Comments on "Air Bubbles in Artificial Hailstones"

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In a series of publications on air bubble size distributions, List and co-workers have come to feel very optimistic that the bubble size distributions can be of great value in interpreting hailstone growth histories. Murray and List (1972) found log-normal size distributions of air bubbles in water drops frozen in a wind tunnel; List *et al.* (1972) found log-normal size distributions of air bubbles in some natural hail growth shells; and List and Agnew (1973) found the same in artificially grown hailstones, virtually all formed in spongy growth, and related the details of the distributions to cloud temperature and liquid water content (LWC). These works hardly mention the mechanisms of air bubble formation and do not attempt to explain the cause of the log-normality of the size distributions. Nevertheless, at first sight the results do seem optimistic.

Further thought and some crude experiments have led us not to share in the optimism for this diagnostic tool. In both of the experimental works (Murray and List, 1972; List and Agnew, 1973), with the possible exception of a few runs in the latter, all or nearly all of the air bubbles form while a spongy, ice-water mixture is freezing solid. The air bubble features are therefore expected to be controlled primarily by this rate of final freezing, and only secondarily by the mode of formation of the sponge. While this point is explicit in Knight and Knight (1968), it appears to have been ignored.

In the experiments of List and Agnew, the final freezing was accomplished by simply turning off the water supply in the wind tunnel and allowing the spongy, artificial hailstones to freeze solid, with the same external temperature as that at which they grew (List, personal communication). It is not surprising that the air bubble features depend upon this temperature in a consistent way, because the final freezing rate also depends upon this temperature in a consistent way. The lower the temperature, the faster the final freezing, and the smaller the air bubbles: this is what their data show. Neither is it surprising that the air bubble distributions depend upon the LWC of the cloud. The higher the LWC during growth,

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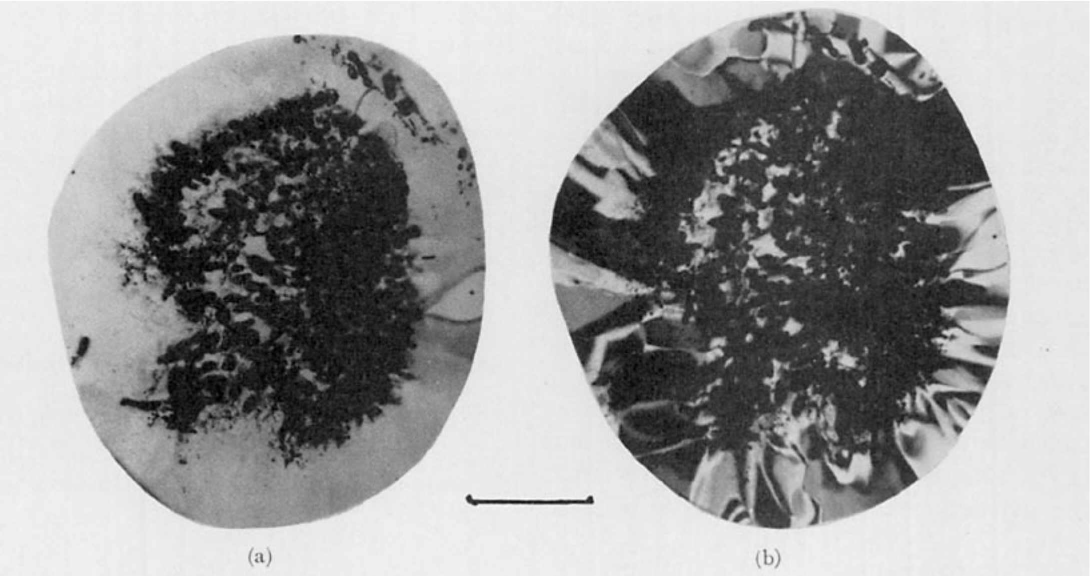

FIG. 1. Section of a water drop frozen in the vertical wind tunnel in plain, transmitted light (a) and between crossed polaroids (b). This drop was supercooled to -11C in a vertical wind of about 6 m sec^{-1}; nucleated by holding a small piece of dry ice (solid CO_2) beneath it for a moment; and left to freeze solid, which took ~1.3 min. The scale mark is 1 mm.

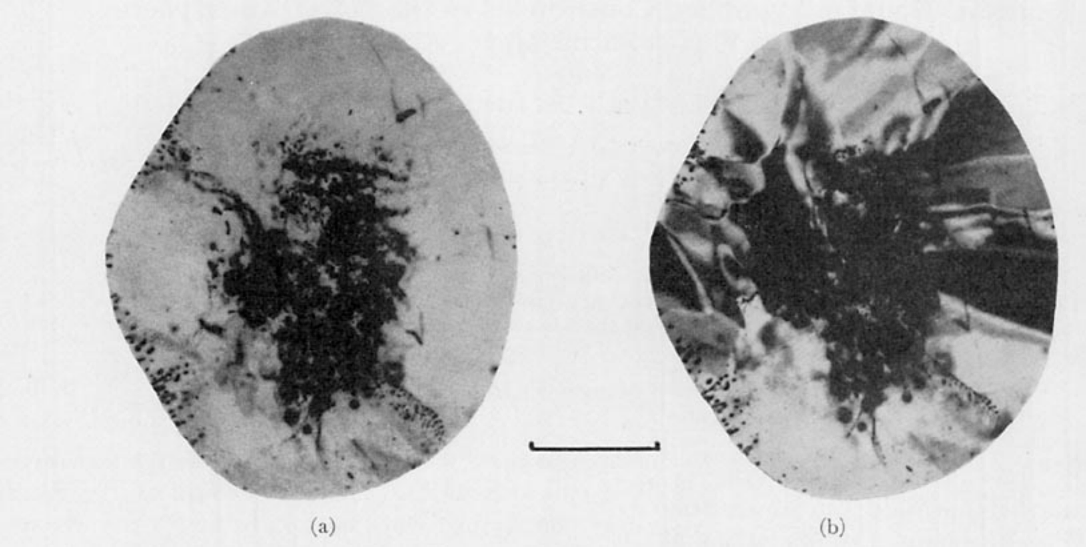

FIG. 2. Section of another water drop treated identically to that in Fig. 1, except that after nucleation the drop was moved to another part of the air stream, where the velocity was lower, and the time that it took to freeze solid was ~4 min. The slower freezing subsequent to nucleation consistently produces a thicker shell of clear ice, with more chaotic (some bigger and some smaller) air bubbles in the center. While the differences in air bubble structure are quite reproducible, the difference in crystal size shown here is not very reproducible, and may not be significant.

the more liquid water will be in the sponge, and the slower the final freezing will be because there is more liquid to freeze. (Note that it is the linear freezing rate, not the volume rate, that is important in air bubble formation.) Obviously, the dimensions of the ice framework will also have some effect on air bubble formation in the sponge during final freezing.

According to this reasoning the air bubble distribuinto is likely to reflect more the conditions *after* than *during* the formation of a spongy hailstone growth layer. In our experience, this relevant history after formation is often after collection of the hailstones at the ground, but in either case this is not a very valuable sort of thing to be able to deduce.

The experiment that List and Agnew need to perform is to grow a series of spongy, artificial hailstones at constant temperature and LWC, and freeze them solid at different rates, to separate the effects of growth conditions from those of final freezing conditions and really decide what is important. Natural hailstones are never expected to have experienced the history that List and Agnew's experiments simulate: growth in a cloud and then final freezing at about the same altitude but out of the cloud.

While we are not equipped to do this experiment, we have done a similar, but simpler one in the NCAR wind tunnel—nucleating large, supercooled water drops to form the spongy ice and then freezing them at different rates afterward. The experimental set-up was much like that in Murray and List, except that the wind velocity was changed immediately subsequent to nucleation to alter the final freezing rate. The effect on air bubble sizes and patterns of differences in the final freezing rate is clearly large (Figs. 1 and 2). This result, with the argument given above, leads us to be pessimistic about this approach to hailstone structure interpretation.

This pessimism is heightened because hail structure interpretations are not susceptible at present to good verification. Interpretations must be very well founded in basic understanding before they can be trusted enough to be useful.

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