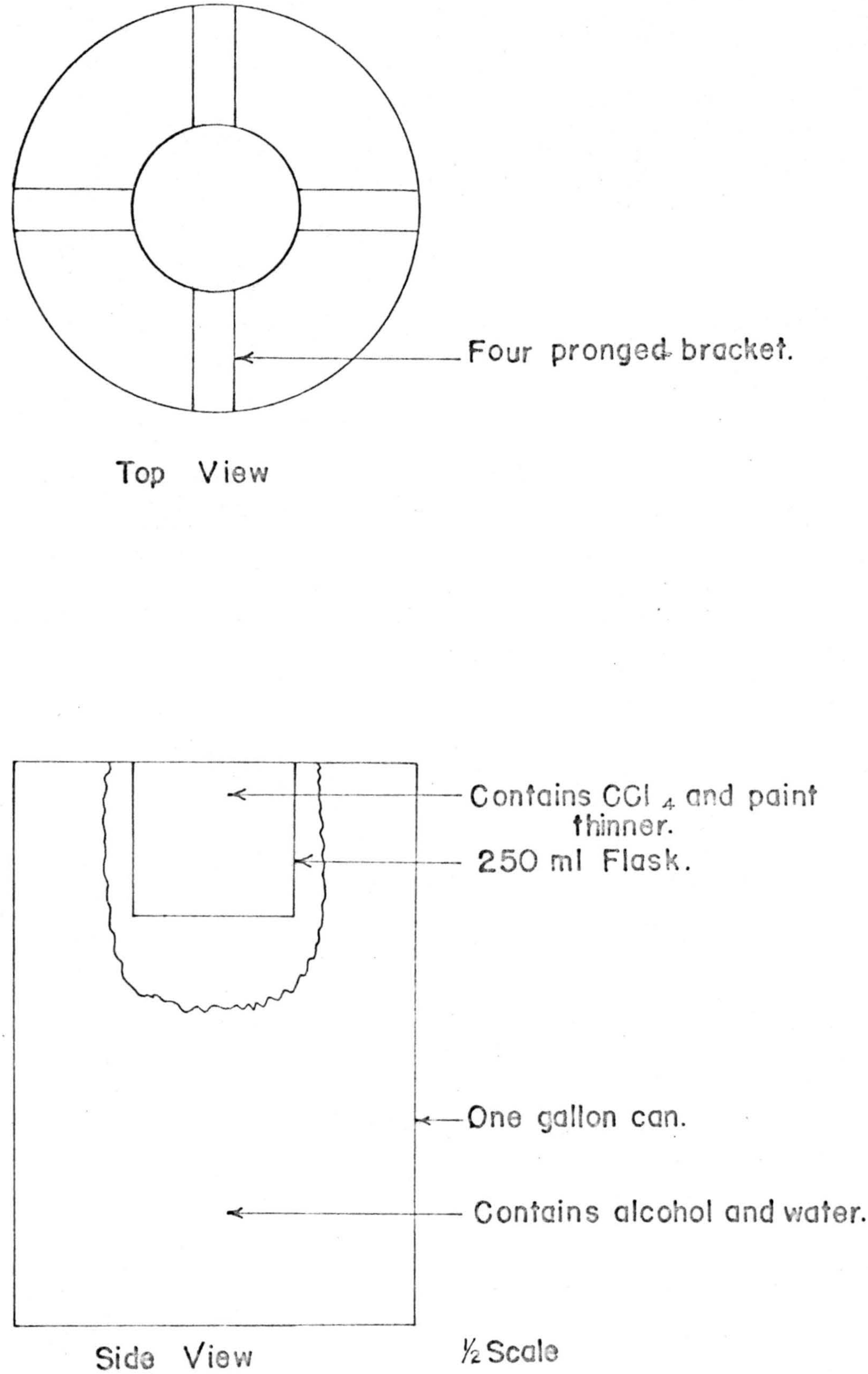

Fig.2 Density Kit

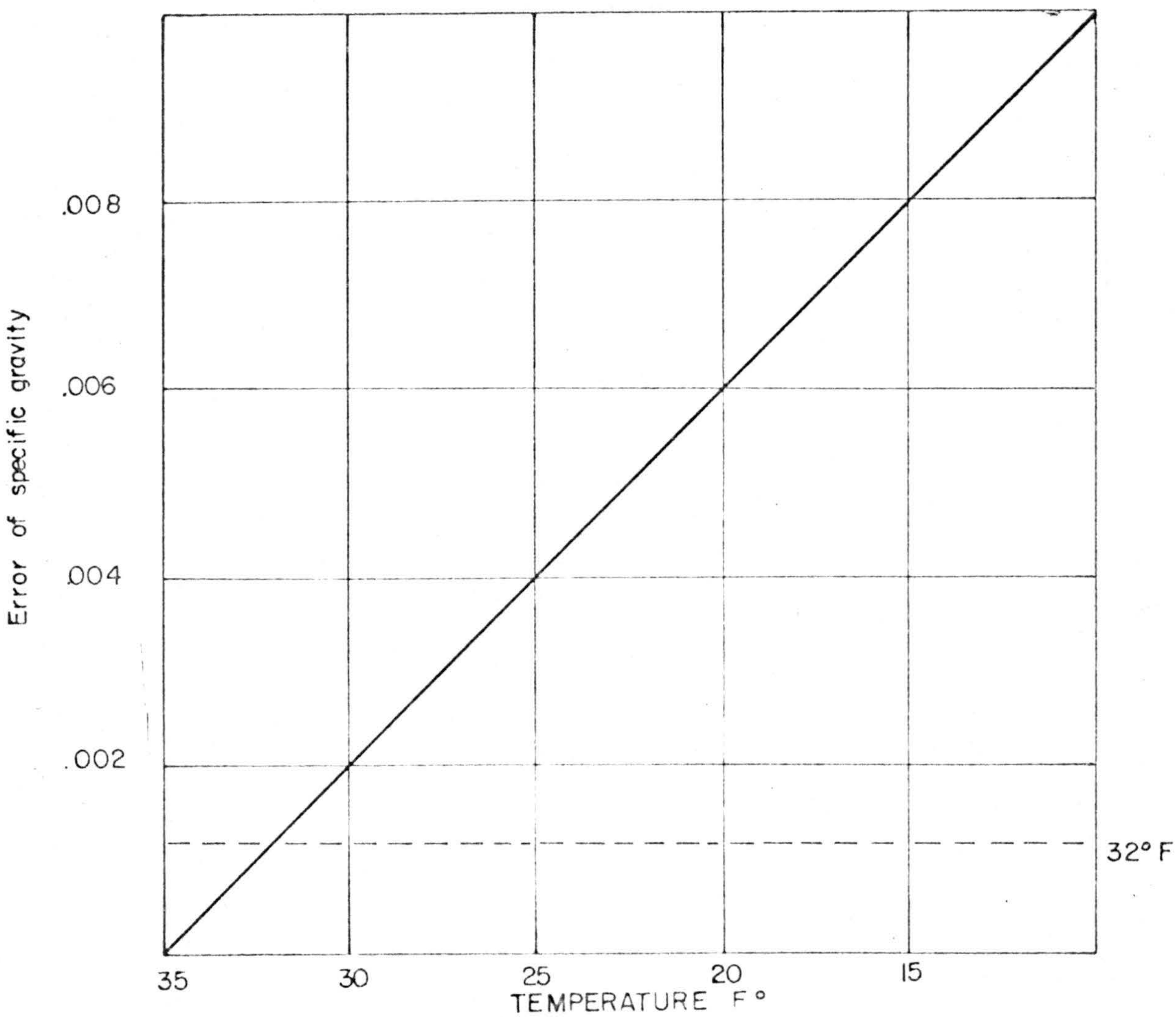

Fig.3 Solution of CCl_4 and paint thinner.

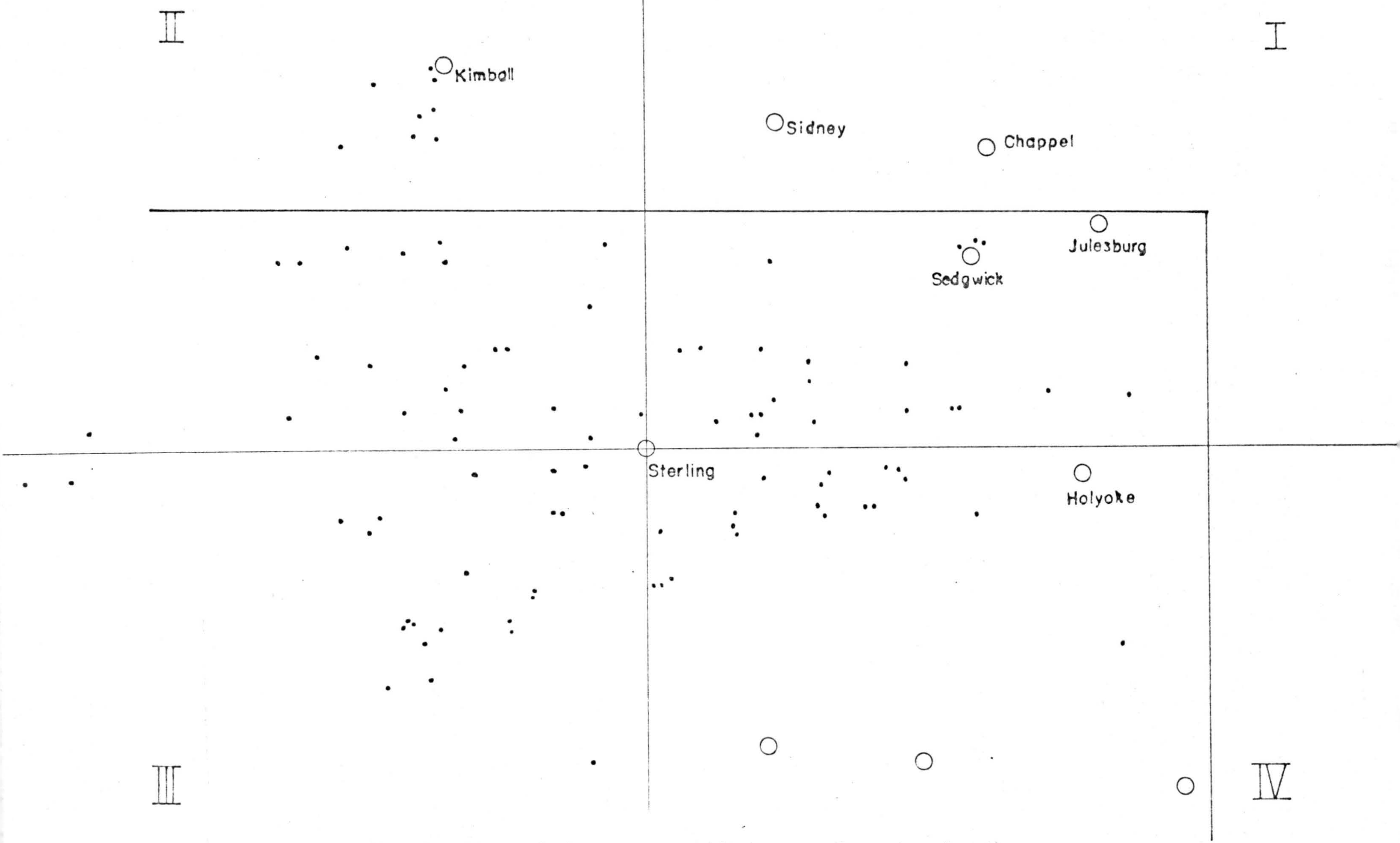

Fig. 4 Map of four geographic areas. Dots show locations from which samples were obtained.

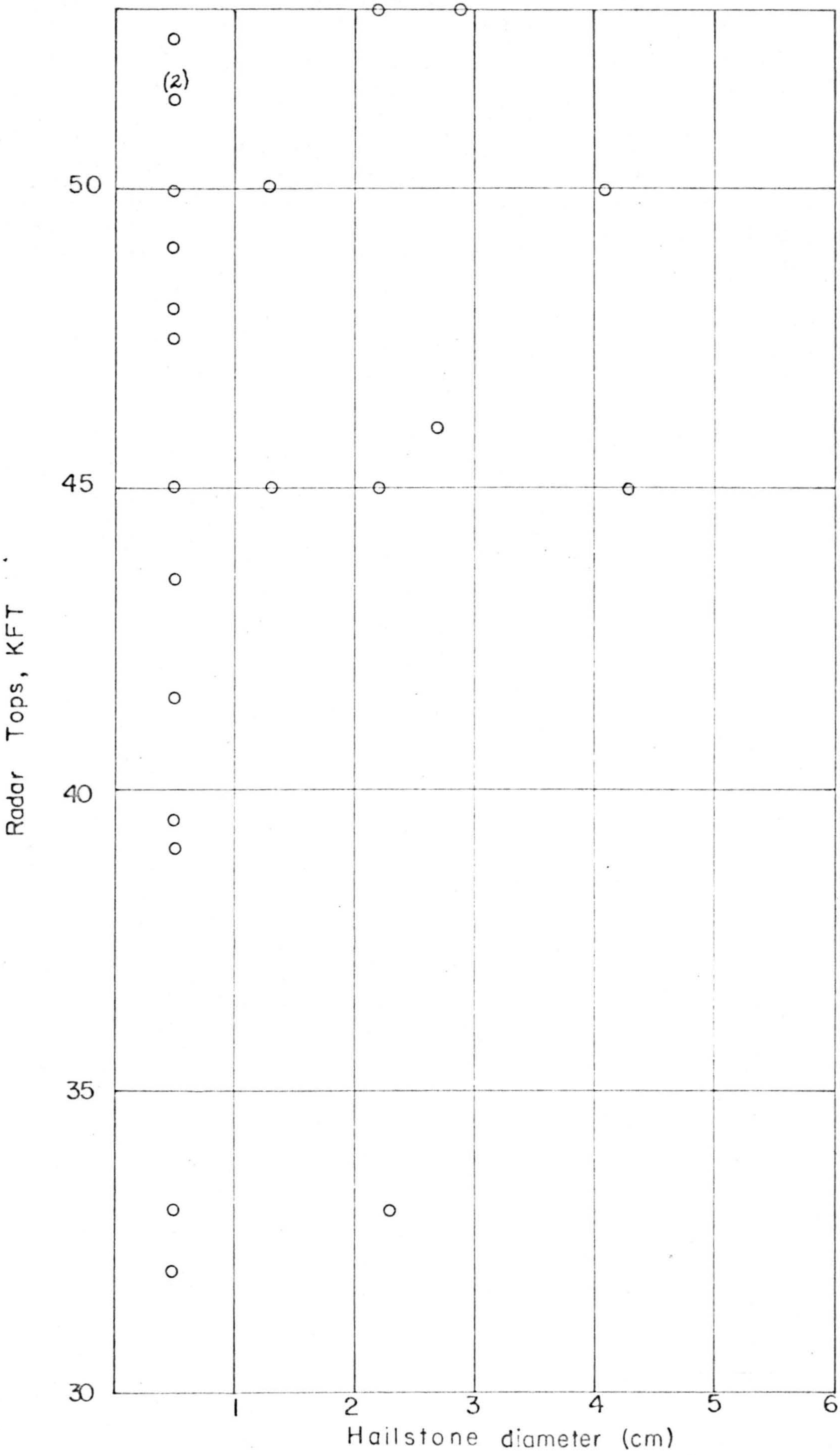

Fig 5 Scatter diagram of hailstone size vs. cloud tops.

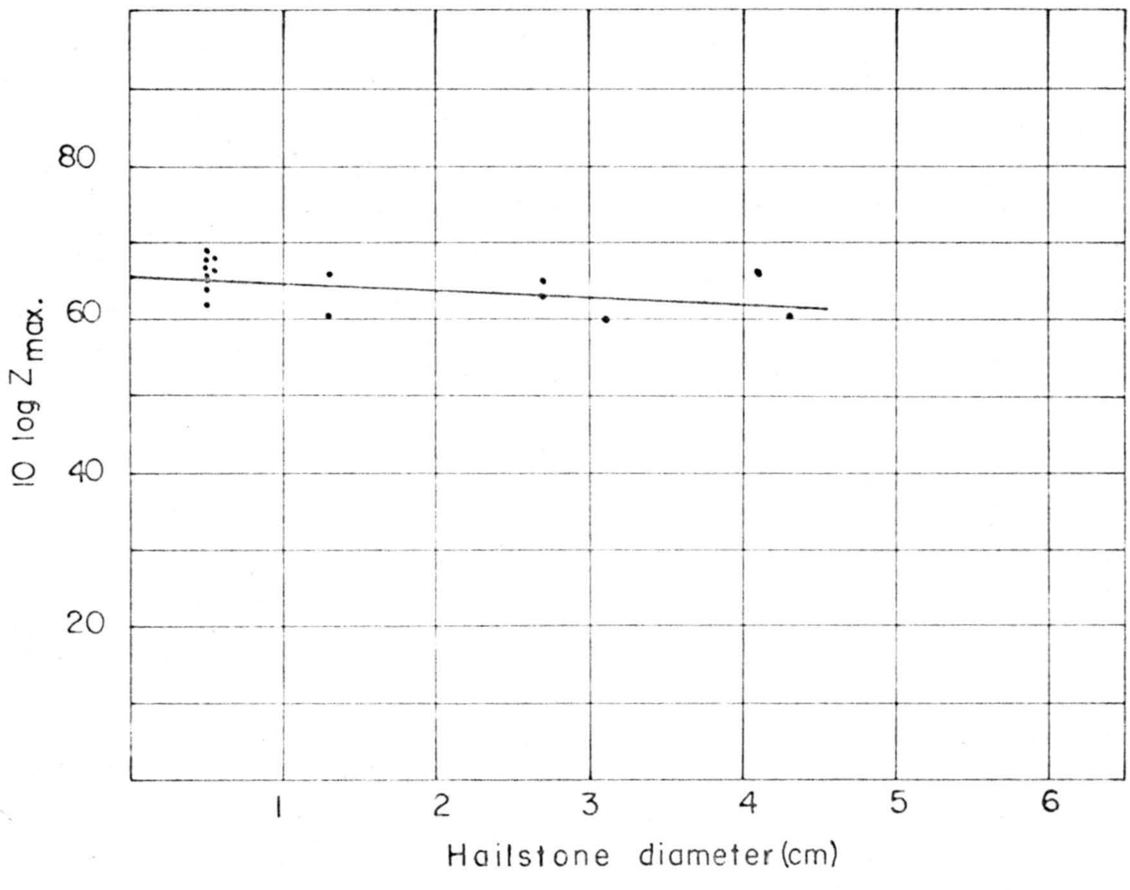

Fig. 6 Scatter diagram of hailstone diameter vs. $Z_{max.}$

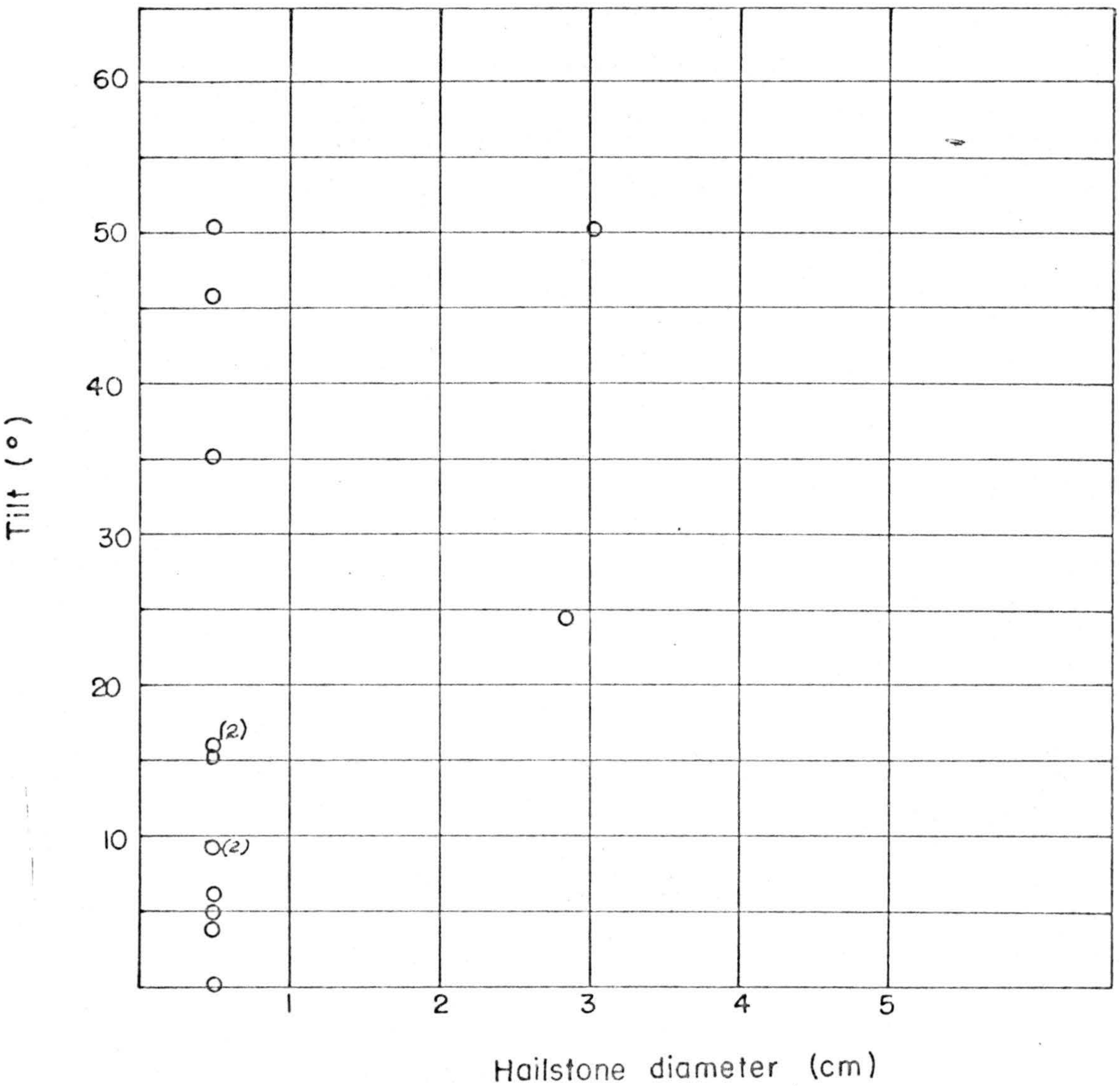

Fig. 7 Scatter diagram of hailstone diameter vs. tilt.

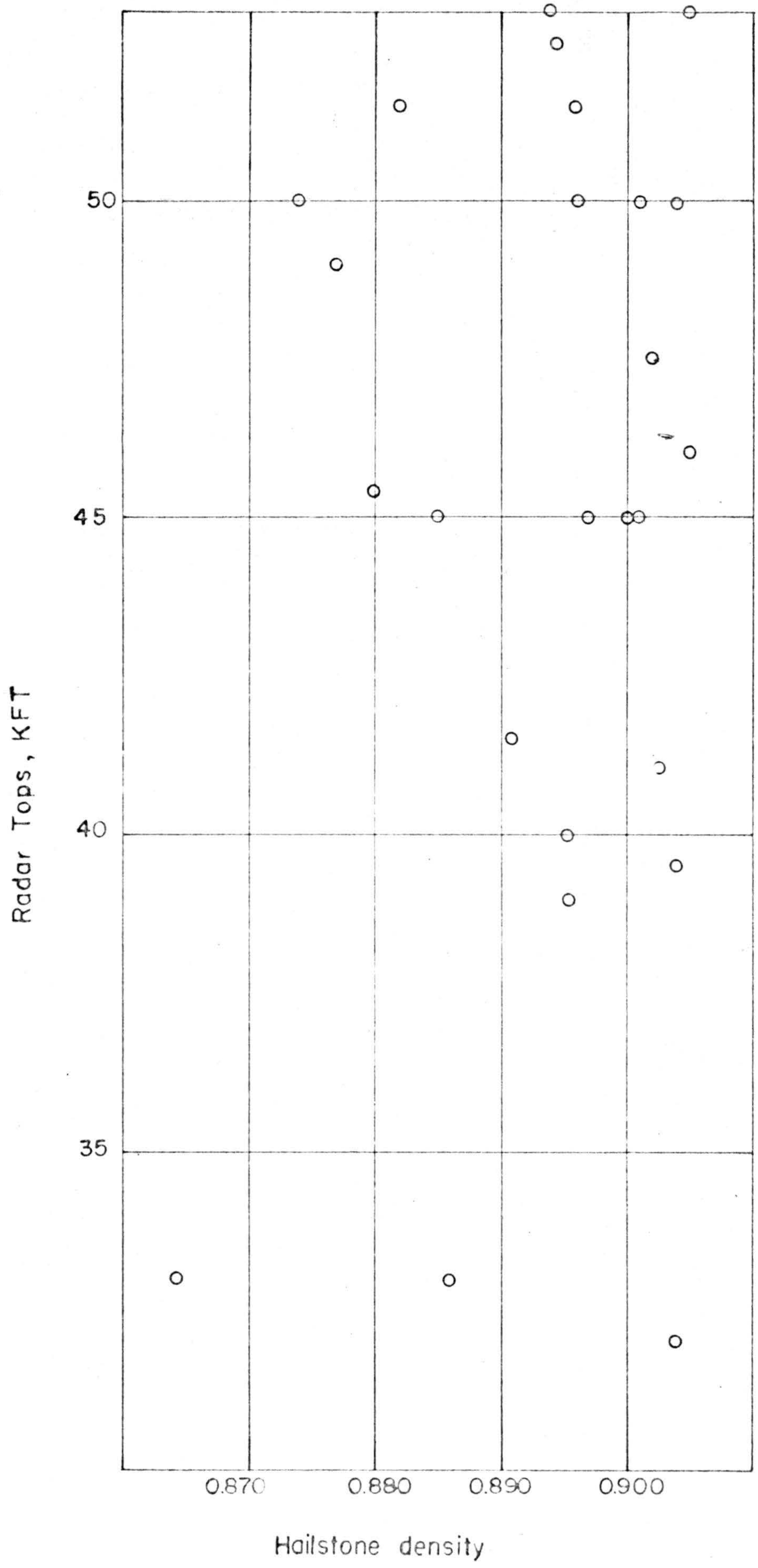

Fig. 8 Scatter diagram of hailstone density vs. cloud tops.

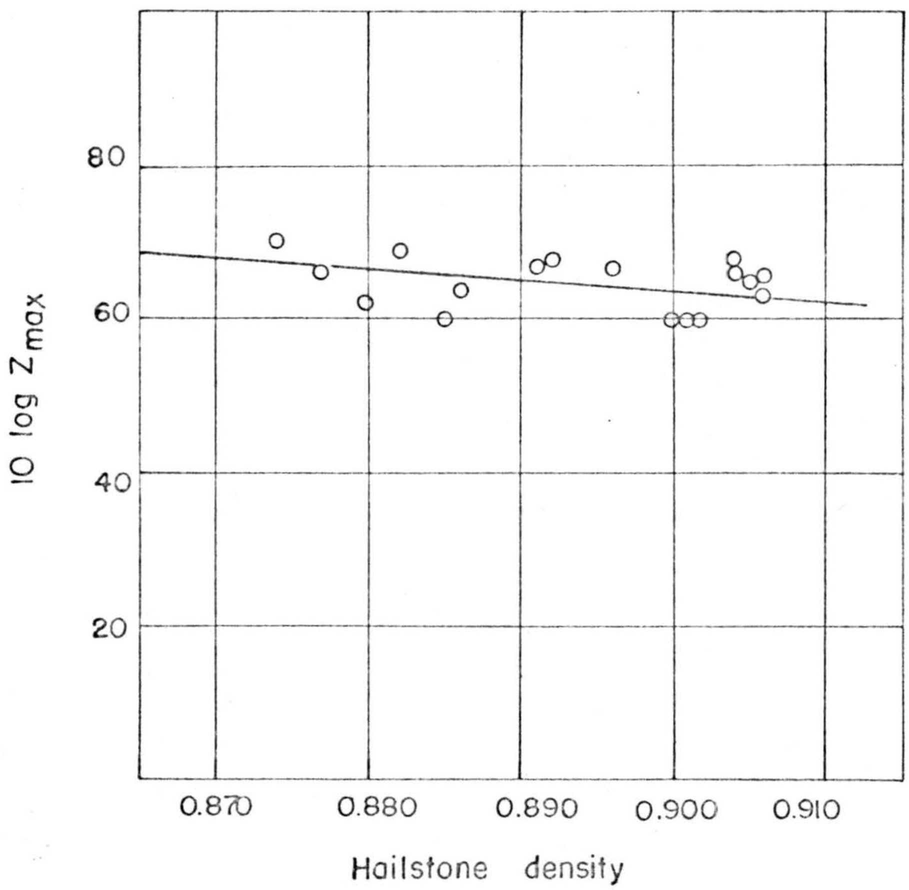

Fig. 9 Scatter diagram of hailstone density vs. Z_{max},

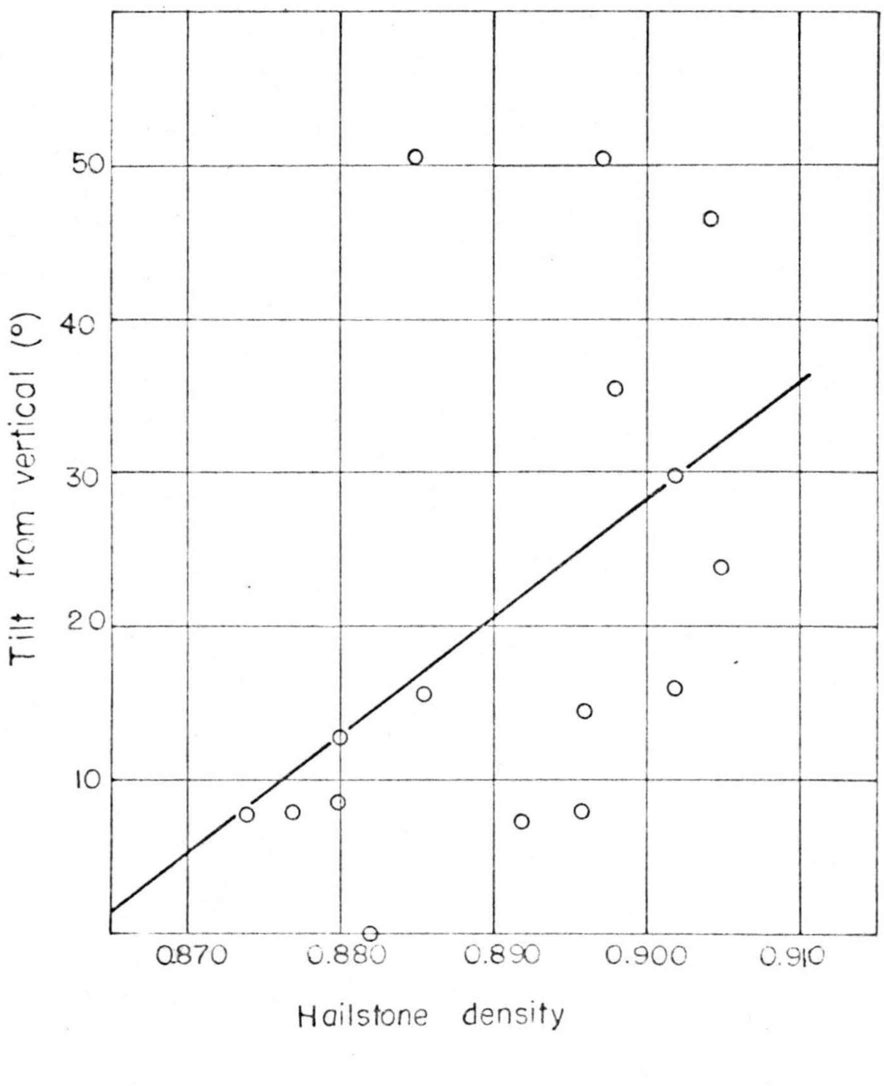

Fig 10 Scatter diagram of hailstone density vs. tilt.