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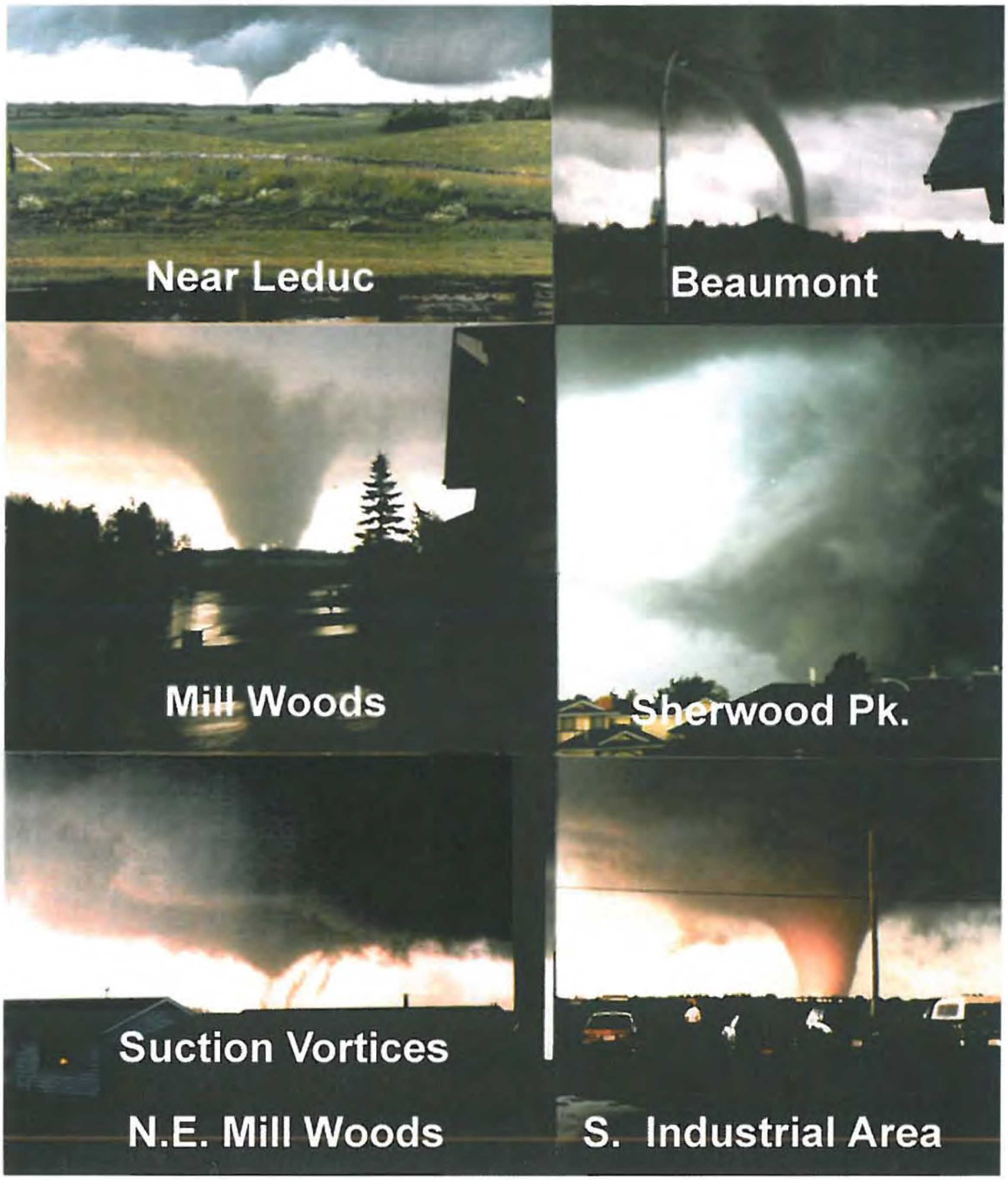
THE EDMONTON TORNADO AND HAILSTORM: A DECADE OF RESEARCH



Photos By Charlton


Aug 2 Charlton


Aug 1 Lee Mason Tools


Nault Lumber


At Sterling Crane


Debarked Trees

THE EDMONTON TORNADO AND HAILSTORM: A DECADE OF RESEARCH

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PREFACE

If you wish to discover what was done to document western Canada's severe storm of the century, this account is for you.

In the decade since the Edmonton tornado, notorious hailstorms have, on occasion, sidetracked the life of most every Albertan. A section on recent investigations into shingle damage by hail is included to inform homeowners of the ongoing problem.

Nevertheless, it is hoped that this report will help us look back to the fateful day when Edmonton was struck by the unimaginable.

PRÉFACE

Si vous désirez découvrir les efforts qui ont été déployés afin de documenter la tempête du siècle de l'ouest du Canada, vous serez plus qu'intéressés par le compte rendu présenté ici.

Durant la dizaine d'années qui a suivi la Tornade d'Edmonton, pratiquement chaque Albertain fut affecté de près ou de loin par une tempête de grêle. Une section relatant les recherches sur les dommages aux bardeaux de toiture causés par la grêle est incluse ici afin d'informer les propriétaires de maison du problème en question.

Nous espérons toutefois que ce rapport nous permettra de réexaminer ce jour mémorable où la ville d'Edmonton fut frappée par l'inimaginable.

August/août 1998

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[1] The current affiliation of the authors to the Department is informal.
Les auteurs ne sont présentement affiliés que de façon informelle au département.

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"at the service of its members
au service de ses membres"

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Cover page: The illustration shown on the cover page is a composite photograph of different tornadoes hitting various locations in Alberta. The photographs shown on the inside cover page illustrate the damage done by some of those tornadoes. You can also see the main author of this special issue examining the debris caused by the severe storms. There are many other interesting colour photographs in this special publication.

Acknowledgement

CMOS is grateful to Environment Canada, Prairie and Northern Region to allow the publication of the exceptional document on tornadoes and hailstorms.

Canadian Meteorological and Oceanographic Society (CMOS)

Aim of the Society

The Canadian Meteorological and Oceanographic Society (CMOS) was formed in 1967 as the Canadian Meteorological Society and was joined in 1977 by the oceanographers. It is a national society of individuals and organizations dedicated to advancing all aspects of atmospheric sciences, oceanography and related environmental disciplines in Canada.

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ABSTRACT

Western Canada's "severe-summer-storm of the century" is described at length. The maps are based primarily on information from a newspaper survey published one week after the Edmonton tornado. All materials are presented from the point of view of meteorologists.

The tornado ravaged areas along the eastern boundary of the city for approximately one hour. It hit the industrial area hardest and was accompanied by extremely heavy rainfall, funnel clouds and two spin-off tornadoes. A swath of giant hailstones, unprecedented for a city in Canada, fell on residential areas. These occurrences, and a windy evening storm, collectively damaged nearly every part of Edmonton on July 31, 1987. For comparison, the research about the Ontario tornadoes of May 31, 1985 is reviewed.

Eleven maps, three tables, and a selection of previously unpublished photographs are included. Some of the damaged industrial sites are described in detail using reports from officials and eye witnesses. Responses to the newspaper survey are used to estimate the additional warning time gained by those citizens who were listening to a radio or watching television.

Approximately 30,000 insurance claims for shingle damage by hail were filed. The hail characteristics reported from various communities are compared with the records of two shingling firms. Laboratory research into hail damage to shingles is examined. The hail swath is compared with that of the 1991 hailstorm in Calgary where the largest insurance loss for a Canadian natural disaster was recorded. However, the Edmonton hailstorm was more severe by most measures.

Many obscure scientific studies and materials related to the Edmonton tornado have been referenced. This study ends with a comparison of the severe thunderstorm risk in Edmonton and Calgary.

RÉSUMÉ

On décrit ici en détail la "Tempête estivale du siècle" de l'ouest canadien. Les cartes présentées sont basées principalement sur des informations obtenues à partir des résultats d'un sondage journalistique publié une semaine après la Tornade d'Edmonton. Le contenu est présenté entièrement selon le point de vue des météorologistes.

Durant environ une heure, la tornade causa ravages et destruction tout le long de la frontière est de la ville. La zone industrielle fut particulièrement affectée. La tornade fut aussi accompagnée de pluies torrentielles et de nuages en entonnoir, et causa la formation de deux autres petites tornades. Des grêlons gigantesques — du jamais vu pour une ville canadienne — tombèrent sur un large corridor de zones résidentielles. Ces événements, combinés avec une autre tempête de vent le même soir du 31 juillet 1987, causèrent collectivement des dommages sur la presque totalité de la ville d'Edmonton. Pour fins de comparaison, nous présentons en revue une recherche sur les tornades du 31 mai 1985 en Ontario.

Onze cartes, trois tableaux, et une sélection de photographies inédites sont inclus. Quelques uns des sites industriels endommagés sont décrits en détail à l'aide de rapports d'experts et de témoins oculaires. Les réponses au sondage sont utilisées pour estimer le temps de réponse additionel dont ont bénéficié les citoyens qui écoutaient la radio ou regardaient la télévision.

Environ trente mille réclamations pour dommages aux bardeaux de toiture furent reçues. Les caractéristiques de la grêle telles que rapportées par différentes communautés sont comparées avec les documents de deux compagnies de bardeaux. Nous examinons également les recherches en laboratoire concernant les dommages aux bardeaux causés par la grêle. Le corridor de grêle est comparé à celui de la tempête de grêle de 1991 à Calgary, où on enregistra les plus grandes pertes d'assurance jamais encourues lors d'un désastre naturel canadien. La tempête de grêle d'Edmonton fut néanmoins plus sévère à presque tous les égards.

Plusieurs études scientifiques et autres documents reliés à la tornade d'Edmonton — la plupart plus ou moins connus — sont mentionnés en référence. L'étude se termine avec une comparaison des différents risques d'orage sévère à Edmonton et Calgary.

Page couverture: L'illustration de la page couverture est une composition photographique de plusieurs tornades frappant différentes régions de l'Alberta. Les photographies que l'on peut appercevoir à l'intérieur de la page couverture illustrent les dommages causés par ces tornades. On peut aussi voir l'auteur principal exminant les débris matériels causés par ces fortes tempêtes. Il y a plusieurs autres photographies en couleurs toutes aussi saisissantes dans cette publication spéciale.

Remerciement

La SCMO remercie Environnement Canada, Région des Prairies et du Nord, pour avoir autorisé la publication de ce document exceptionnel sur les tornades et les tempêtes de grêle.

Société canadienne de météorologie et d'océanographie (SCMO)

But de la Société

La Société canadienne de météorologie et d'océanographie (SCMO) a été formée en 1967 comme la Société canadienne de météorologie à laquelle se joignirent en 1977 les océanographes. C'est une organisation nationale regroupant des individus et des organismes voués à la promotion de la météorologie et de l'océanographie ainsi que des disciplines environnementales connexes sous tous leurs aspects au Canada.

Adresses électroniques de la SCMO

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August / Août 1998

1. URBAN TORNADOES IN CANADA

The public has not forgotten the devastating tornado of Friday, July 31, 1987 which struck Edmonton, Alberta (1987 population 584000, 53° 34'N, 113° 31'W, elevation 680 m). It killed 27 people, hospitalized 53 more, and caused injuries requiring treatment at 6 hospitals to approximately 250 others. Fatalities were confined to the industrial area (12) of east Edmonton and Strathcona County and to the Evergreen Mobile Home Park (15), where 133 homes were destroyed, in rural northeast Edmonton.

At 1455 Mountain Daylight Time (MDT), the Alberta Weather Centre (ALWC) received its first report about the tornado from a viewer 10 km south of the city. The ALWC transmitted a Tornado Warning at 1504 MDT, approximately 25 minutes before the first fatality occurred. Because of communication problems, many radio stations received their first reports about the tornado from their listeners (Hage, 1987a).

a. An outbreak of tornadoes in Ontario, in retrospect

On Friday, May 31, 1985, 2 tornadoes killed 12 people in southern Ontario: 8 in Barrie, 2 in Grand Valley, and 2 in Tottenham (Newark, 1985). These were 2 of 7 tornadoes to traverse southern Ontario that day (Lawrynuik et al., 1985; Leduc et al., 1986), and all occurred where power and telephone service had, in general, been lost. The 7 tornadoes touched down 13 times (Witten, 1985). At nearly the same time as the last fatality occurred, 1700 Eastern Daylight Time (EDT), the Ontario Weather Centre issued its first Tornado Warning, though in the previous 2.5 hours it had issued several Severe Thunderstorm Warnings, each including a note that tornadoes could develop (Leduc et al., 1986). Also at 1700 EDT, the first of 28 tornado touchdowns south of the Great Lakes occurred near Lake Erie on the Ohio-Pennsylvania border. Before sunset, tornadoes had caused 17 deaths in Ohio and 65 deaths in Pennsylvania (Witten, 1985). Not surprisingly, residents of Ontario, Ohio, and Pennsylvania refer to May 31, 1985 as "Black Friday", a term frequently used by Albertans to refer to the day of the Edmonton tornado (Diotte, 1997).

Carter et al. (1989a) conducted an epidemiological study for the regions affected by the Ontario tornadoes. Social workers surveyed most of the injured, and the fatalities were surveyed by proxy. Affected but uninjured people were also surveyed, and their responses were used as matched controls. Forty-eight people were hospitalized with serious injuries, including 2 who were still disabled 2 years later, and an additional 233 people were treated in emergency rooms. The seriously injured spent a total of approximately 600 days in acute care. In an unpublished epidemiological study of the Edmonton tornado, Carter et al. (1989b) found that 46 seriously-injured people spent a total of 930 days in acute care.

Fortunately, the Ontario tornadoes did not strike a mobile home park. Carter et al. (1989a), however, found that 5 of the 6 people killed in residences were in buildings where the ground floors became airborne, a common event when violent winds buffet a mobile home park. Hundreds of houses were subjected to the winds of the Ontario tornadoes, but the floors of just 22 houses became airborne. Of these 22 houses, only 2 were known to have been built to the pertinent anchorage requirements of the National Building Code of Canada (Carter et al., 1989a; Allen, 1986). Lux (1990) concluded that the Edmonton tornado did not lift the ground floor of a frame house.

Ontario Tornadoes, May 31, 1985 (Harris, 1985) includes hundreds of photographs with detailed captions and, of particular interest to researchers who study the behavior of people encountering disasters (such as those who contributed ,to Handmer and Penning-Rowsell (1990)), dozens of stories from people who wished to relate their experiences.

b. Studying the Edmonton tornado

A survey form was published by Edmonton's 2 daily newspapers (combined circulation 293,000) just 8 and 9 days after the tornado. It gave citizens of central Alberta an opportunity to tell their stories to meteorologists at the University of Alberta and to future generations. A map of reported hail-size categories and a preliminary analysis of perceived warning times, both derived from the 815 responses to the survey, have already been published (Hage, 1987a; Charlton et al. 1990; Charlton et al. 1995).

The Edmonton tornado has been examined from a variety of perspectives. The official review of the local severe-weather-warning system by Hage (1987a) included a survey of the damage path, analysis of the weather conditions during the day of the tornado, commentaries by ALWC forecasters specializing in severe weather, and the results of a telephone survey conducted 6 weeks after the tornado to determine the public's perceptions of the severe-weather-warning system. In response to the conclusions published in the Hage report, an operational Doppler radar system was installed near Edmonton in 1991, the first in Western Canada. The first Doppler radar system in Canada, now used for both research and operations, was installed at King City, north of Toronto, in 1985 (Nichols and Crozier, 1989).

Reports from emergency response agencies, the Insurance Bureau of Canada, and utility companies were published in **Tornado: A Report** (Alberta Public Safety Services, 1990). The report also included a discussion of the climatology of tornadoes in Alberta by K. D. Hage and a brief review of the weather warning system by A. F. Wallace, the severe weather coordinator at the ALWC. The unedited versions of the submissions to **Tornado: A Report** were placed in file 89-340 at the Alberta Archives. Other publications by forecasters at the ALWC, the main forecasting office in Alberta, described the weather systems that traversed Alberta on July 31 and the area damaged by the tornado (Bullas and Wallace, 1987; Atchison, 1988; Paruk, 1988). By a remarkable coincidence, the forecasters had a new Director of Western Region of the Atmospheric Environment Service. Having moved to Edmonton from central Canada, Brian O'Donnell's first day on the job was the day of the tornado!

The difficulties that insurance companies experienced in settling claims were documented by Deibert and Wood (1988). An assessment of building damage was conducted by Lux (1990), a structural engineer who also provided information to Carter et al. (1989b). The scattering and subsequent clean-up of hazardous materials were reported by Holmes (1989, 1990) of Alberta Public Safety Services. A householder survey of people who lived in 2 areas where the tornado passed through was conducted 70 weeks after the event; their recoveries were studied and the results were incorporated into an unpublished Doctoral dissertation for the Department of Educational Psychology, University of Alberta, by Caine (1989). The transportation of the injured to city hospitals was investigated by Scanlon and Hiscott (1994). The experiences of some of the injured were described in an article about the tornado in Reader's Digest (Tower, 1989). A Master of Science thesis by De Serres (1996) applied the theory of crisis management to the Edmonton tornado.

Between 1500 and 1605 MDT, the tornado, moving from south to north through east Edmonton, left a continuous damage swath 37 km in length, ranging from 100 m to more than 1000 m in width. Immediately to the west, an area of 125 km^2 was struck by tennis-ball-size hail. According to Alan Wood, the regional vice-president of the Insurance Bureau of Canada (Edmonton office), there were 60000 successful automobile and building insurance claims, and 50000 of these were paid for hail damage. Numerous reports of giant hailstones were carried by the media, and one of the hailstones recovered by a citizen set a new Alberta mass record. The present authors have determined that at least 2 individuals in south Edmonton were rendered unconscious by blows from hailstones. In **Urban Hailstorms: A View From Alberta,** Charlton et al. (1995) described the weather events across the province for the day of the Edmonton tornado and compared the 1987 Edmonton storm with 8 major urban hailstorms, 4 in Alberta and 4 outside Canada.

This article includes a set of detailed maps showing the areal distribution of various storm-related parameters within the Greater Edmonton region (Edmonton, St. Albert, and Sherwood Park). These maps are apparently unprecedented for studies about tornadoes and hailstorms. Numerous new sources are used to supplement the information gathered from the newspaper survey; these sources include photographs from air surveys, the records of two roofing companies, and the results from the telephone, householder, and epidemiological surveys. Tabulations of flooding and sewer blockage incidents and rainfall rates, all obtained from the Water and Sanitation Department (EWS) of the City of Edmonton, are also used.

c. Canadian studies of urban tornado climatology

In addition to the Ontario tornadoes of May 31, 1985, Newark (1985) listed 4 other Canadian tornadoes or series of tornadoes that have caused tragedies: 9 people were killed in Windsor, Ontario on April 3, 1974; 17 perished in Windsor on June 17, 1946; 28 died in Regina, Saskatchewan on June 30, 1912; and, 9 or 11 people lost their lives between St. Zotique and Valleyfield, Quebec on August 16, 1888.

From his exhaustive examination of newspapers and local histories from Alberta and Saskatchewan, Hage (1990) determined the numbers of tornadoes that struck Edmonton and Calgary, Alberta and Regina and Saskatoon, Saskatchewan from 1890 to 1989: Edmonton had 12, Calgary, 3, Regina, 17, and Saskatoon, 10. Similarly, but for the period 1910 to 1960, Hage (1987b) provided the numbers for Moose Jaw, Saskatchewan 6, Lethbridge, Alberta 2, and Medicine Hat, Alberta 4. Hage (1994) published a booklet for 1879 to 1984 that contained tables of occurrences in which deaths, injuries, or property damage were caused by tornadoes, windstorms, or lightning in Alberta. He was preparing a similar volume in 1995 using information for Saskatchewan. Estimates of the numbers of tornadoes that struck 11 Canadian cities during climatological periods of varying lengths were performed by Murray (1990). Newark and McCulloch (1992) used tornado climatologies to determine the risk, weighted by population, for each of 49 Canadian cities. They suggested that their calculations should be used to plan a Doppler radar network for Canada. Etkin (1995) discussed the apparent increase in the frequency of tornadoes in Western Canada. Joe et al. (1995) reviewed techniques used by Environment Canada to forecast the development of severe storms.

2. THE NEWSPAPER SURVEY

While assisting employees of the Alberta Weather Centre (ALWC) with their field investigation of the tornado's damage track (Wallace, 1987), Charlton and Wojtiw decided that a public survey, distributed in the daily newspapers, was warranted. On August 3, financing for the research was obtained from the Central Research Fund of the University of Alberta. Financial arrangements for publishing the full-page survey form were managed by the City of Edmonton. The survey, published Saturday, August 8 by the Edmonton Journal and Sunday, August 9 by the Edmonton Sun, is shown in Fig. 1. Most of the questions in the survey were taken from a form used by the Volunteer Weather Watchers (VWW), a group that is organized by the weather offices of Environment Canada to report severe-weather events every summer. The form published by the newspapers, however, also had to elicit information from the public about the efficacy of Environment Canada's weather warning system. It also included questions about the availability of frozen hail samples, photographs, and video tapes. Interpretation of some returned survey forms proved to be challenging; these problems are discussed in later sections, and a modified survey form, one that should avoid such difficulties, is available from Charlton.

Figure 2 is a map showing selected Edmonton roads, residential areas, and the tornado path. The units of the coordinate grid are miles because most main roads are 1 mile apart. (The legal land location of coordinates 0 east and 0 north is the southwest corner of S 18, T 51, R 25, W4.) There are no "correction lines" within the area of the map; therefore, the grid is representative of the legal survey lines. The positions of important sites which are not denoted on the maps will often be described by their coordinates.

Of the 815 survey participants, 755 of them were present within the boundaries of Fig. 2 during the afternoon or evening of July 31. The phenomena experienced by each of the 755 respondents were prioritized such that encountering the tornado was given highest priority, and not experiencing severe weather of any kind was given lowest priority. The location of each respondent at the time of his highest priority experience was converted into coordinates. The **Archive Report** (Charlton et al., 1989) contained tabulated data organized by the respondents' positions within the grid. The tabulated data, available in hard copy and computer diskette (Apple and PC formats), consisted of all parameters derived from the newspaper survey. Analysis of this data, particularly the mapping of it, is the principal purpose of this study. Copies of both the **Archive Report** and the survey responses were given to the archives at the University of Alberta and the Provincial Museum of Alberta. Respondents' names and addresses have been removed from the forms housed at the Museum. Forms held at the University archives are available only to bona fide researchers.

The path of the tornado, shown in the maps, was based on the damage survey conducted by local meteorologists (Wallace, 1987), including Charlton and Wojtiw. Arrows represent sections of the path where "considerable or greater" damage occurred, and dashed lines indicate regions of only "general" damage. The tornado path is included in Fig. 2 to show its proximity to roads, neighbourhoods, and 4 important industries in east Edmonton: the tornado travelled between 2 operating oil refineries, and it came dangerously close to Edmonton's largest chemical plant, an Edmonton Power thermal-electric generating station, and the Maple Ridge Mobile Home park! Clearly, numerous near-tragedies were barely avoided, a fact that few authors of previous studies have noted. Figure 3 is one of a series of the only known set of photographs taken from north of the river in which the tornado was clearly depicted. It shows the tornado passing to the east of Imperial Oil's Strathcona refinery. At that position, the tornado was approximately 2 km east-northeast of the ALWC. An abridged tabulation of facilities struck by the tornado will be included in Section 3.

The dots and circles in Fig. 4 show the locations of the 755 survey respondents within Greater Edmonton. These clearly indicate that reports were received from virtually all residential areas (shown by shading), and that workers in the industrial area, where the tornadic winds apparently reached their greatest speed, were especially generous in reporting their experiences. Instances of sewer flooding, denoted by the circles, will be discussed in Section 3. Figure 4 also shows that the tornado was outside the city's boundary as it moved from 8.2 N to 12.0 N, an area of heavy industries in Strathcona County. As stated earlier in this section, the dots and circles

The Edmonton Sunday Sun, August 9, 1987 **15**

A Public Request to share your Storm Experiences

Meteorologists at the University of Alberta would like all Edmonton-area residents to share their experiences of the July 31 tornado by mailing this survey.

We would like to hear from people in Calmar, Beaumont and other badly hit areas. Within the City, we would like responses from all sectors, so that the extent of hail and rain damage can be accurately determined.

THE COMPLETED SURVEYS WILL BE PUT TO THE FOLLOWING USES:

1 To assess public opinion on the efficiency of our storm warning system. Your responses will be tabulated immediately so that a study can be conducted into possible improvements in this system. For this reason, it is important that we hear from you within a week.

2 Meteorologists at the University of Alberta, the Alberta Weather Centre, and the Alberta Research Council would like to use your comments to better assess the severity of the storm. If you have hailstone samples, we hope that you can save them in sealed plastic bags in a cold freezer. Within a month or two a graduate student doing research may contact you in the hope that you will make your hailstones, no matter what size, available for study.

3 Within six months we will photocopy all responses to the survey, organize them by name and area, and file them with the Edmonton Public Library for use by present and future generations. Please remember that it is critically important to study past storm occurrences in great detail if we are to learn from our experience and attempt to minimize damage in the future.

If you live out of town, please feel free to give land locations in quarter section, township and range. Also feel free to approximate times when events occurred. If you cannot recall, just put a question mark in the space.

We deeply sympathize with those who lost loved ones and their homes in the storm. However, we hope that they, too, will share their experiences through this survey.

Please mail your completed forms to
R CHARLETON
METEOROLOGY DIVISION
GEOGRAPHY DEPARTMENT
UNIVERSITY OF ALBERTA
EDMONTON, ALBERTA
T6G 2H4

N/A - Not Applicable
~ - Approximate
? - I don't know

Fig. 1a. The survey form as published in the Edmonton Sun on August 9, 1987, nine days after the Edmonton tornado. The form used on August 8 by the Edmonton Journal had identical artwork but a different page shape. Part 'a' shows the preamble and part 'b' shows the reports.

Fig. 1b.

Todays Date

Your Name

Your Home Address

Your Type of Work

Your Phone Numbers

Where Did You Encounter the Severe Weather?

Time of Encounter (Use ~ if approximate)

Friday, July 31, 1987, ______ p.m. to ______ p.m.

How Much Warning? ______ minutes

How were the Times Above Determined? (Check)

☐ Stopped Clock ☐ Memory ☐ Other

Type of Encounter (Check)

☐ Tornado ☐ Hail ☐ Violent Wind ☐ Violent Rain

☐ Other

What First Made You Aware of the Danger? (Check)

☐ Weather Forecast ☐ Unusual Cloud ☐ Rainfall
☐ Weather Radio ☐ Funnel Cloud ☐ Talking
☐ Radio or TV Report ☐ Hail Noise ☐ Screaming
☐ Electricity Failure ☐ Wind Noise ☐ Other

Please Explain:

What Response Did You Take to the Warnings?

Please Explain:

TORNADO REPORT

Was Funnel Seen? ☐ Yes ☐ No (Check)

Did it Touch Ground? ☐ Yes ☐ No (Check)

Time Began Lasted ______ min.

Closest Distance

Direction From You

Funnel Type (Check)

☐ Multiple ☐ Smoke-Like ☐ Columnar ☐ Cone ☐ Rope
☐ Unknown ☐ Other

If Multiple, How Many?

From Which Direction Did it Move?

Unusual Noise? ☐ Yes ☐ No (Check)

Unusual Sky Colour? ☐ Yes ☐ No (Check)

If Yes, Describe

Video Movies? Photos?

WIND REPORT

Damaging? ☐ Yes ☐ No (Check)

Time Began: Lasted: ______ min.

Describe:

How Damaging? (Check) ☐ Twigs Off Trees ☐ Branches Off
☐ Shingle Damage ☐ Trees Down ☐ Windows Broken

☐ Other:

HAIL REPORT

Largest Size (Check) ☐ Shot ☐ Pea ☐ Grape ☐ Walnut
☐ Golfball ☐ Tennis ☐ Larger

Most Common Size

Spacing on Ground

Time Began: Lasted: ______ min

Describe Largest Stone and Measure It, Please

Frozen Samples Photos?

RAIN REPORT

How Much? (Check) ☐ Light ☐ Heavy ☐ Flooded Eaves
☐ Flooded Sewers ☐ Flooded Road ☐ Other

Time Began Lasted ______ min.

Describe

DAMAGE REPORT

Number of Human Fatalities Number of Human Injuries

Number of Animal Fatalities Number of Animal Injuries

Describe Property Damage (Objects Moved, Their Weight Anchored?)

Are Photos Available? ☐ Yes ☐ No (Check)

Who Took The Photos and Where Do They Live

Who Else May Have Information? Name, Address, Phone

Further Comments:

If you have any further questions, please feel free to call us at 432-5672, 432-5405, or 432-5406.

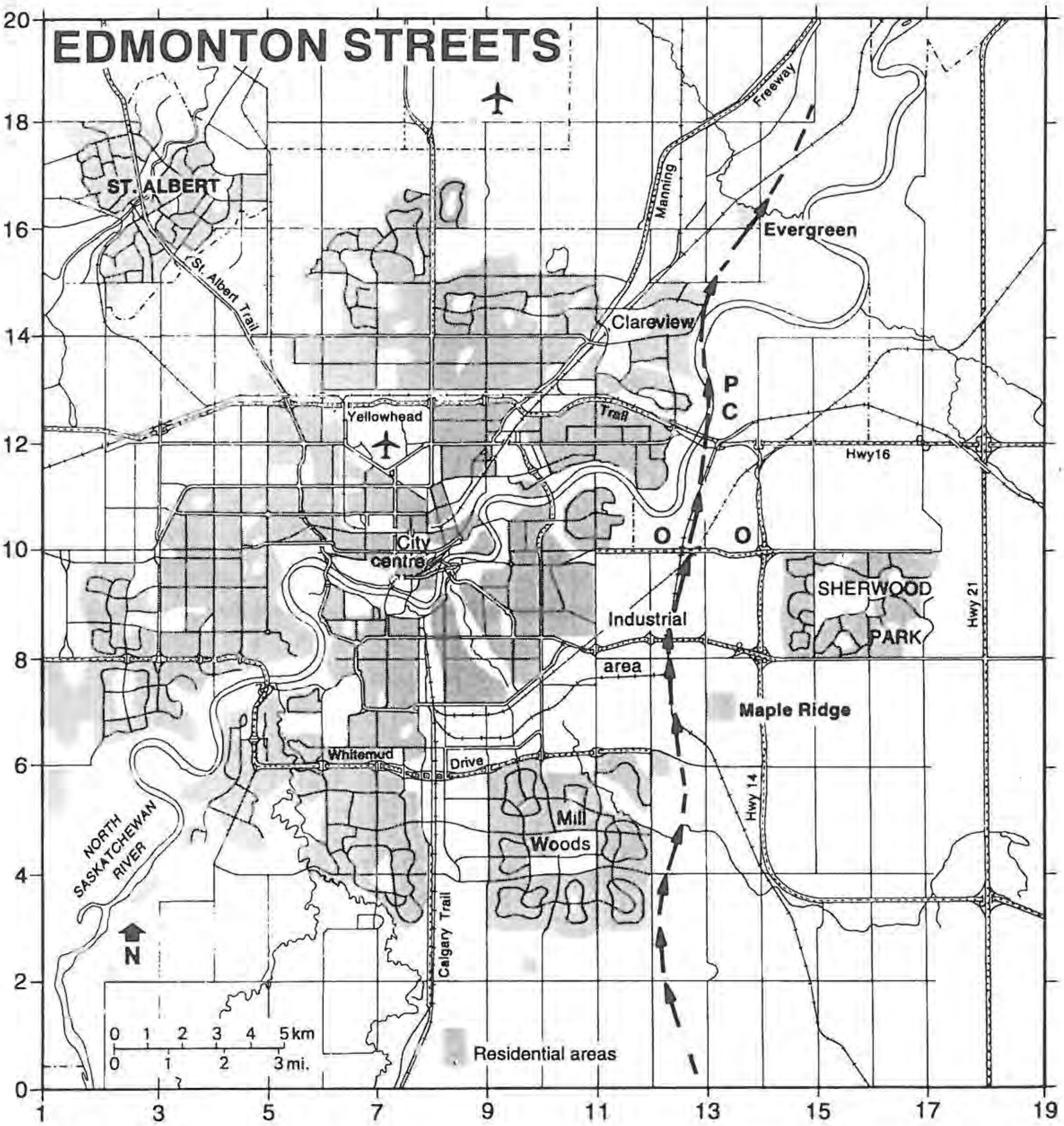


Fig. 2. Map of Greater Edmonton showing the river, major streets, and main communities. Coordinates are in miles to fit the legal land survey. The tornado path of July 31, 1987 is shown by arrows in areas of greatest damage and by dashed lines where damage was of lesser extent. Oil refineries are depicted by 'O's; Imperial Oil's Strathcona refinery lies to the west of the tornado path, and Petro Canada's Edmonton refinery lies to the east. The Celanese Canada chemical plant is depicted by a 'C' and Edmonton Power's Clover Bar electricity plant is depicted by a 'P'. Evergreen and Maple Ridge are mobile home parks. The Municipal Airport lies north of the city centre. The Namao Airport lies north of the Edmonton city limits.

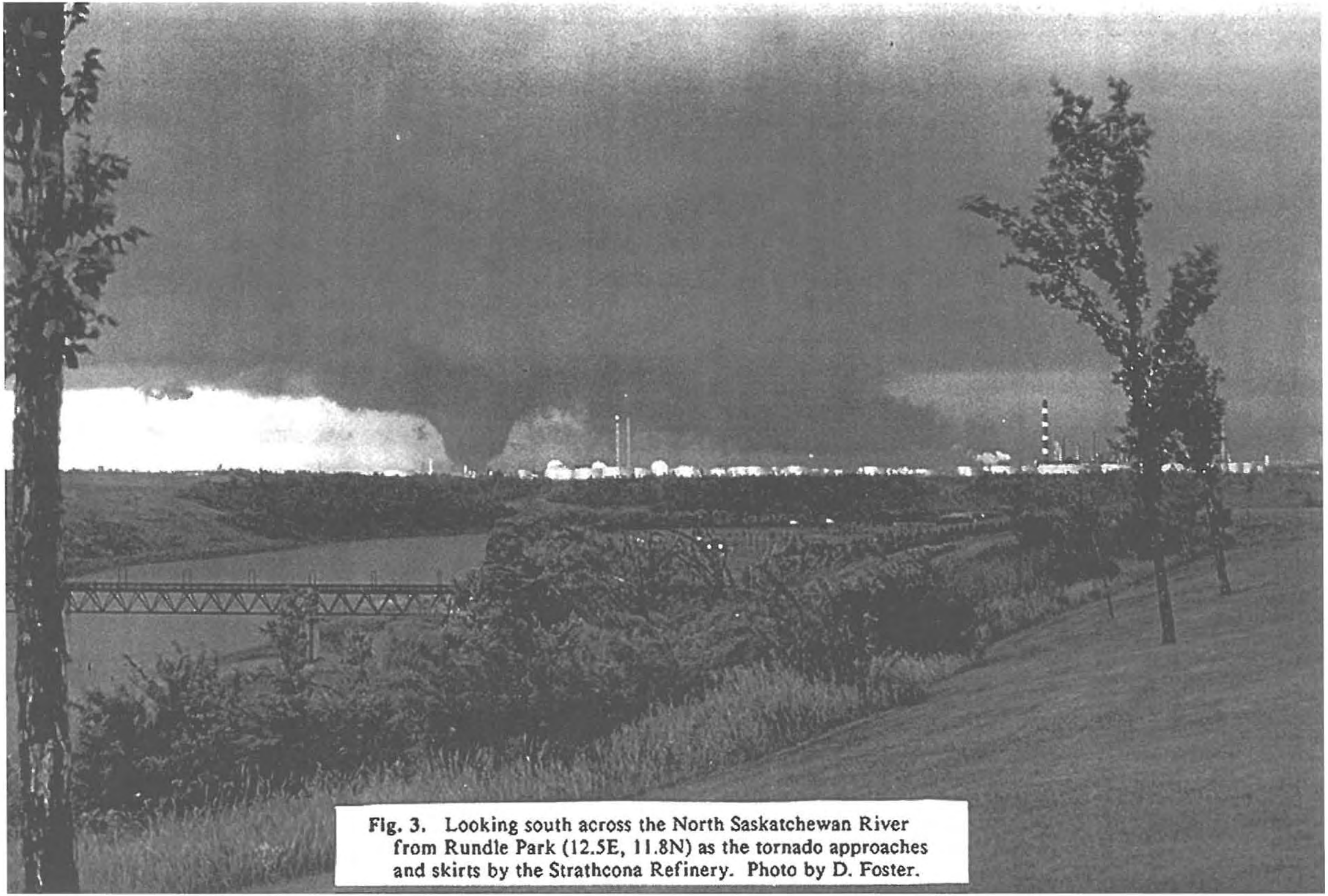


Fig. 3. Looking south across the North Saskatchewan River from Rundle Park (12.5E, 11.8N) as the tornado approaches and skirts by the Strathcona Refinery. Photo by D. Foster.

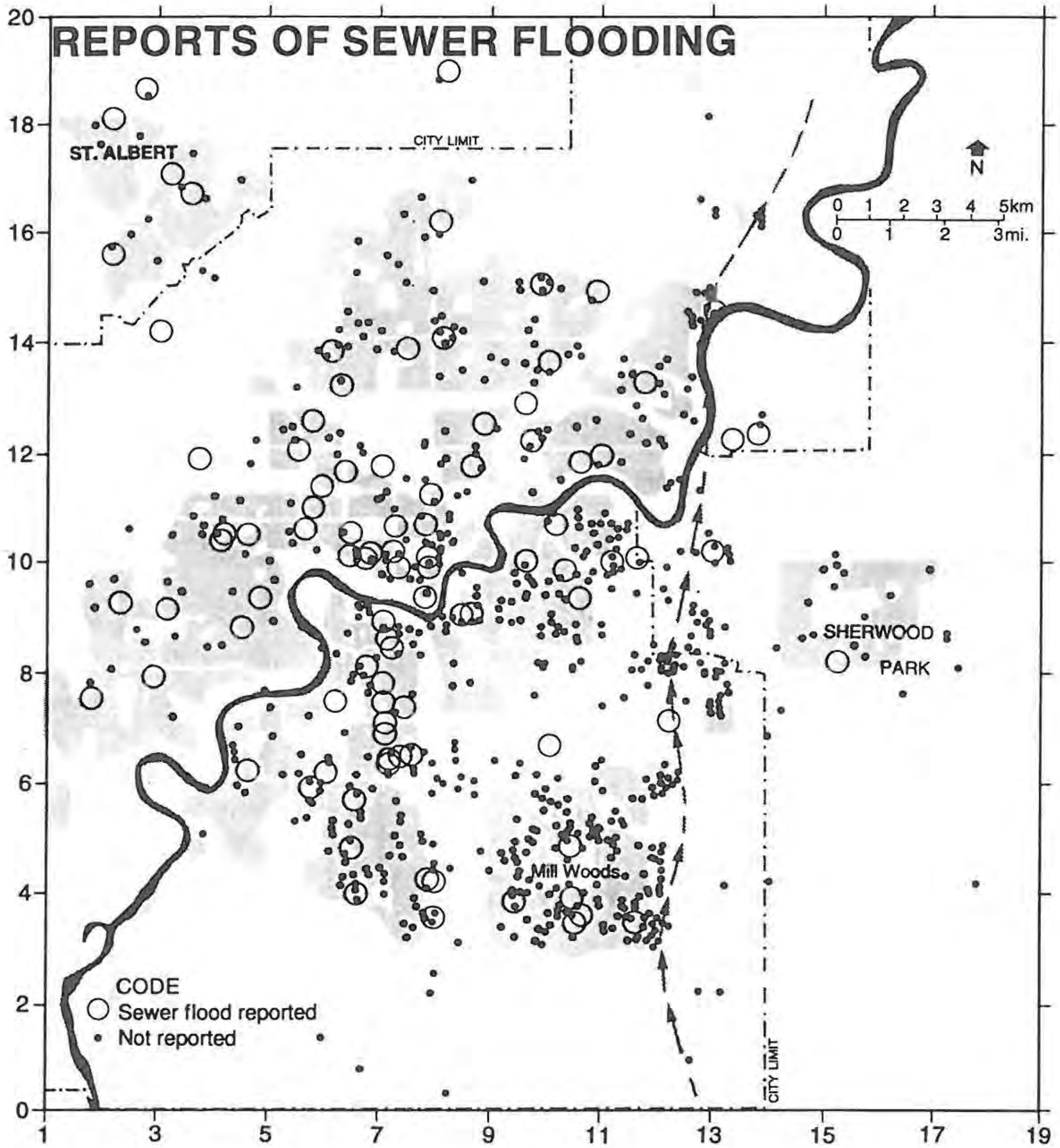


Fig. 4. The locations of 755 respondents to the survey, plotted where they had their most extreme weather experience. Circles denote those who reported sewer flooding.

plotted on the map are placed where the respondents encountered their most-severe weather experiences. The original survey numbers were plotted by hand at the participants' locations on a 104 cm by 122 cm (1:30000) base map. To prevent overlapping, some of the respondents' positions were shifted by a small amount; consequently, some of the coordinates listed by Charlton et al. (1989) were not perfect representations of the participants' locations. Altering the coordinates, however, made the maps less prone to overlapping data. The errors introduced by the shifting of coordinates are easily seen in 2 areas of Fig. 4: a number of respondents appear to be located in the farm fields to the east of Mill Woods or directly on the river.

3. INFORMATION FROM VARIOUS SOURCES

Most of this section describes, in considerable detail, the materials compiled to plot the non-survey information shown in Fig. 5. For the eighth anniversary of the tornado, The Edmonton Journal published their rendition of an early version of Fig. 5, along with an article which described this research (Barret, 1995).

a. Flooding

The reports of sewer flooding made by 94 respondents are represented by circles in Fig. 4. Unfortunately, the Rain Report (Fig. 1b) did not explicitly request "flooded basement", though many survey participants checked 'other' and stated that their basements flooded. The regions where sewer flooding was common (Fig. 4) were, to a considerable degree, in the same areas where basement flooding was common, as reported by Edmonton Water and Sanitation (EWS) and outlined in Fig. 5. Minor flooding at both the Charles Camsell (5.8 E, 11.6 N) and the General (7.1 E, 9.8 N) hospitals proved to be modest inconveniences (Scanlon and Hiscott, 1994).

EWS tended to 271 flooded basements reported from 1500 MDT July 31 through August 4 (Bowen, 1994). Crews also cleaned 64 street locations flooded because of plugged catch basins, and they refit 39 lifted manhole covers (Bowen, 1994). The 4 areas enclosed by bold dotted lines in Fig. 5 encircle 153 of the 271 flooded basements; the fine dotted line encloses all but 18 of the 271 reports. The number of homeowners who drained their basements without assistance could not be determined. EWS divides the city into 25 service areas. The numbers of lifted manhole covers and plugged catch basins, which caused streets to flood, are plotted in Fig. 5 near the developed centre of each service area.

b. Rain in Greater Edmonton

The patterns of flooding in Figs. 4 and 5 suggest that the heaviest rains fell in south-central and north Edmonton. EWS provided records from their 16 tipping-bucket rain gauges (Ward, 1994). The operation of each gauge was monitored by comparing its measurements with weekly amounts collected in cylindrical rain gauges placed at the same site. Furthermore, the tipping-bucket gauges were calibrated at least once per year. The tipping-bucket gauge at the Municipal Airport (7.2 E, 12.0 N) was shared with Environment Canada. The Canadian Armed Forces and EWS both had a tipping-bucket gauge at CFB Edmonton, known locally as the Namao Airport (9.2 E, 18.7 N). For each EWS tipping-bucket rain gauge, the information was stored on-site using battery powered equipment, and later transferred to EWS via telephone lines. The transmission of the data compiled during the storm was delayed, but none of the information was lost. The rainfall amounts were available for 5 minute intervals. Figure 5 shows the 24 hour and maximum 60 minute rainfall totals from 16 sites for July 31. The 24 hour rainfall amount plotted in northeast Edmonton (13.5 E, 17.0 N) was from a cylindrical rain gauge located at a climatological station sponsored by Environment Canada.

Figure 5 indicates that most areas in south-central and north Edmonton received more than 40 mm of rain on July 31, and near the regions of frequent basement floodings, approximately 30 to 40 mm of rain fell in one hour. The low values at 5.8 E, 10.4 N, that is, the station with the hourly and daily totals of 2 mm, were obviously caused by a malfunction. All other EWS gauges recorded their maximum 60 minute totals as the tornadic storm passed over the city, and they seemed to operate correctly. Heavy showers also accompanied a windy evening storm that struck Edmonton at 1800 MDT, after doing extensive hail damage to crops southwest of Edmonton (Charlton et al., 1995), but the 60 minute precipitation amounts did not match those from the afternoon storm. Apparently, one-hour rainfall amounts of 30 to 40 mm were capable of causing widespread flooding. For any location in Edmonton, the average time between one-hour rainfalls of 30 mm or more is approximately 5 years, and for 40 mm or more, it is approximately 15 years (Bruce, 1968).

A 4 m x 8 m oval-shaped, storm-water tunnel buried in the Kennendale Ravine of south Clareview ('B' in Fig. 5 and Table 1) suffered damage when the tornado passed its outlet to the river causing a local pressure decrease. The bottom of 330 m of the pipe was pulled towards the top of the pipe! Replacement of this section of the tunnel

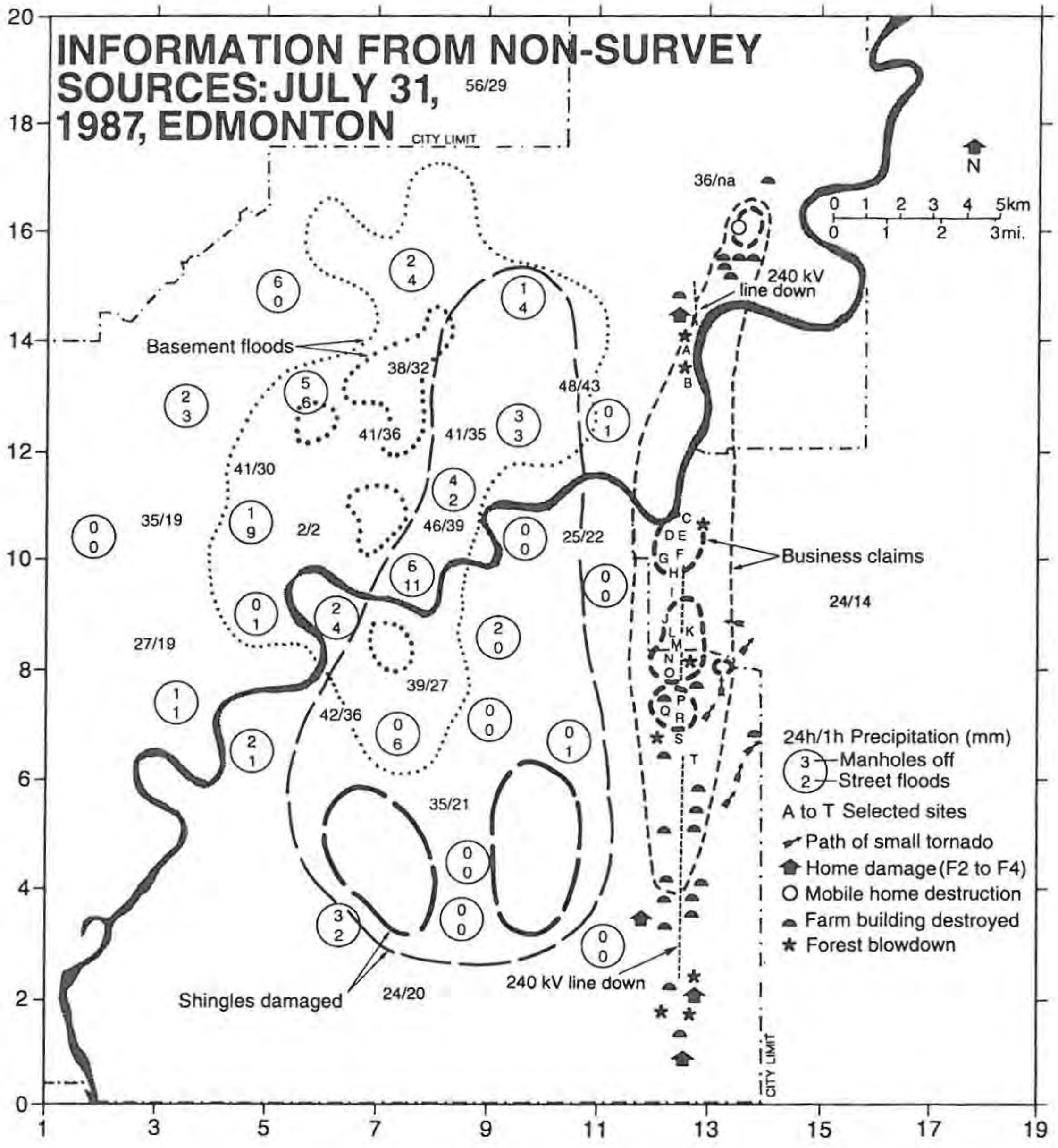


Fig. 5. Overview of the storm events based on non-survey information. Generalized regions of basement floods, shingle repairs, and business claims are circled and centres of concentration are circled boldly. Selected damage sites labelled A to T are described in Table 1.

Table 1. Selected damage sites located in Fig. 5.

A	Belmont Drive-In	Screen of abandoned theatre toppled onto field.
B	Kennedale Ravine outlet	330 m of a 4 m by 8 m buried oval-shaped corrugated-steel storm sewer was sucked flat.
C	Strathcona Science Park	Excavators at Archeological Centre sought shelter but tornado lifted and passed overhead, sparing the building.
D	CN Railway	Several cars derailed. Leaks from tank cars included propane.
E	Central Fabricators	Major damage to cranes and building. Ten-minute forewarning saved workers. Moment-resisting steel frame tested to limit.
F	Tiger Chemicals	Dry and wet chemicals released into ditches on site but some might have reached the river. Management and employees were unavailable.
G	Pounder Emulsions	Diesel oil and asphalt spilled. Tanks wrecked or blown off site. Dikes and tanker trucks used to contain spill. Clean-up took over one year. Contaminants reached river.
H	Texaco refinery	Moth-balled refinery. Empty 22 m tank skipped for 170 m around its horizontal axis, jumped power lines, and landed on middle of a public road.
I	Stelco steel mill	$12 million damage. Fume ducts and 20 m building tossed about. Wind entered open west end of 300 m long building and toppled overhead cranes from their rails at severely damaged east end where the tornado passed.
J	Canada Packers Poultry	Strong concrete block building with concrete beam roof had little damage in spite of direct hit. Attached steel-framed, two-storey office building needed rebuilding. Ammonia and other spills entered river via ditches.
K	Atlas Construction & Crane	Steel-framed two-storey building with two service bays was severely damaged. Equipment was scattered. Propane tank leaked.
L	Great West Steel	Large steel-framed warehouse scattered.
M	Laidlaw Waste Disposal	Building destroyed. Dumpsters thrown about and 23 trucks destroyed.
N	Byers Transport	Major shipper lost buildings and dozens of trucks. Sub-basement saved employees. Loss of radioactive shipment prompted an investigation.
O	Dillingham Construction	Steel-clad warehouse was levelled and aluminum-clad warehouse lost its sheathing. Extensive debris.
P	Lee Mason Tools	Three-section reinforced concrete-block building was demolished. Fatalities and injuries were reduced when machine tools held roof above floor.
Q	Norton Steel	Steel-framed warehouse reduced to debris.
R	Nault Sawmill & Lumber and Weyerhaeuser Canada	Twenty-five metre concrete roof collapsed. Access to injured restricted by weight of beams. Lumber spread over large area.
S	CN Railway	Locomotive and a train of loaded cars took direct hit. Cab filled with rubbish. 240 kV power lines fell across train. Empty shunted boxcar toppled onto crew.
T	Windsor farm	PCB filled transformers in storage were damaged. After million dollar clean-up, land remained posted.

cost more than $2 million. Christopher Ward and Andy Bowen, employees of EWS, stated that the blockage of the storm-water tunnel probably did not contribute significantly to the street, sewer, or basement flooding in the catchment area to the west. Immediately after the tunnel folded upward, it probably burst, allowing storm water to flow beneath the collapsed section. Bowen does not know whether the storm sewer was plugged by heavy rain when the tornado passed its outlet at approximately 1545 MDT. At that time, the 2 tipping-bucket gauges closest to the storm sewer, Kennendale Yard and Norwood, had 5 minute rainfall rates which were equivalent to 70 mm per hour and 80 mm per hour, respectively. The tornado also drew air through a 300 m long building at Stelco Inc., though the building, unlike the Kennendale storm sewer, was not sucked flat. The damage to Stelco Inc. is discussed in sub-section g.

c. Weather across Alberta

Charlton et al. (1995) noted that rainfall continued intermittently in Edmonton from 1500 MDT July 31 through August 2, and the total for these 2 days was roughly 100 mm. They also reported that an intensifying low pressure system, which remained in northern and central Alberta for 30 hours, brought an average of 33 mm of rain on July 31 to an enormous area northwest of Edmonton. This area, 277000 km^2, is about 80 percent the size of Germany! Using the data from the 0600 MDT, July 31 radiosonde weather balloon released near Edmonton, Charlton et al. (1995) estimated precipitable water to be only 32 mm. That is, if all the water vapour in the atmosphere that day was condensed, it should yield only 32 mm of rain. Clearly the weather system was very efficient at producing widespread rain. Paruk (1988) reported that widespread flooding occurred northwest of Edmonton where rainfall amounts for the period July 31 to August 2 exceeded 300 mm at one location and 200 mm at 2 other locations. In this region, Canadian National suffered damage to its north-south line and a train derailment which was not widely reported. Even if the tornado and swath of enormous hail had not occurred, the rainfall in Alberta beginning July 29, when the tropical air arrived, and ending August 4, when the low pressure system dissipated, would be regarded as exceptionally severe.

Charlton et al. (1995), utilizing lightning flash records, showed that the thunderstorm which eventually spawned the tornado moved northeastward from the Rocky Mountains, then gradually turned eastward when it was between 100 km and 200 km southwest of Edmonton, and it finally proceeded northward just as the tornado formed. Other storms traversing central Alberta that day had relatively straight paths as they moved from the southwest to the northeast. Equipment failure caused by lightning on July 30 prevented detailed weather-radar data from being recorded. Thus, the exceptional path of the tornadic storm could not be examined using radar imagery.

d. An introduction to the examination of hail damage using reshinglings

The billing records of the A Clark Shingle Company were examined to determine the distribution of reshinglings that this company performed after the tornado. Reshinglings completed in 1990, a year when no severe hailstorm struck Edmonton, were also inspected. The large area enclosed by the fine long-dashed line in Fig. 5 contains 84 percent of the reshinglings done between August 1, 1987 and July 31, 1988. The 2 small areas delineated by bold long-dashed lines contain 53 percent of the reshinglings completed in those 12 months. These 2 areas of south Edmonton were relatively new communities; the area west of 8 E is known as Kaskitayo, and the area to the east of 9 E is the western part of Mill Woods.

Figure 5 indicates that the 4 regions where flooded basements were common and the 2 areas where shingles replacements were frequent were clustered well away from each other and from the path of the tornado. It also indicates that nearly every community was affected to a significant degree.

e. The distribution of disaster assistance

Frank Nesbitt, an employee of Alberta Public Safety Services, an agency of the Government of Alberta, provided a list of 259 businesses which suffered damage between July 25 and August 3 and applied to the provincial government for disaster assistance. Loans and grants totalling $20.8 million were provided to 214 successful business claimants. The agency dispensed federal and provincial funds to other groups as well: $4.6 million to 472 individuals, $2.6 million to 335 farmers, $4.7 million to 8 municipalities, and $3.6 million to 12 government departments (Alberta Public Safety Services, 1990). The Edmonton Journal (1996) reported that a lawsuit which delayed the completion of the assistance program was settled in 1996.

To document the effects of the storms which raked central Alberta on July 31, Charlton et al. (1995) mapped the distributions of disaster-assistance applicants from rural Alberta and farmers who received crop insurance payments. The map showed a good relationship between the paths of lightning activity and damage in rural areas.

The list (Nesbitt, 1994) had the names and mailing addresses of the 259 business applicants. It did not differentiate between successful and unsuccessful claimants, nor did it note the amount of assistance that applicants were seeking. Some of the mailing addresses were likely not the locations at which damage occurred; more suitable addresses were sought in a 1987 telephone book or, if necessary, by telephoning the businesses, provided that they still existed in 1995. At least 152 of the 259 business applicants had assets within the fine short-dashed line in Fig. 5. This line forms a crude replica of the tornado path and encompasses an area which is nearly 3 km wide in places. Wallace (1987) concluded that the maximum width of "general" damage was 1.3 km. Of the 259 business claimants, 135 resided within the 5 small areas outlined by bold short dashes in Fig. 5. Eighty-five applicants with addresses in Greater Edmonton were located outside of the fine short-dashed line; presumably, their losses were not caused by the tornado. Claims were made by several transportation, holding, and property companies, and the locations of their damaged assets could not be readily ascertained. Firms with mailing addresses outside of Greater Edmonton were ignored, except if the locations within Greater Edmonton where these firms had assets were known.

Although some of Canada's more prominent industries were included on the list of disaster assistance applicants, \$20.8 million dispersed to all businesses by governments was small compared to \$150 million paid to businesses by the insurance industry.

f. Air surveys

A set of 1:1500 colour air-survey photographic prints was obtained from Alberta Public Safety Services (Nesbitt, 1995). The photography was conducted on August 4, 1987 by Western Remote Sensing (now defunct). The firm did not give Alberta Public Safety Services the negatives from the survey, and the negatives have not been located. These excellent photographs were used to locate and identify nearly all of the industries damaged by the tornado, though the names of all of these industries are not documented in this study. The colour prints were donated to the Department of Earth and Atmospheric Sciences at the University of Alberta. The Edmonton Space and Science Centre made duplicates of some of the prints for a severe weather display shown in 1996.

Two sets of black and white stereo photographs from air surveys conducted on August 3 and August 6, 1987 by Global Remote Sensing were also examined. The negatives from the first flight remain with the firm, and those from the second flight, along with 1:2500 prints with overlays for use in public displays, are owned by the Public Works department of the City of Edmonton. The set of prints from the later flight included photographs of east Mill Woods and the undeveloped area southeast of Mill Woods, areas which are not depicted in the colour photographs. Several instances of significant house, farm, or tree damage, shown in Fig. 5, were found when these photographs were examined.

A set of colour slides was kept at the ALWC archives (Vickers, 1995). This set consists of 13 images of damage sites taken from an aircraft by Brian Smith for research conducted at the University of Chicago. Smith, an employee of the National Weather Service in Valley, Nebraska in 1995, provided information about the photographs. Fujita stated that all of Smith's photographs had been donated by the University of Chicago to the United States archives after Fujita retired. The limited-edition memoirs of Fujita (1992) included 4 images of tornadic damage in Edmonton selected from Smith's set; each photograph was described briefly.

Charlton's collection of video tapes of television newscasts also proved useful for developing Fig. 5, especially those segments taken from aircraft a few hours after the tornado dissipated. Unfortunately, aviators with the Canadian Forces, stationed at the Namao Airport, were not asked to conduct an aerial survey of the tornado path; presumably, the military could have flown on the evening of July 31 or on August 1, a day of inclement weather, and carefully photographed the damaged areas before much of the debris was moved.

g. Selected damage sites

The letters A through T, plotted in Fig. 5, represent an interesting selection of damage sites; these are described in Table 1. A variety of sources were used to develop the concise descriptions contained in Table 1: Charlton's extensive collection of newspaper articles; notes made during conversations with dozens of people who lived or worked in the vicinity of the tornado path; conversations with Scott Alexander and David Ungstad, structural engineers associated with the Department of Civil Engineering, University of Alberta, who examined damaged buildings in the industrial area; the 4 sets of aerial photographs discussed above; the responses from survey participants; and the reports from various agencies contained in **Tornado: A Report** (Alberta Public Safety Services, 1990). Information gained from a meeting with Greg Smith, an employee of the Occupational Health and Safety branch of the Department of Labour, Government of Alberta, was also helpful for developing the descriptions. He had experience with search and rescue procedures for mine disasters and, thus, was given the task of coordinating the search and rescue teams which rummaged through the collapsed buildings in the industrial area. He has an impressive set of photographs showing damaged buildings and debris-laden fields, as well as an excellent recollection of the damage he witnessed in the industrial area. The descriptions in Table 1 were developed prior to discovery of the study by Lux (1990). Lux's descriptions of sites E to R were in good agreement with those given in the table.

The descriptions for the sites where the Emergency Response Team or dangerous goods inspectors responded to reports of hazardous waste spills (sites D, F, G, J, K, N, and T) were, to a considerable degree, derived from a chapter in **Tornado: A Report**, but the locations of Tiger Chemicals and Pounder Emulsions shown in that report were incorrect; they have been plotted at their appropriate locations in Fig. 5. At site D, several Canadian National Railways (CNR) boxcars and tank cars derailed; at site S, 1 boxcar was toppled. Two employees of CNR provided detailed information about these sites: J. Albert, a yard supervisor, and W. Logozar, a locomotive engineer. Logozar was in the cab of the locomotive at site S. He submitted a completed survey in 1987 (Charlton, 1989).

Some of the events at the Archaeological Centre (site C) were documented in a letter which accompanied a returned survey (Charlton, 1989). To supplement this information, 2 employees responsible for the County of Strathcona's science park in 1994, the warden, Cliff Lacey, and a ranger, Ed Whitelock, were contacted.

The 300 m building enclosing the steel-rolling mill at Stelco Inc. ('I' in Fig. 5 and Table 1) suffered substantial wind damage to its interior and exterior as the tornado passed its east end. It had numerous ventilation louvers, and its east and west doors were open; consequently, the damage was probably not induced by static pressure loss. Apparently, Stelco suffered the greatest financial loss of any business: $12 million damage to equipment and a number of buildings (Webster, 1987).

A modest number of the badly damaged buildings in the industrial area are described in Table 1. (Lux (1990) described the damage to several other buildings in this area.) Annotated black and white photocopies of the colour aerial photographs of the industrial area were made. The name and address of nearly every damaged business shown was written on the copies. These copies were invaluable for quickly identifying buildings of interest and were borrowed by the Edmonton Space and Science Centre for developing their display about the Edmonton tornado.

h. Damage to houses and farm buildings and forest blowdowns

There are 4 locations where symbols for structural damage to wood-frame houses are plotted in Fig. 5: Clareview, where 16 houses lost roofs and some walls, and another house retained only a small section of one wall; Mill Woods, where approximately 10 houses were structurally damaged but did not need to be rebuilt; one rural area of Edmonton (12.8 E, 1.8 N), where 3 houses lost much of their roofs; and another (12.6 E, 0.8 N), where one house was structurally damaged. Many of the badly damaged houses were modern two-storey buildings (Lux, 1990). No media reports about the structural damage at the 2 rural locations were found. On August 1, 1987, Charlton observed the damage to the 3 houses at 12.8 E, 1.8 N while he was exploring the region for evidence of tornado damage. The damage to the house at 12.6 E, 0.8 N was found while examining the air photographs kept by Public Works, City of Edmonton.

Aerial photographs were used to search for destroyed farm buildings; the destruction of a few of these buildings was documented in the newspapers and by Wallace (1987), but most sites shown in Fig. 5 were undocumented.

Forest blowdowns were also located using the aerial photographs. Most undeveloped land in Greater Edmonton has been cleared for farming, but some woodlots have survived. The blowdowns noted in Fig. 5 were levelled stands of trees; the destruction of an isolated pocket of trees was not considered to be a blowdown. The 2 blowdowns in the river valley, near sites A and B, had the feather-like fall pattern typical of a violent downburst of wind, rather than the swirl pattern expected of a suction vortex embedded within the tornado's violent circulation. Patterns of tree falls due to a long-lived tornado were discussed at length by Fujita (1989). He examined aerial photographs depicting the path carved through Teton National Forest in Wyoming by a tornado which struck on July 21, 1987. Brian Smith explained that the short time between this storm and the Edmonton tornado, 10 days, was, to a large degree, the reason why researchers at the University of Chicago never completed their study of the Edmonton tornado.

i. Power line damage

In **Tornado: A Report** (Alberta Public Safety Services, 1990), TransAlta Utilities detailed the magnitude of the damage that they suffered. The tornado toppled 49 steel towers suspending 240 kV lines, 17 steel towers carrying 138 kV lines, and more than 200 wooden power poles. Rebuilding the network of power lines cost $8 million. Figure 5 shows the locations of 2 sections of downed lines: a section, 12 km in length, stretching south from a substation near the oil refineries (shown in Fig. 2) and a 2 km section positioned approximately 100 m east of the row of badly damaged houses in Clareview. On May 31, 1985, Ontario Hydro lost a total of 15 towers at 4 locations along the 117 km path of the Grand Valley-Tottenham tornado in southern Ontario (Gorski, 1985). On 3 occasions in the previous 7 years, tornadoes had destroyed 29, 15, and 7 of Ontario Hydro's towers.

Edmonton Power's main generating station, known as the Clover Bar station and labelled 'P' in Fig. 2, is located in the river valley, approximately 2.5 km south of TransAlta's 2 km section of downed 240 kV transmission towers and 200 m from the path of the tornado. It also lies directly across the river from the outlet of the Kennendale Ravine storm sewer ('B' in Fig. 5). The station is connected to TransAlta's network of 240 kV lines, but the power sent from this site to the residents of Edmonton was unaffected by the loss of these lines. Its power was carried by 72 kV lines which cross the North Saskatchewan River in a tunnel beneath the river. John Mulka, the manager of the station at that time, stated that the plant temporarily lost the use of one of its 2 operating generators after debris struck an insulator. Minor repairs to the plant cost approximately $50,000. The document submitted by Edmonton Power to **Tornado: A Report** does not mention the Clover Bar generating station, but it does describe the company's efforts to restore power to the badly damaged regions of the city, including the devastated Evergreen Mobile Home Park. Few residential areas lost power for a significant period. Thus, most residents with AC-powered radios could receive bulletins as the tornado passed through the region.

j. Other tornadoes in Greater Edmonton

The tracks of 2 small but destructive "spin-off" tornadoes are shown in Fig. 5. Both of these tornadoes occurred while the main tornado travelled one to 2 km to the west. Their existence was not reported until 1995. The southernmost one was mentioned by Wilf Seutter during a conversation about damage caused by the main tornado. Seutter's family watched this small tornado move northward from their acreage, near the start of its path, after it had flattened some trees in their woodlot. Discussions with Seutter prompted a visit to the nearby farm of Stanley Stannard who had 30 m of his barn roof (14.0 E, 6.7 N) blown from over his head. His wife had been watching the main tornado from their house and telephoned him just before the barn roof was removed. The roof came to rest against their house.

The other spin-off tornado apparently formed at 13.1 E, 7.4 N, immediately west of the Maple Ridge Mobile Home Park. Its approach was observed by Rick Scott of Scott Steel Ltd (13.4 E, 7.7 N). This tornado destroyed the company's 45 m by 15 m truss roof and apparently caused a 200 tonne car-ferry deck under construction to hover; it continued moving northward across an open field and then damaged the roofs of Guardian (then Hyalog) Oilfield Services (13.3 E, 8.0 N) and Capital Industrial Sales (13.3 E, 8.2 N). Shortly thereafter, it lifted and passed over an undeveloped region, turned westward, and finally dissipated near the main tornado. The latter stages were witnessed by employees of Blanchard Transport (13.9 E, 8.3 N) and the Shell-Sherwood oil marketing terminal (13.7 E, 9.1 N). This tornado may have caused the local centre of disaster assistance claims (13.3 E, 8.0 N) which lies east of the main tornado path (Fig. 5). This area is known as Elmjay Business Park.

4. SIGHTINGS AND WARNINGS

The Tornado Report in the survey form (Fig. 1b) includes sketches of 5 funnel types: rope, cone, columnar, smoke-like, and multiple. Figure 6 shows the funnel types observed by the respondents as the digits '1' through '5'. Generally, the larger the digit, the more severe the funnel type. The positions of the digits in Fig. 6 accurately depict the positions of the participants when they saw the tornado. After examining the distribution of funnel types shown in Fig. 6, one is likely to pose 2 questions. Firstly, what did observers in west Edmonton really see? Secondly, what tornadic phenomena were reported as multiple funnels, that is, code 5?

a. Observations of funnel clouds other than the Edmonton tornado

All reports of funnel clouds from participants west of 11.0 E were examined in detail. For most of these reports, the times of the observations and the directions from the respondents to the phenomena were determined. In Fig. 6, these directions and times are placed beside the plotted digits, which represent the observed tornado shapes. Most digits without a time or direction arrow are observations consistent with the passing of the main tornado. The city is quite level, and, not surprisingly, people could see the tornado from a distance of several kilometres. Several participants saw the main tornado from positions between 8.0 E and 10.0 E, an average distance of 5 km (3 miles) from the path. One report from the western edge of the

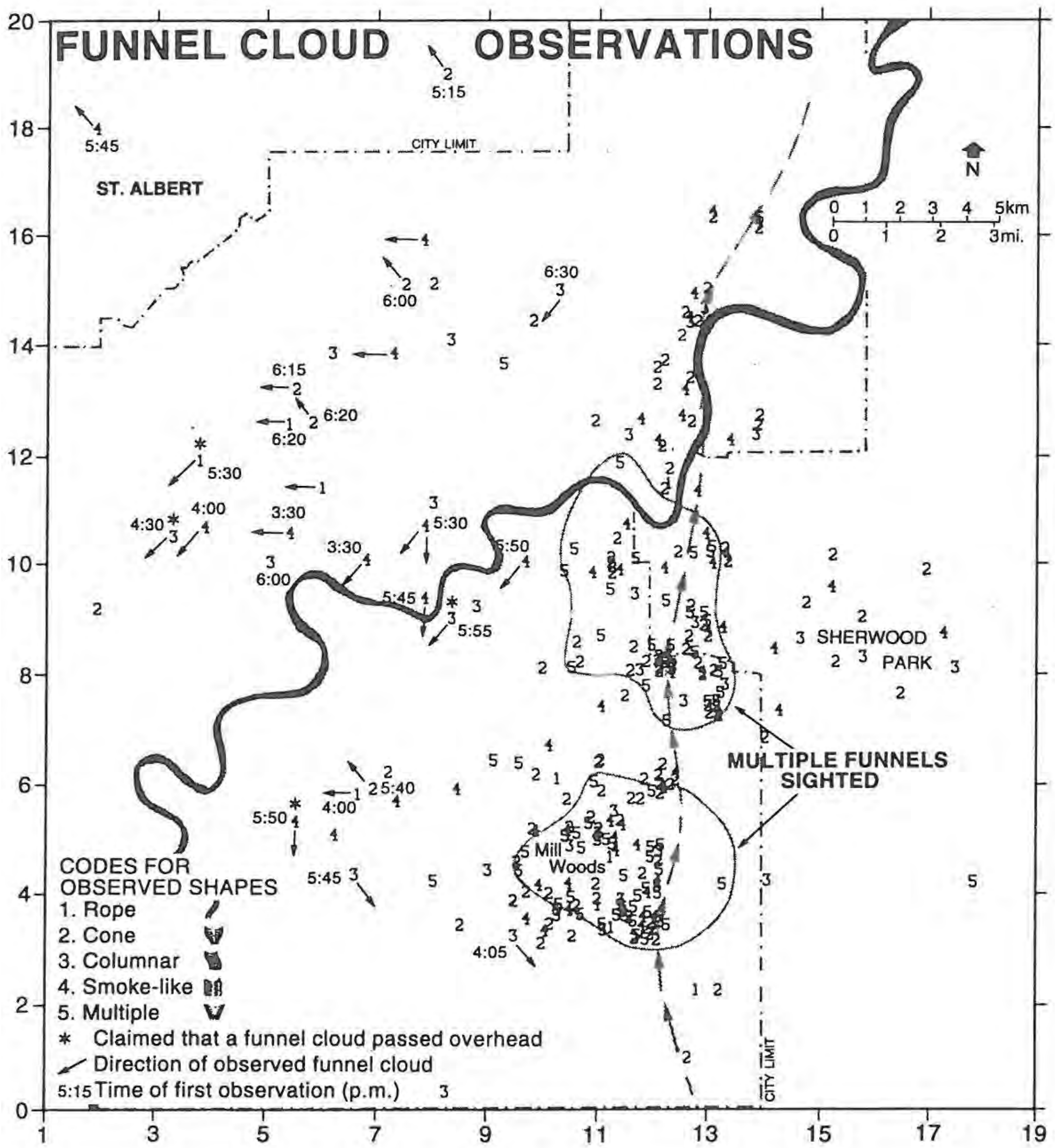


Fig. 6. Funnel cloud observations showing the most severe reported shape. Most plotted shape codes in west Edmonton are accompanied by the time of observation and a direction arrow to show which way the observer was looking when the funnel cloud was seen. No funnel clouds in west Edmonton were seen to touchdown. None of the viewers in east Edmonton reported seeing either of the two "spin-off" tornadoes depicted in Figure 5.

city (1.9 E, 9.1 N) was approximately 16 km from the tornado. This was the most distant observation which could have been a sighting of the main tornado. The ALWC maintained a tornado warning until 1900 MDT, nearly 3 hours after the tornado dissipated. The caution of the ALWC was justified. The last funnel cloud observation by a survey participant was made in north Edmonton (10.1 E, 15.0 N) at 1830 MDT. Citizens were paying great attention to the sky after the tornado had dissipated because accounts of damage and death were being broadcast, and the tornado warning remained in effect. Most of the funnel cloud reports from west Edmonton were clustered around 2 periods: 1600 MDT, roughly the time when the tornado dispersed, and 1800 MDT, about the time when a second storm buffeted west and central Edmonton with hail, rain, and strong winds. None of these observers in west Edmonton, however, claimed to have seen a funnel cloud touchdown, excluding the main tornado. Surprisingly, none of the respondents reported seeing the spin-off tornadoes depicted in Fig. 5, though the Stannards noted the damage done to their barn in their returned survey (Charlton et al., 1989).

The tornado list in **1987 Summer Severe Weather Program** (Alberta Weather Centre, 1984-1995) had 5 entries for July 31: the Edmonton tornado, rated as an F4 on the Fujita Tornado Intensity Scale (Fujita, 1973), a tornado ranked as an F2 that moved through the countryside from south of the city to east of it, and three F0 tornadoes. These F0 tornadoes were spotted to the north, northwest, and southwest of Edmonton, but none was close enough to be seen from the city. Curiously, the only reference to funnel cloud sightings in Greater Edmonton, other than those for the main tornado, is in a single sentence, found on page 41, in the **Hage Report** (Hage, 1987a). The sightings of funnel clouds other than the main tornado, displayed in Fig. 6, are evidence of the severity of the storms in Greater Edmonton during the few hours following the main tornado.

b. Observations of the Edmonton tornado

All but 6 of the sightings of multiple funnels, digit '5', are enclosed by 2 lines in Fig. 6, and within these 2 regions the observations of multiple types outnumber any other funnel type. Respondents might have recorded seeing multiple funnels when they witnessed one or more of a few possible phenomena. For example, they might have seen 2 or more tornadoes, collections of rotating debris and dust, or, most likely for July 31, cloud-like vertical streaks known as suction vortices which, sometimes, circulated around the tornado. Suction vortices were clearly recorded on 2 amateur videos which were incorporated into a widely-distributed video production by the ALWC titled **Edmonton Tornado - July 31, 1987** (Alberta Weather Centre, 1988). The suction vortices were often visible when the tornado was not obscured by rain, debris, or by dense cloud in the funnel. The ground was still damp from the frequent showers in the preceding days; this prevented the wind from raising dust and obscuring the tornado's cloudy features.

Photographs and video tapes were reviewed, and the funnel types that were recorded in these media were compared with the types noted in Atchison (1988), Bullas and Wallace (1987), and Wallace (1987). The photographs and tapes showed that the tornado began as a rope (digit '1'), but occasionally transformed into a narrow cone (digit '2') as it moved toward Mill Woods. The southernmost codes plotted in Fig. 6 agree with these observations. Just before the tornado struck southeast Mill Woods, it was shaped like a cone, and it had numerous suction vortices moving around it. Victor Chung (1988), a Ph. D. candidate at the Department of Earth and Atmospheric Sciences, University of Alberta, used a video recording taken from east-central Mill Woods to estimate the tangential speeds of 2 co-occurring suction vortices; he concluded that these were moving at approximately 68 km/h and 94 km/h. When the tornado battered southeast Mill Woods, it was a massive, well defined but usually featureless rotating column (code '3'), though it might have been described as a broad cone as well. Figures 7 and 8 are 2 previously unpublished photographs taken in southeast Mill Woods (11.9 E, 3.7 N). Figure 7 shows part of a roof being torn from a house, and Fig. 8, taken moments later from a nearby location, shows an enormous column looming over homes near the damaged house. A few moments later the tornado lifted, as depicted by dashed lines in Fig. 6, and moved toward and above an isolated housing development (Larkspur Lake) extending eastward from northeastern Mill Woods. In this region (12.5 E, 5-6 N), spectacular suction vortices were seen revolving around the funnel cloud. Many participants who were in Mill Woods during the tornado's passage claimed that the tornado had more than one shape, but only the digits corresponding to the most severe of these types were plotted in Fig. 6.

At approximately 12.5 E and 6.5 N the tornado descended to ground level again, and, in the shape of a massive cone, it began to ravage the southern part of the industrial area with winds presumably reaching or exceeding 331 km/h, the minimum speed for the F4 category of the Fujita scale. The F scale category was estimated from the types of damage seen in the area (Wallace, 1987). As it moved into the north end of the industrial area (12.5 E, 10 N), the tornado changed to a column. Nonetheless, the shapes reported by respondents throughout the industrial area were predominantly of

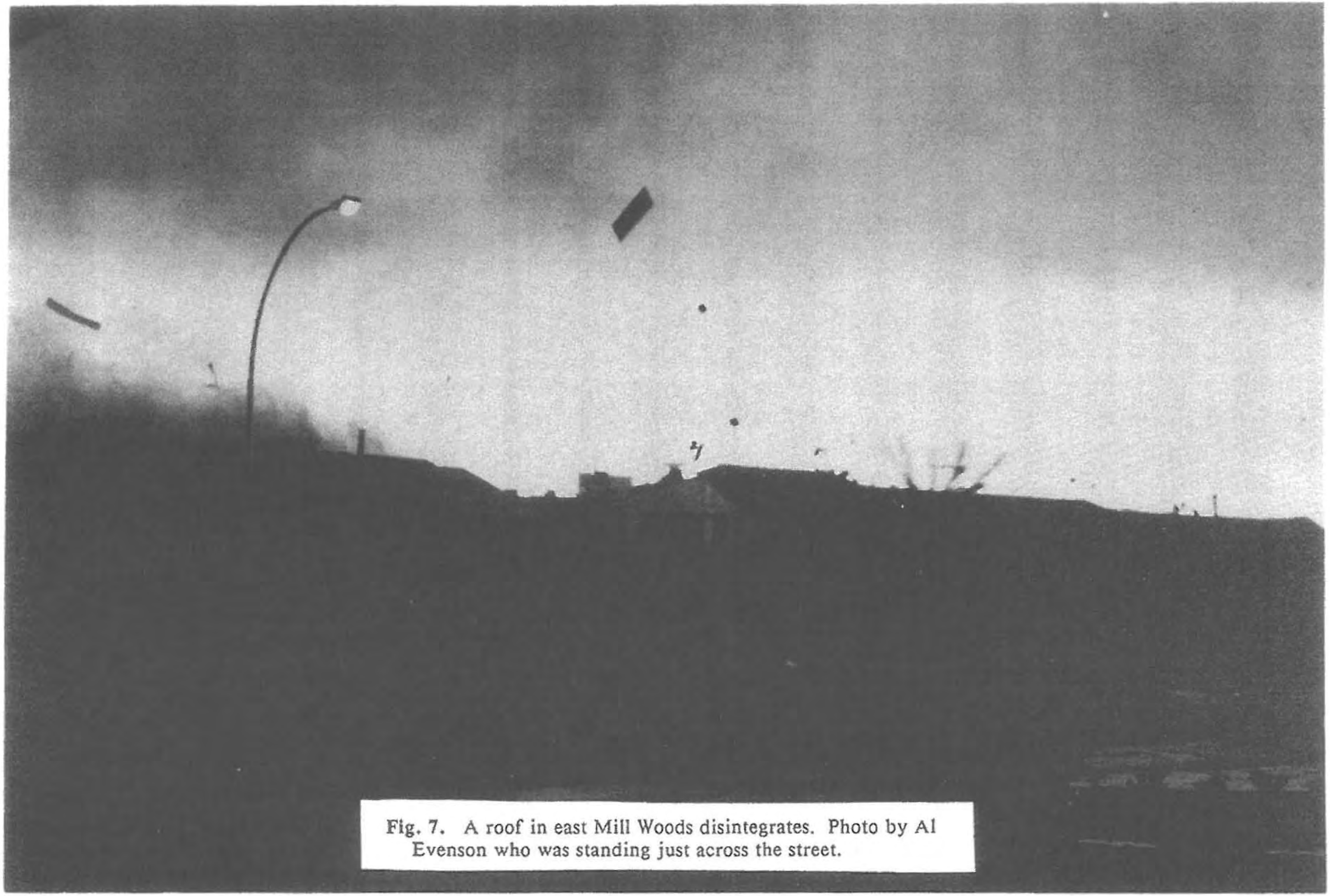


Fig. 7. A roof in east Mill Woods disintegrates. Photo by Al Evenson who was standing just across the street.

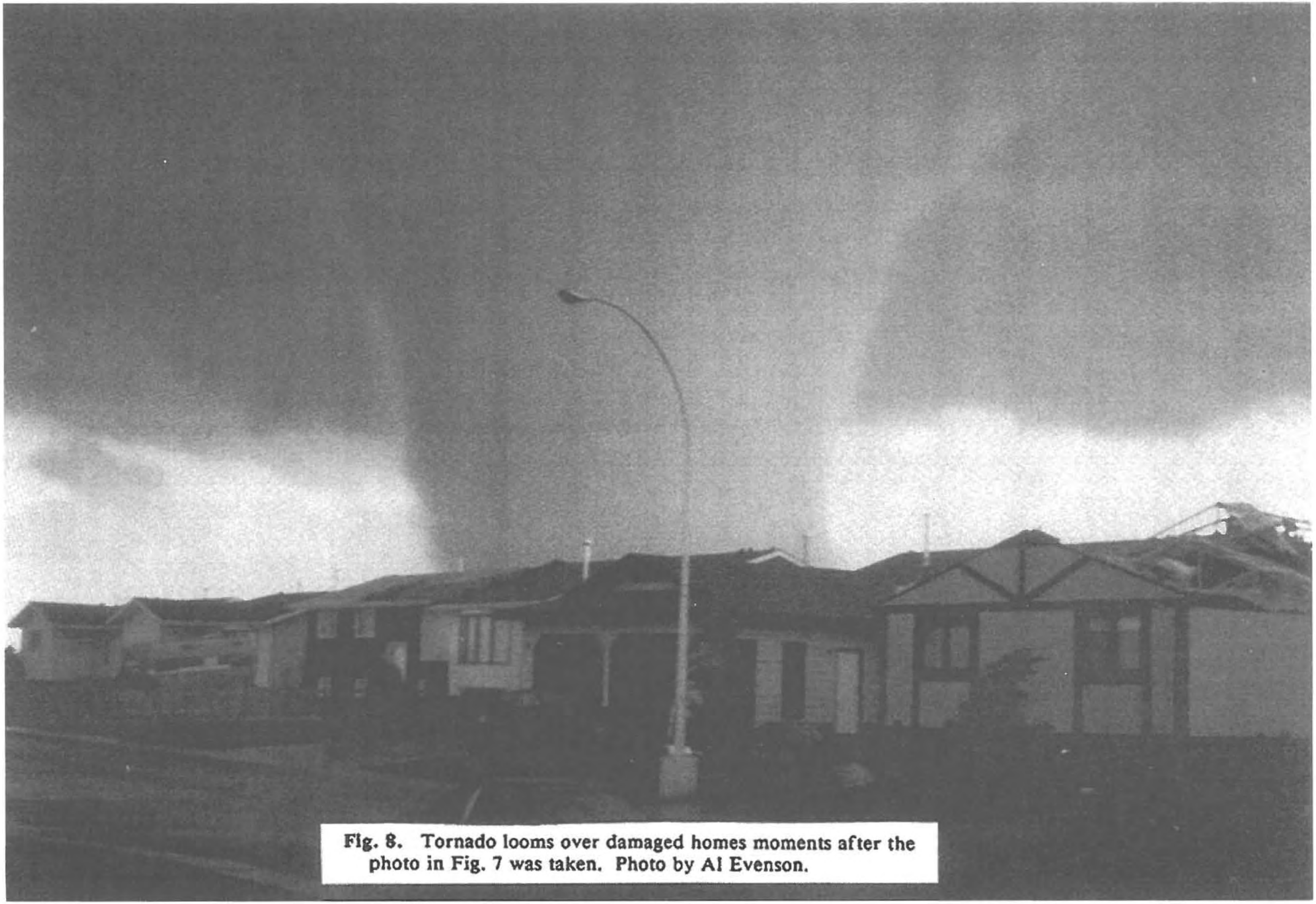


Fig. 8. Tornado looms over damaged homes moments after the photo in Fig. 7 was taken. Photo by Al Evenson.

multiple funnel and cone types, though none of the viewers in Sherwood Park, east of the industrial area, recorded a multiple funnel type. Apparently, the distance to Sherwood Park was too great for people to see detailed tornado structure.

A video recording of the tornado travelling between the Sherwood Park Freeway (8.3 N) and Baseline Road (10.0 N) was taken from the building which houses the ALWC (11.1 E, 9.7 N). The recording showed a tornado which varied between a column and a broad cone shape as it flung debris over a wide area. A study of the video by Chung (1988) determined that the debris was travelling at 144 to 209 km/h as the tornado crossed the Sherwood Park Freeway, a region where the damage to industrial buildings suggested F4 winds. Bluestein and Golden (1993) discussed a variety of methods for observing tornadoes and noted several reasons why wind speeds derived from photogrammetric analysis might lead to an underestimate of maximum wind speed. Lux (1990) estimated that the minimum wind speed required to cause the tumbling of the empty oil tank at the abandoned Texaco refinery (site H in Fig. 5 and in Table 1) was 200 km/h.

Good photographs or video tapes of the tornado when it was immediately south of the river valley, in the river valley, in east Clareview, and approaching Evergreen were difficult to find. This was usually attributed to increasingly heavy rainfall, confirmed by, for example, viewers located at the ALWC building. Figure 3, discussed in Section 2, was one of a set of photographs taken from north of the river, apparently just before the heavy rain began. Figure 6 shows many reports of a smoke-like tornado (digit '4') from both east and west of the river between 12 N and Evergreen (16 N). These reports suggested that the tornado's approach was indeed obscured by rain during its latter stages. Just 2 reports of multiple funnels were received from observers north of the North Saskatchewan River. Meteorologists from the ALWC found but one pair of photographs of the tornado as it entered Evergreen. This two-exposure panorama reveals an enormous wall of diffuse cloud, but not a distinct tornado. Good photographs of the Edmonton tornado, taken before it crossed the river, were included in Atchison (1988) and in 2 memorial booklets: **Black Friday** by Davidson and Diotte (1987) of the Edmonton Sun, and **Tornado '87** by The Graphic Edge (1987). **Black Friday** has been updated by Diotte (1997).

The various shapes of the Edmonton tornado, documented in previous studies, photographs, and video tapes, were also reflected in the responses to the survey. Several participants decided that none of the 5 funnel types shown on the survey was an accurate representation of their sightings; rather than choosing the closest shape categories, they drew sketches of the tornado.

c. Warning times from various surveys

Respondents to the newspaper survey were asked to denote the types of severe weather that they encountered and to estimate the amounts of warning time, in minutes, that they received. Charlton believed that analysis of their warning times should provide insight into the efficiency of the severe-weather-warning system and, thus, assist the federal review team chaired by K. D. Hage. The team's findings are commonly called the **Hage Report** (Hage, 1987a). Preliminary analysis given to Hage by Charlton showed that almost 50% of respondents claimed that they had 0 minutes warning of the severe weather they encountered, and 20% claimed that they had more than 15 minutes warning. After further examination, however, Charlton concluded that attitudes toward agencies empowered to protect the citizenry, particularly the ALWC, varied widely among participants. An analysis employing warning times from only those respondents who had witnessed the tornado should be more reliable: Carter et al. (1989a) found that victims of the May 31, 1985 tornadoes in Ontario had "vivid recollection and detailed knowledge of circumstances even months after the event".

Figure 9 is a map of the warning times and locations of respondents who saw a tornado or funnel cloud. These times vary greatly, even those from the same neighbourhoods. The recorded warning times probably represented one of 3 intervals: warning to sighting of the tornado, warning to experiencing the tornadic winds, or sighting to experiencing the tornadic winds. As noted earlier, most tornado and funnel cloud reports west of 8 E were not observations of the Edmonton tornado; consequently, the warning times from these reports were not analyzed. Of the 212 participants located east of 8 E who saw the tornado, 62% had some warning time, and 25% received a warning broadcast by radio or television.

Warnings broadcast before the tornado dissipated came from one of the 4 television stations and an undetermined number (at least 6) of the 15 radio stations serving Edmonton (Hage, 1987a). Hage also provided the times when 14 of the 19 broadcasters first received notifications of the tornado; 13 of these 14 broadcasters learned about the tornado in the first 30 minutes of its existence. This left an ample amount of time to warn most of the city. Nonetheless, many of these 13 broadcasters were slow to report the existence of the tornado to their audiences. Hage (1987a) did not discuss the reasons for this discrepancy. Many of the newspaper survey respondents complained that the stations they were

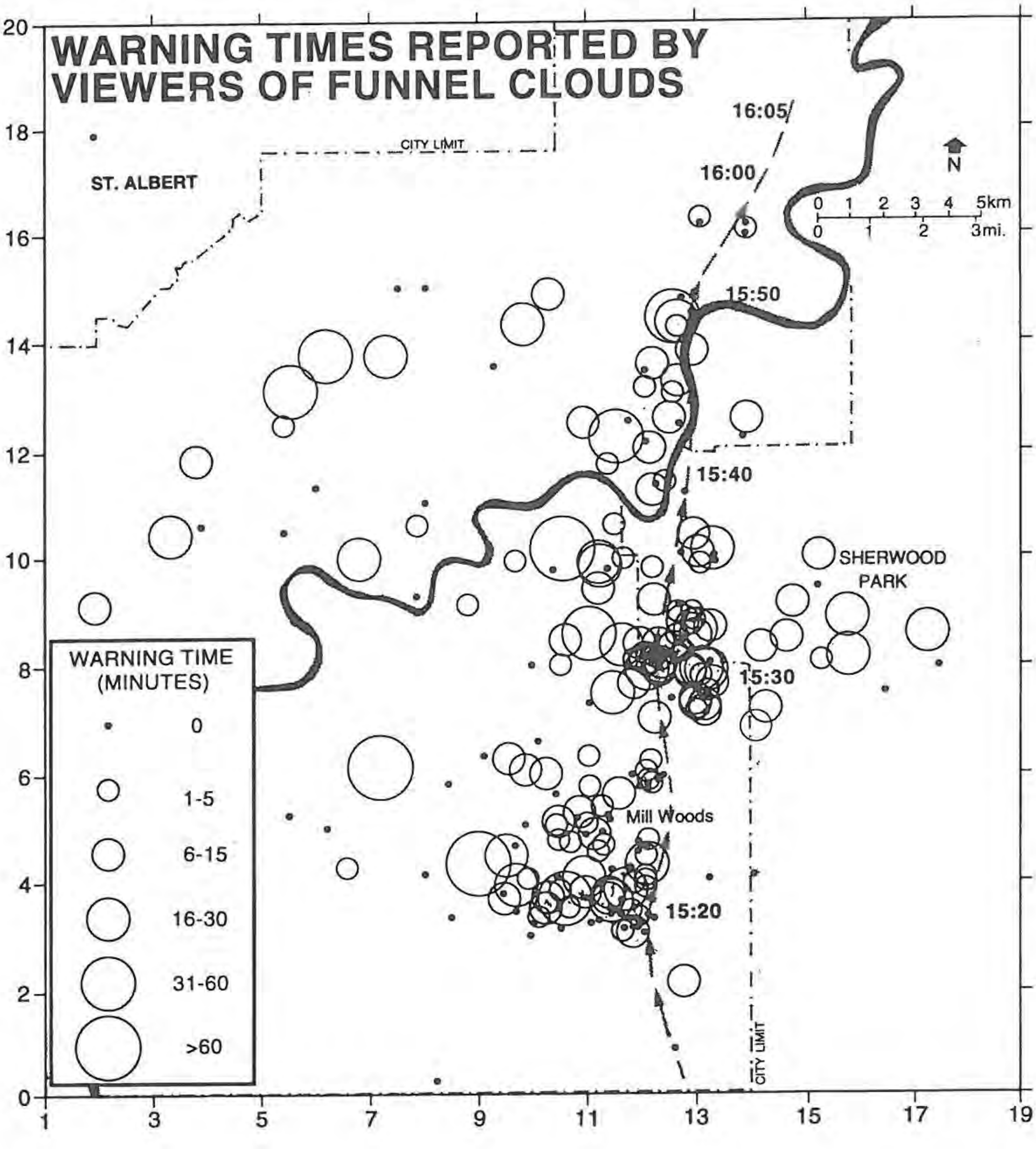


Fig. 9. This map suggests that there was no obvious increase in warning times along the tornado path. More than 45 minutes after the tornado had first touched down, 40 percent of viewers near the tornado reported having had no warning.

patronizing did not notify them of the tornado until it had passed their neighbourhoods; numerous participants protested that some stations maintained regular programming throughout the lifetime of the tornado.

Results from a telephone survey conducted 6 weeks after the tornado (Hage, 1987a) indicated that 80 of the 100 people surveyed in east Edmonton had been aware of the approaching tornado, and that 42% had been warned via radio or television. The question about broadcast warnings in the telephone survey, like that in the newspaper survey, did not differentiate between warnings carried by radio and warnings carried by television.

Sixteen months after the tornado, Caine (1989) interviewed 77 people from Evergreen and 48 people from east Clareview to assess their recoveries from the disaster. Of the 125 people surveyed (97% owned their own homes), 65 claimed to have been in the path of the tornado, 110 had some property damage, and 52 suffered over 25000 dollars of damage. When asked "Did you get any warning of the tornado?", just 17 of the 125 respondents replied "Yes"; therefore, 86% of the 125 respondents were not aware that the tornado was approaching their homes. The 17 people who were forewarned were asked "How were you warned?" and given a choice of answers: 7 saw the approaching tornado, 10 were warned by friends including some by telephone calls, and just 3 heard a warning carried by the radio. The 108 people who had no warning were not asked whether they had a radio or television turned on during the tornado's lifetime.

Hage (1987a) conducted an on-site survey between August 10 and September 20. He interviewed both staff and managers from 18 industries struck by the tornado. At least 9 managers believed that their employees had been forewarned, including 2 who mentioned receiving warnings by radio.

The findings of these 4 surveys are shown in Table 2. The percentages of respondents who were forewarned varied greatly, 14% to 80%. Similarly, the percentages of respondents who were forewarned by a radio or television broadcast ranged widely, 2% to 42%. These values yield no firm conclusions about warning times or the effectiveness of the electronic media in disseminating the warnings.

d. Warning times from epidemiological studies

Table 2 also gives information about warning times taken from 3 epidemiological studies of tornadic events: the Edmonton tornado (Carter et al., 1989b), the tornadoes in southern Ontario on May 31, 1985 (Carter et al., 1989a), and the tornadoes in Alabama and Georgia on March 27, 1994 (Schmidlin and King, 1995). The study by Schmidlin and King (1995) placed greater emphasis on determining perceived warning times than did the other 2 epidemiological studies, and, thus, it is likely to be of greater interest to most meteorologists. One week after the tornadoes passed through rural areas of Alabama and Georgia, Schmidlin and King drove through the affected areas. They were attempting to contact anyone who had been injured, slightly or seriously, or could describe the circumstances pertinent to someone who was no longer capable of responding because of serious injury or death. Schmidlin and King asked the same set of questions used by Carter et al. (1989a). The epidemiological studies emphasized the cause and type of injuries experienced by their respective participants. For deceased respondents, the causes of deaths were determined by the appropriate medical authorities.

The dissemination of weather warnings to the public varied considerably among the 3 regions discussed in the epidemiological studies. Carter et al. (1989b) believed, incorrectly, that no warnings were carried on television before the Edmonton tornado dissipated (see Table 2). For analysis of radio warnings they referred their readers to Hage (1987a) who, in addition to other information, reported that a popular Edmonton radio station, CJCA, broadcast their first tornado warning at 1513 MDT, approximately 7 minutes before the tornado reached the southeast corner of Mill Woods. In Ontario, power failures terminated the broadcasts of local radio and television stations serving the region traversed by the tornadoes (Carter et al., 1989a; Allen, 1986). As expected, Carter et al. found that none of their participants in Ontario received a broadcast tornado warning. During a conversation, Carter suggested that telephone service in the region was also disrupted. For Alabama and Georgia, the National Weather Service issued tornado warnings for 11 of the 12 counties that tornadoes passed through; these were issued typically 10 to 20 minutes before the first deaths (Schmidlin and King, 1995). Nevertheless, Schmidlin and King (1995) stated that many of the people who lived in rural areas claimed that they did not receive a broadcast warning. Still, 29% of survivors received a broadcast tornado warning, a slightly higher value than was found for tornado viewers in east Edmonton (25%). If Schmidlin and King had included uninjured persons in their survey, the percentage of interviewees who received a broadcast warning would probably be larger, though interviewing only those people who were at least slightly injured ensured that all participants had been near the tornado.

Table 2. Frequency of forewarning as determined by various surveys.

	Type of Survey				Epidemiological Studies		
	Newspaper	**Telephone**	**Recovery**	**Industrial**	**Edmonton**	**Ontario '85**	**Alabama-Georgia '94**
No. of respondents	212	100	125	18	189	163	51
Author	Charlton et al.	Hage (Criterion)	Caine	Hage	Carter et al.	Carter et al.	Schmidlin and King
Location and conditions	E. Edmonton Tornado viewers	E. Edmonton. At home on day of tornado	Clareview and Evergreen. Homes in or near the tornado path	E. Edmonton. Industries struck by the tornado	Fatalities and injured in Evergreen and at industries	Fatalities, injured and uninjured at three damaged areas	Fatalities and injured in rural areas
Time conducted after tornado	1 week	6 weeks	70 weeks	2 to 7 weeks	40 weeks	17 weeks	1 week
Forewarned	62%	80%	14%	±50%	75-80%	77% 9% > 1 min	90% of survivors
Forewarned in part by radio or TV	25%	42%	2%	11%	Not recorded for radio. Zero % for TV	Zero %	29% of survivors

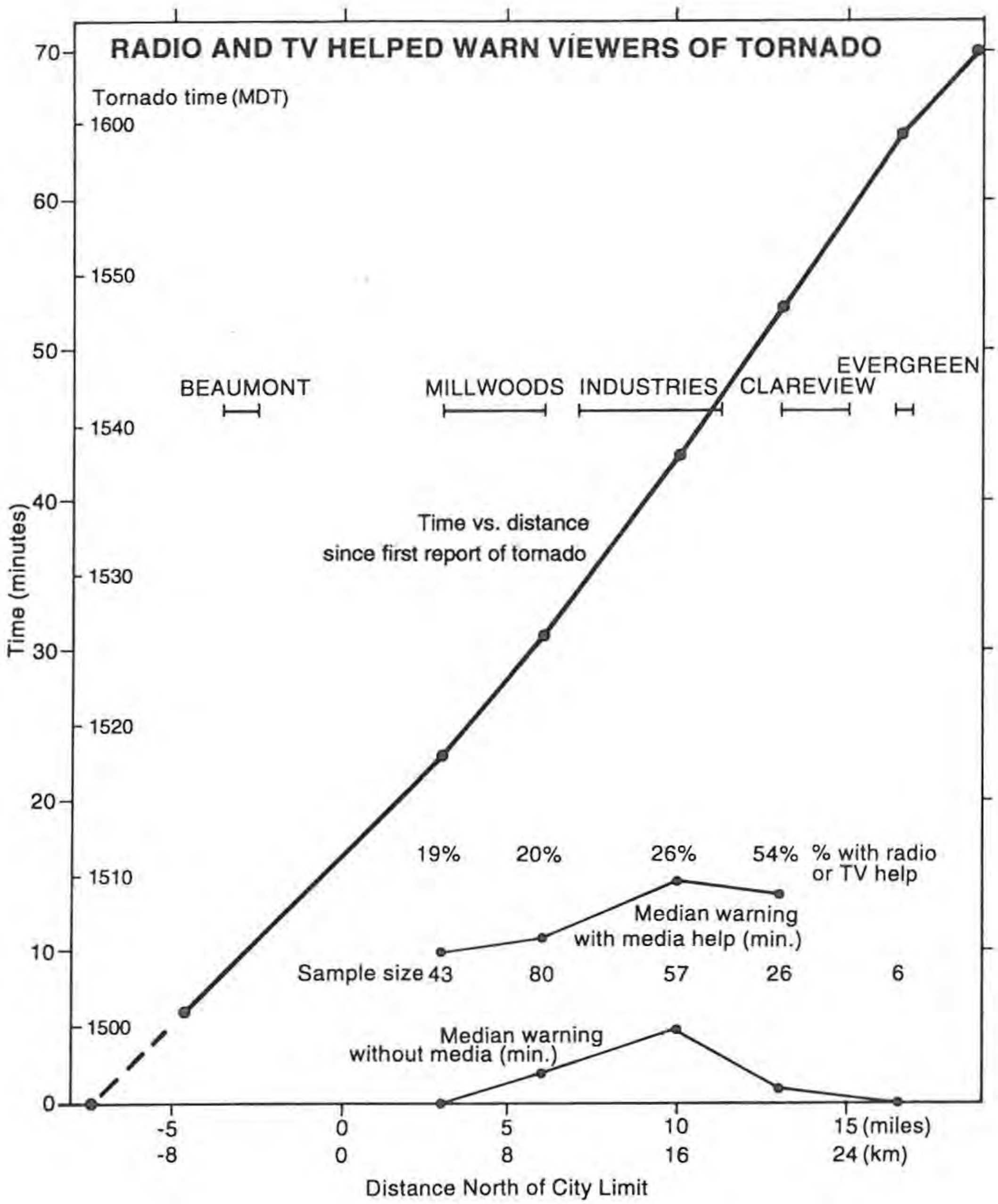
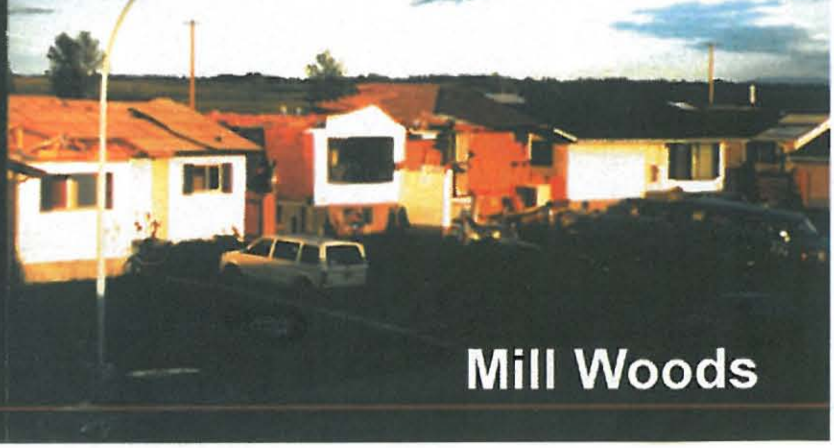


Fig. 10. Straightness of the bold diagonal time-distance line suggests that the tornado speed was nearly constant. Listed percentages indicate that by the time the tornado reached Clareview, 54 percent of viewers had been warned by reports on radio or TV. Median warning times for viewers east of mile 9 are depicted by separate lines for those with radio or TV assistance and for those without media help. The increase in warning time attributable to radio or TV reports is represented by the space between these 2 lines. It appears to have remained constant at 10 minutes, independent of the increasing age of the tornado. Sample size, listed in the figure, however, was small, and the scatter of reported warning times for each community defied more detailed analysis.


Residential
Areas
Only Photos From Evergreen - by M. Murray


Two days before

Clareview


Mill Woods

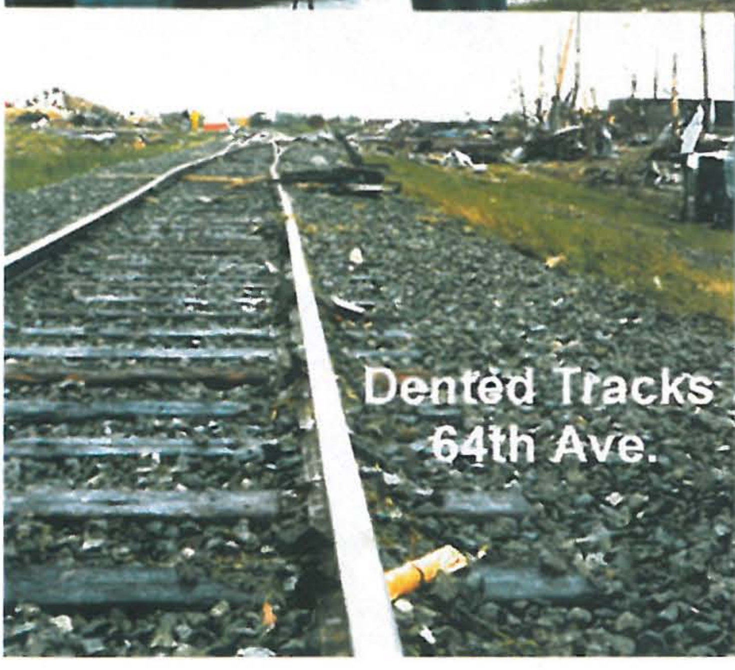
Marianne with a V8

Industrial Damage

Kennedale Sewer

Weatherman Comments

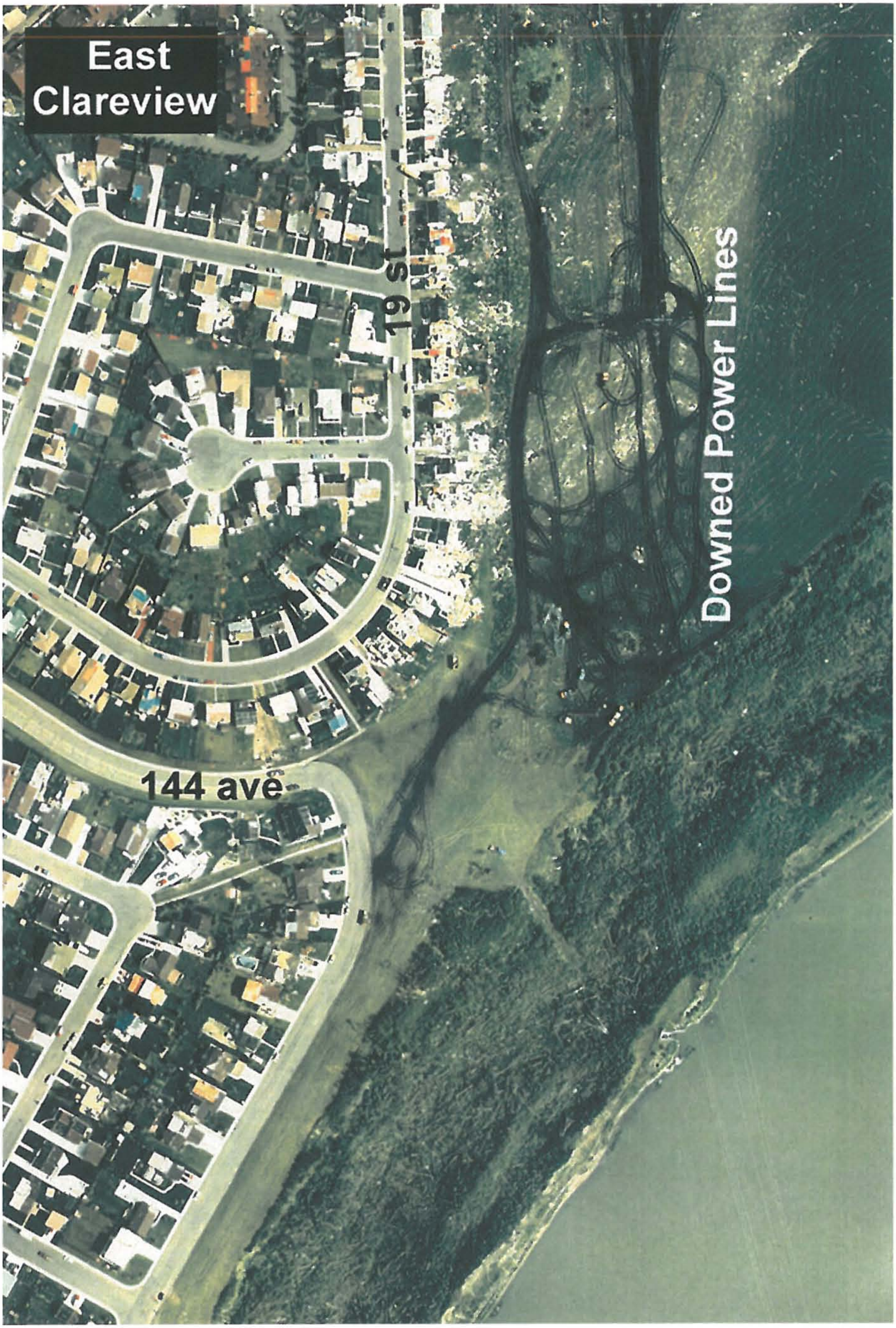
Reinforced Concrete Blocks
Near Sherwood Pk. Freeway



Dented Tracks
64th Ave.

Texaco Tank at
Baseline Rd.


Near Baseline Rd
(101 ave)
Everall Const.
Baseline Rd. (101 ave)
Texaco
CNR
Alberta Truss
CPR
Railway St.


East Clareview
19 St
144 ave
Downed Power Lines

e. Warning times and respondents' positions

A deeper analysis of the information about warning times gathered from the newspaper survey is displayed in Fig. 10. The 212 tornado viewers east of 8 E (Table 2) were divided into 5 groups representative of their northwards positions. Because of the small number of respondents in far-north Edmonton, the 5 groups were not allocated an equal number of participants. Each group was subdivided into 2 categories: those with television or radio assistance, and those without. Figure 10 shows that these 5 groups, from south to north, had 43, 80, 57, 26, and 6 people, and the percentages of these who received a warning via radio or television were 19, 20, 26, 54, and 0%, respectively. Thus, with the exception of the 6 respondents from Evergreen, participants in north Edmonton were more likely to receive a warning by radio or television than those south of the river. The median warning times for both categories of each group are shown graphically in Fig. 10. Median warning times were typically 10 minutes greater for those who were warned by broadcast media than those who did not receive such a warning. Median warning times for both categories increased gradually with time until the tornado approached Clareview, where it became obscured by rain; here, the warning time for those without media assistance declined precipitously to approximately one minute.

The heavy solid line in Fig. 10 depicts the tornado's location against the elapsed time since the first touchdown. It also represents the maximum possible warning times as one moves northwards, excluding the possibility of a respondent interpreting a forecast of severe weather as a tornado warning. The funnel cloud was first sighted at 1455 MDT near Leduc by Tom Taylor. He saw it touchdown for a period of 10 seconds and then promptly telephoned the ALWC (Environment Canada, 1987). The data given in Fig. 10 show that median warning times for both categories failed to increase in proportion to the growth in maximum possible warning times; nevertheless, radio and television broadcasts appear to have provided approximately 10 additional minutes of warning, and the proportion of citizens who were warned by radio or television apparently increased as the tornado travelled northward. This analysis of intra-city warning times seems to be unique for the literature about tornadoes.

5. THE GREATEST HAILSTORM

Charlton et al. (1995) argued that the hail which accompanied the Edmonton tornado was unprecedented in Canada, and that the swath of giant hail they described was better documented than hail swaths from any other urban storm. Giant hailstones of various shapes and opacities, collected and photographed by M. Madsen in south-central Mill Woods (10.3 E, 3.0 N), are shown in Fig. 11.

The times when hail commenced in Greater Edmonton, as recorded by respondents to the newspaper survey, were plotted on a map (not included). Hail from the tornadic storm fell on virtually all of east and central Edmonton sometime between 1500 and 1600 MDT. Some regions of west Edmonton were also hit by hail during this period. The estimates of hail commencement times also delineated the second thunderstorm, which traversed Greater Edmonton between 1730 and 1800 MDT, bringing hail to St. Albert, west Edmonton, and central Edmonton. The funnel cloud sightings associated with this second thunderstorm were discussed in Section 4, and the wind damage attributed to this storm will be revealed in Section 6.

a. The hail swath in Edmonton and comparisons with the 1991 Calgary storm

Figure 12 is an updated map showing the size category of the largest hailstone reported by each participant who completed the Hail Report in the survey. The categories, plotted as numbers 1 through 7, were denoted by the names of common objects. The minimum accepted dimensions for the categories were established by Charlton et al. (1995): 1 (Shot) 0.2 cm; 2 (Pea) 0.5 cm; 3 (Grape) 1.2 cm; 4 (Walnut) 2.1 cm; 5 (Golfball) 3.3 cm; 6 (Tennis ball) 5.2 cm; 7 (Larger) 7.8 cm. The diameter of a standard golfball is 4.4 cm, for a tennis ball, 6.4 cm. Of the 755 respondents within the area of the maps, 638 provided a maximum hail-size category. Shown in Fig. 12, the boundaries of walnut-, golfball-, and tennis ball hail enclose local areas in which at least one half of all hailstone reports were for those categories or larger categories; for example, at least 50% of the digits plotted within all sectors of the tennis ball boundary are '6' or '7'.

The areas of the regions within the boundaries and the areas of residential housing (see Fig. 2) in these regions were determined: for walnut, 92 km^2 including 36 km^2 of residential area; for golfball, 53 and 18 km^2; for tennis ball, 125 and 57 km^2. Therefore, the total area of large hail, that is, walnut-size or larger, was 270 km^2. Of this,

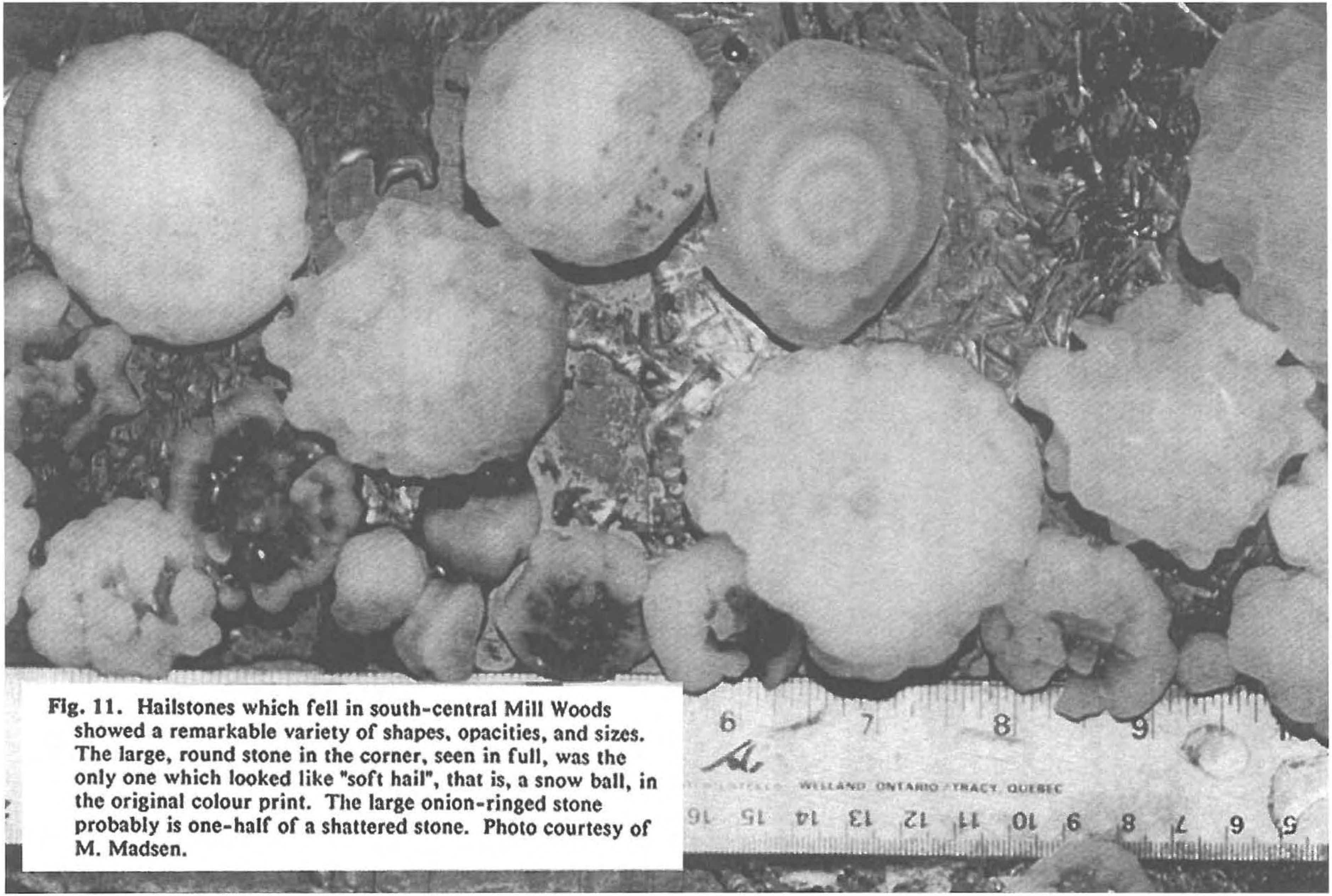


Fig. 11. Hailstones which fell in south-central Mill Woods showed a remarkable variety of shapes, opacities, and sizes. The large, round stone in the corner, seen in full, was the only one which looked like "soft hail", that is, a snow ball, in the original colour print. The large onion-ringed stone probably is one-half of a shattered stone. Photo courtesy of M. Madsen.

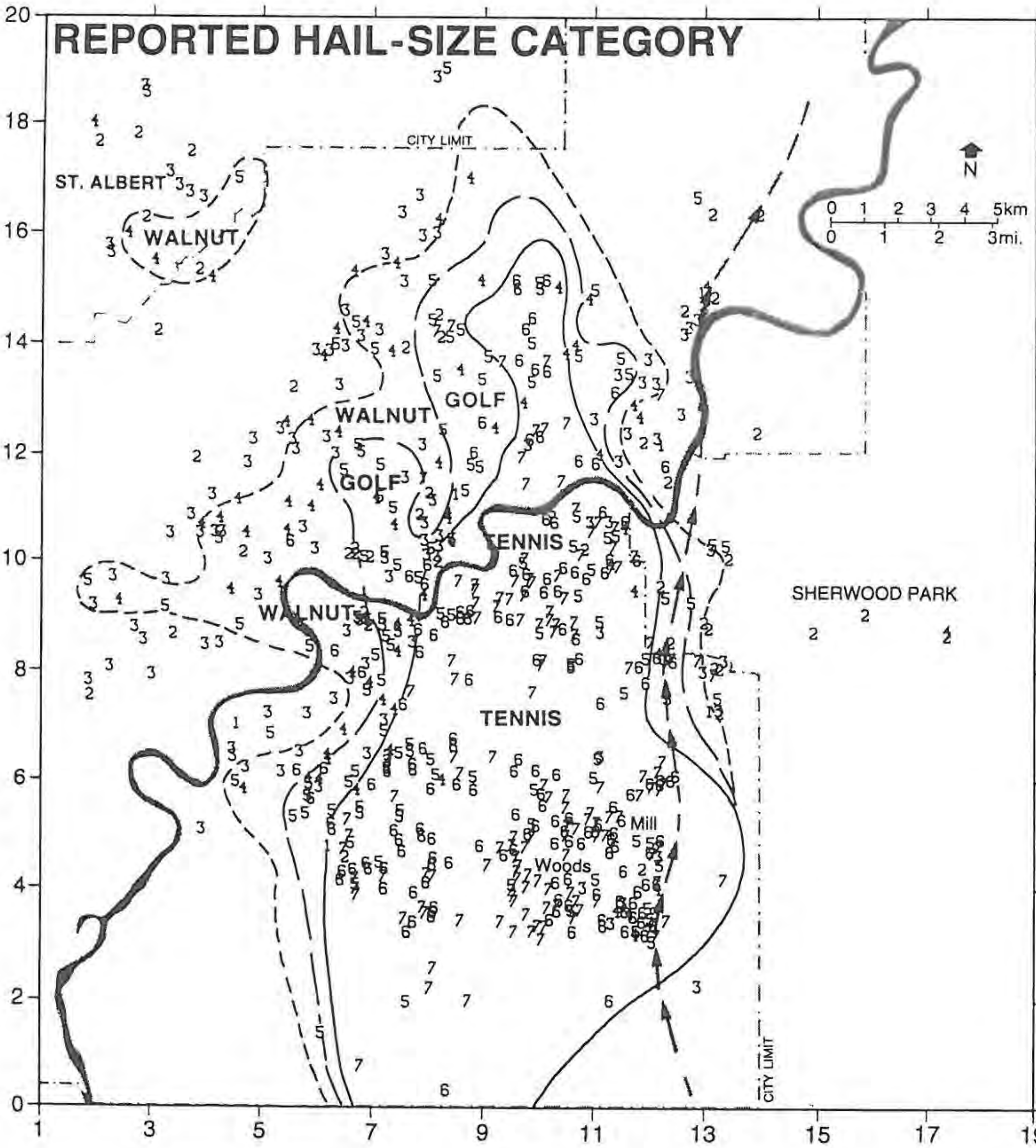


Fig. 12. Map showing maximum hail size reported by 638 respondents to the survey and the path of the Edmonton tornado. Plotted numbers 1 through 7 represent shot, pea, grape, walnut, golfball, tennis ball, and larger than tennis ball, respectively. The boundaries of regions where, locally, most hail size reports were for walnut or larger, golfball or larger, and tennis ball or larger are shown by short-dashed, long-dashed, and solid lines, respectively. The tornado path is shown by arrows where it was severe and by dashes where it was weak.

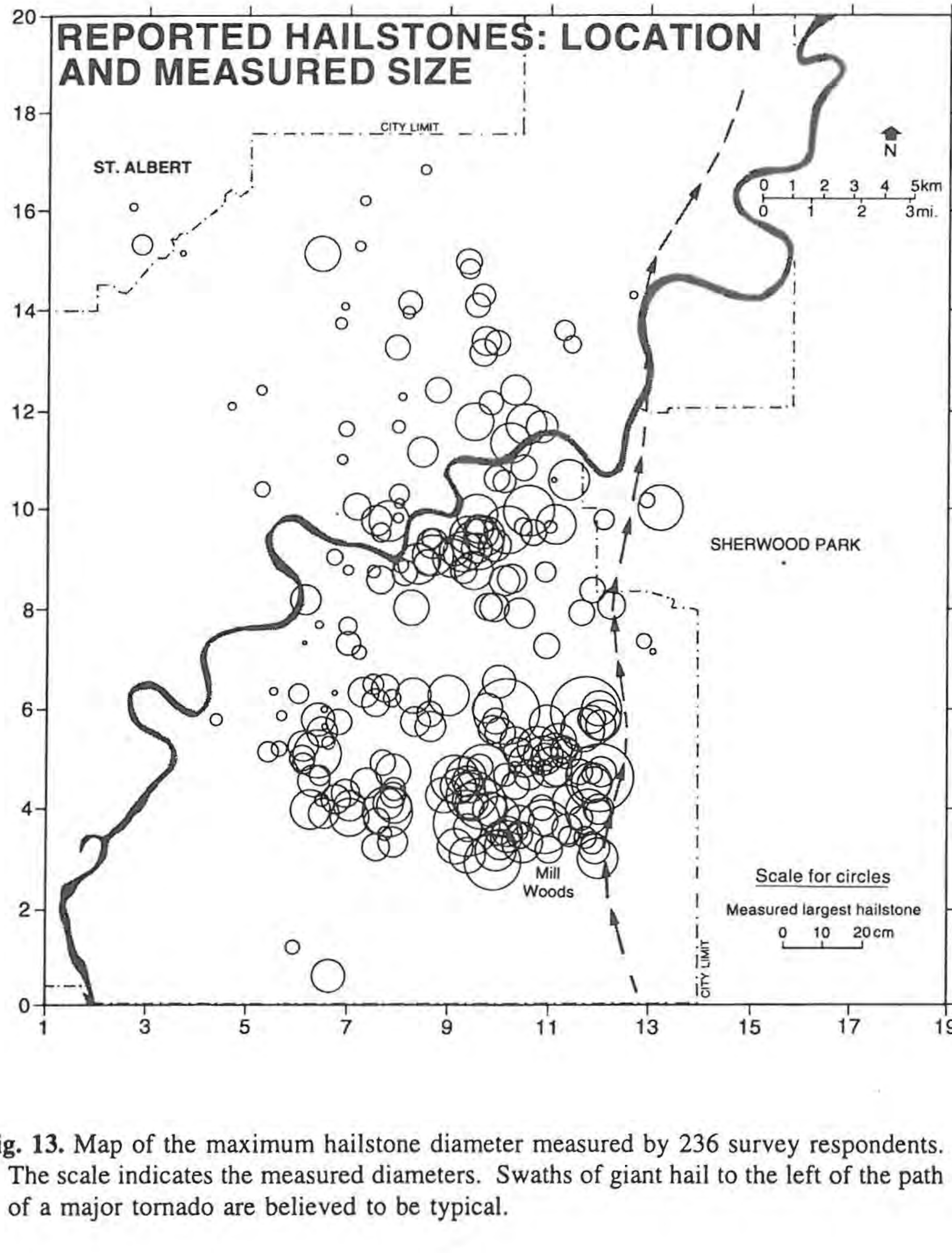


Fig. 13. Map of the maximum hailstone diameter measured by 236 survey respondents. The scale indicates the measured diameters. Swaths of giant hail to the left of the path of a major tornado are believed to be typical.

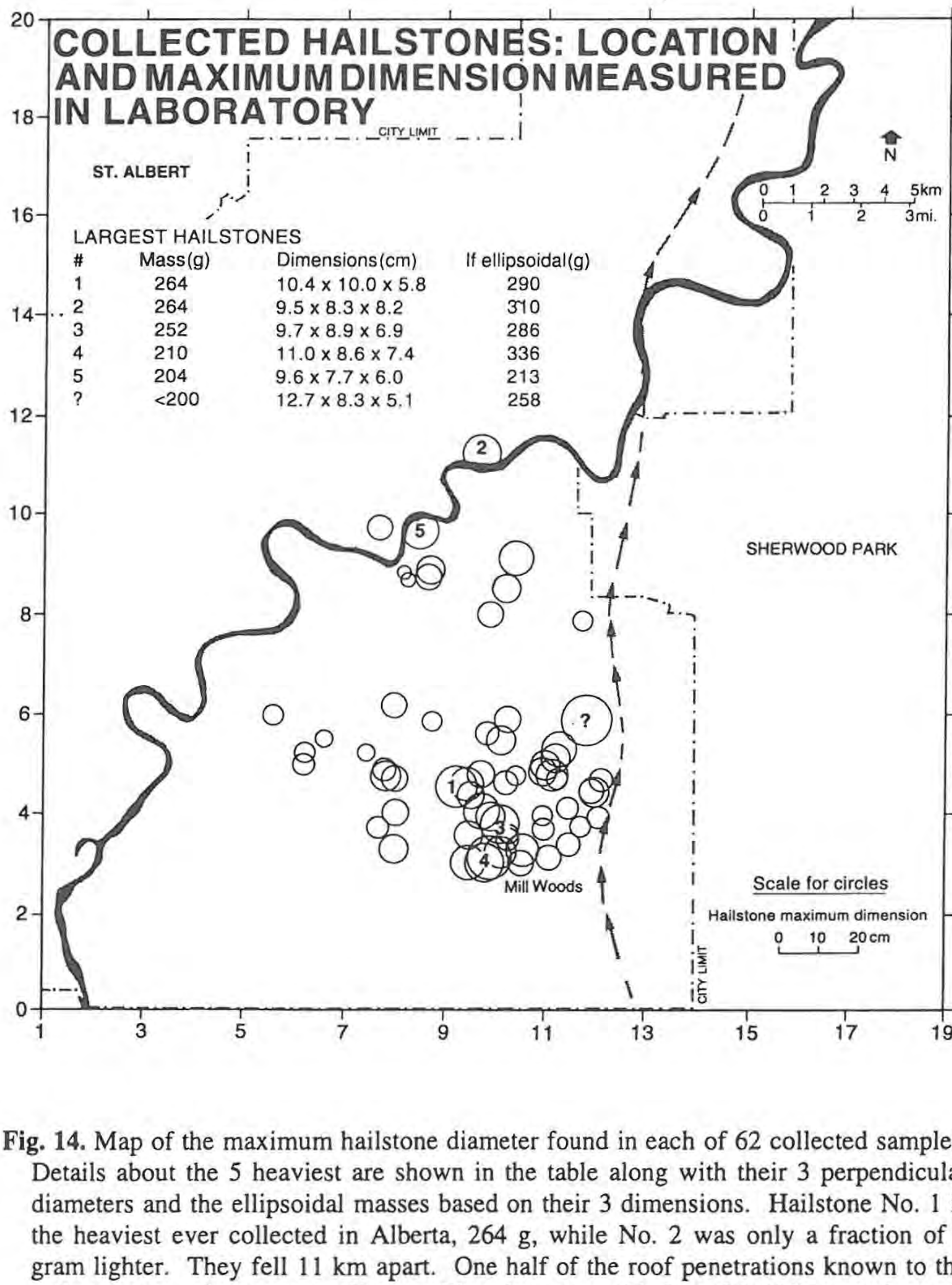


Fig. 14. Map of the maximum hailstone diameter found in each of 62 collected samples. Details about the 5 heaviest are shown in the table along with their 3 perpendicular diameters and the ellipsoidal masses based on their 3 dimensions. Hailstone No. 1 is the heaviest ever collected in Alberta, 264 g, while No. 2 was only a fraction of a gram lighter. They fell 11 km apart. One half of the roof penetrations known to the authors occurred near stone No. 4. The glass pyramid-shaped buildings and exotic plants at the Muttart Conservatory, where stone No. 5 was collected, were badly damaged.

residential zones occupied 111 km^2. In 1987, the residential area of Greater Edmonton (Edmonton, St. Albert, and Sherwood Park) was 169 km^2. Postal delivery information for 1987 (Canada Post, 1987) indicated that there were 154000 houses in Edmonton, and 174000 in Greater Edmonton. (The population of Greater Edmonton was approximately 3% smaller than that of Metro Edmonton, as defined by Statistics Canada.) In this study, the definition of a house includes duplexes and row houses. Alan Wood of the Insurance Bureau of Canada estimated that there were 32000 successful insurance claims made by holders of homeowner policies, and at least five sixths of these claims (27000) were for hail damage. Assuming that the size of a residential area was proportional to the number of houses in it, 66% of all houses in Greater Edmonton lay within the area of large hail, and 44% lay within the area of giant hail, that is, golfball or larger. The area of tennis ball or larger encompassed 34% of all houses. Yet, at the most, just 18% of all Greater Edmonton homeowners (32000 of 174000) made a successful insurance claim.

Policy holders made successful claims for damage caused by the September 7, 1991 hailstorm to 60000 of the 217000 (28%) houses in Calgary (1991 population 714000, 51° 04' N, 114° 04'W, elevation 1080 m). To augment the preliminary claims information provided by the Insurance Bureau of Canada, Charlton et al. (1995) surveyed Calgary residents requesting that participants report their maximum hail sizes and how many of the 4 houses nearest to their houses needed reshinglings. Forty-five of the 60 participants resided within the 130 km^2 damage area, which was later delineated by 2 insurance adjustors who spent a full year assessing claims for damage caused by the storm. Just 3 of these 45 reported tennis-ball-size hailstones, and only one reported larger than tennis ball. Of the other 41 in the damage area, 22 reported golfball, 16 reported walnut, and 3 reported pea or grape. The discrepancy between insurance claim rates for the 1991 Calgary storm, where tennis-ball-size hail was a rarity, and the 1987 Edmonton storm, where it was common, will be discussed in Section 7.

b. Measurements of hailstones

The survey form requested that participants measure their largest hailstones. The largest measurement given by each of the 236 respondents who answered the request are displayed in Fig. 13 as a circle of proportional diameter. Many participants from Mill Woods claimed to measure hailstones with diameters greater than 10 cm.

Hail samples, most consisting of several hailstones, were collected from 63 participants; nearly all of the samples were collected within 3 weeks of the storms. Two exceptional samples were collected after a belated public appeal by Charlton was published by the Edmonton Sun on March 25, 1988. One sample included the Tews hailstone (264 g) which set the Alberta record for hailstone mass, and the other included the Smegal hailstone, which was only a fraction of a gram lighter (a record hailstone is usually named after the person who originally collected it). These 2 hailstones had fallen about 10 km apart and were in good condition when collected from their owners on the same day in the spring of 1988. Tews' experiences while collecting the record hailstone were documented in the Edmonton Journal (Retson, 1994). The previous Alberta record, the Wilson stone (249 g), and the present Canadian record, the Gawel stone (290 g), found near Cedoux, Saskatchewan in 1973, were discussed by Wojtiw and Lozowski (1975).

The maximum dimension of the largest hailstone in each of 62 of the 63 samples is plotted in Fig. 14 as a circle of proportional diameter. One measurement was lost and could not be retaken because the freezer used to store the samples failed and some melting occurred. Time and travel constraints, as well as the modest sizes of hailstones reported by some respondents, restricted the collection of samples to, primarily, south Edmonton. If all 240 available samples had been retrieved, this collection would still be smaller than the more than 300 samples retrieved from Edmonton by the Alberta Hail Project after the August 4, 1969 hailstorm (Rogers and Summers, 1971). The largest hailstone collected at that time was only 104 g (Rogers, 1970). The world's most costly hailstorm occurred in Munich on July 12, 1984, but scientists retrieved hail samples from only 10 locations (Binder, 1985). The literature documenting these urban hailstorms was reviewed in Charlton et al. (1995).

The table in Fig. 14 shows the masses and the 3 orthogonal dimensions of the 5 heaviest hailstones, and those of a large but desiccated hailstone. The participant who collected the desiccated hailstone, labelled '?' in Fig. 14, reported its maximum diameter to be 17.8 cm; but its maximum dimension, when collected by a researcher more than a year later, was 12.7 cm. This hailstone was originally stored in a self-defrost freezer; it subsequently crumbled when it was examined in the laboratory. Its mass, measured at the laboratory, was less than 200 g. The other collected hailstones did not seem to experience similar decreases in mass and structural integrity. For example, 2 well-preserved samples of hailstones that fell on July 31, 1987 were collected in the summer of 1994; these 2 samples are not documented in this study. Examination of the 5 heaviest hailstones, numbered 1 to 5 in Fig. 13, indicated that all were made of solid ice when they fell; that is, none of the 5 were "soft" or "spongy".

The calculated masses of perfect, solid-ice ellipsoids with orthogonal dimensions identical to those of the 5 largest hailstones are shown in the table in Fig. 14. The deficit between a measured mass and its ellipsoidal equivalent suggests the degree to which the hailstone deviates in shape from a simple ellipse. If the largest dimension of a hailstone included a spike or a pronounced lobe, as some of the hailstones shown in Fig. 11 do, the mass of the hailstone would be considerably less than the ellipsoidal mass. None of the 5 heaviest hailstones had identical measured and ellipsoidal masses, but only the mass of hailstone '4' differed radically from its ellipsoidal mass (Fig. 14).

The growth of a hailstone is highly dependent upon its fall speed which is, for a given mass, dependent upon its shape (Charlton and List, 1972; Knight and Knight, 1970). The largest hailstones from the collected samples were, in general, quite smooth. This observation may be useful to researchers testing their numerical cloud models by comparing their results with the hailstones which fell on Edmonton. Such a test has been proposed by H. D. Orville of the Institute of Atmospheric Sciences, South Dakota School of Mines and Technology, Rapid City.

c. Comparison of respondent measurements with laboratory measurements

Fifty of the 63 respondents who provided samples reported measurements of their largest hailstones. They measured their hailstones without assistance from the researchers who subsequently collected their samples. The researchers assumed that the largest hailstones in the samples were the stones measured by the participants and that the participants measured the maximum dimensions. Charlton et al. (1995) included a scatter diagram which compared their measurements with those taken by the participants. One half of the measurements of maximum dimensions by participants were more than 20% larger than those taken in the laboratory. Apparently, many rounded their measurements up to the nearest 0.5 inch (1.27 cm). When that amount was subtracted, agreement with the laboratory measurements was much better.

These 50 respondents, however, were more accurate in categorizing their largest hailstones. Nineteen reported larger-than-tennis-ball hailstones, but 10 had collections which contained no hailstones large enough for that category (7.8 cm), as defined by Charlton et al. (1995). But only one of these 10 respondents failed to submit a hailstone with a maximum dimension larger than the diameter of an actual tennis ball (6.4 cm). Thus, all but one of these 19 were technically correct. Twenty-three reported tennis-ball-size hailstones; just 3 supplied hailstones smaller than the minimum for that category (5.2 cm). Golfball-size hailstones were recorded by 6 participants; all 6 were larger than 3.3 cm, the minimum for the category, but one was larger than 7.8 cm, the minimum for larger-than-tennis-ball. None of these 50 participants claimed that their largest hailstone was walnut sized, the minimum for large hail. Two of these 50 respondents failed to categorize their largest hailstones, although they did provide a measurement. Thus, 43 of the 48 respondents (90%) who categorized their measured hailstones did so correctly. Such accuracy, however, may not be achieved when citizens categorize small hail (shot, pea, or grape). Many meteorologists claim that the public usually overestimates the size of hailstones, but no other study comparing measurements or size categorizations made by the public with measurements taken in a laboratory was found. The **Archive Report** (Charlton et al., 1989) included all measurements taken by the respondents and the researchers.

6. DAMAGE REPORTS

Figure 15 includes a detailed sketch of the path of tornado damage, the hail boundaries from Fig. 12, and coded reports of damage described by survey respondents. This rendition of the path of tornado damage, along with the times when the tornado was at certain locations, was adapted from the field study organized by Wallace (1987). The appropriate Fujita Tornado Intensity Scales (Fujita, 1973), FTIS, determined by ALWC meteorologists (Wallace, 1987), are plotted beside each region of "considerable or greater damage", depicted by dark shading. Fujita (1971) associated each "F number" with a single word describing damage and with a suggested minimum wind speed: F0 (light, 64 km/h), F1 (moderate, 117 km/h), F2 (considerable, 181 km/h), F3 (severe, 253 km/h), F4 (devastating, 331 km/h), F5 (incredible, 418 km/h), F6 (inconceivable, 513 km/h).

a. Damage reported in the field survey

As meteorologists conducted the field study, they used the specific types of damage associated with each F number to classify the damage along the tornado path. For regions with shingle damage or some snapped or uprooted trees, the damage was labelled F1; if roofs were pulled from frame houses but walls remained, mobile homes (trailers) were destroyed, or empty railroad boxcars were pushed on their sides, the damage was categorized as F2;

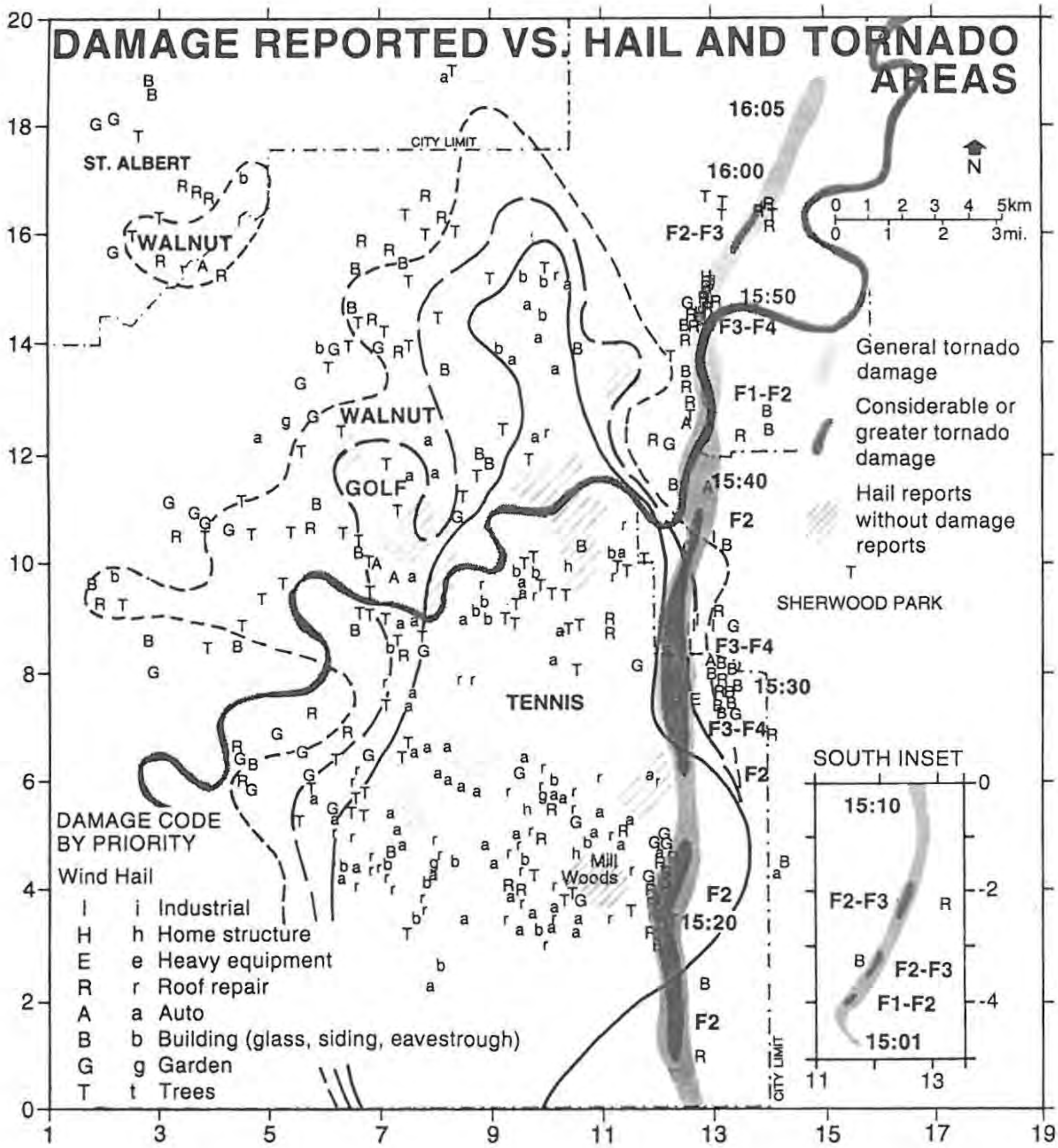


Fig. 15. Damage types reported by survey respondents are compared with the areas depicting hail-size categories, general tornado damage, and considerable or greater tornado damage. The inset map shows the tornado path south of the city limits. Categorization of damage reports was prioritized according to the list of damage codes shown. The cause of damage, wind or hail, is shown with capital or lower case letters, respectively. Predominance of capital letters along the tornado path and lower case letters in the southern half of the tennis ball area illustrate the main areas of wind damage and hail damage. Strong winds in west Edmonton during the evening storm are also confirmed. Fujita's intensity scales and timing of the tornado's progress were taken from the field survey reported in Wallace (1987).

for areas where roofs and some walls were torn from frame houses, trains were overturned, sheathing was torn from steel framed structures, or automobiles were lifted from the ground and rolled, damage was labelled F3; in areas where frame houses were levelled, the steel frames of structures were badly damaged, trees were debarked, or cars or trains were tossed or rolled for sizable distances, damage was ranked F4. No instances were found where frame houses were lifted from their foundations, steel-reinforced pre-stressed concrete buildings were demolished, or automobiles were tossed vast distances like a missile; therefore, none of the damage observed during the field study was ranked F5. Fujita (1971) contained detailed information about the development of the Fujita Tornado Intensity Scale (FTIS): for example, the minimum wind speed needed to produce F1 damage, and thus an F1 tornado, is the same as that needed to upgrade a tropical storm to a hurricane.

Figure 15 includes an inset depicting the 4.8 km damage path south of the city limits, but it does not show the location of the first touchdown, which occurred at 1455 MDT. This time represents 0 minutes in Fig. 10. Wallace (1987) reported that no damage to the fields and trees could be found in the region where the first touchdown was believed to have occurred. Using the average speed of the funnel cloud between the second touchdown and the city limit (0.0 N), the first touchdown was estimated to have occurred 12 km south of the city limit.

b. Damage reported by participants

The responses from the 755 participants within Greater Edmonton were scrutinized for information about damage. Many respondents recorded damage to more than one object. Reports about the damaged objects were organized into 8 groups which, if prioritized, corresponded to the table of damage codes shown in Fig. 15. Opinions about the durability of various structures defined the order of the groups. Thus, all of the damage recorded in each survey form could be represented by a maximum of 8 damage groups, each of which was subdivided by the cause of damage, hail or wind; the group of highest priority for each respondent was the one plotted in Fig. 15: lower case letters were used as symbols to denote hail damage, and capital letters were used for wind damage. For example, the damage report of a respondent who saw branches pulled from trees by wind, an automobile dented by hail, and a house without all or part of its roof would be categorized as 'T', 'a', 'H', but his response would be plotted in Fig. 15 as 'H'. Generally, the more money needed to repair the damage, the higher the priority of the damage. Each damage code in Fig. 15 was plotted at the location where a participant observed his damage of highest priority. The symbols were plotted by hand and, when necessary, shifted from their exact positions to avoid excessive overlapping.

Some of the groups included one type of damaged object, others included many types: structural damage to industrial buildings was classified as "Industrial"; "Home structure" required structural damage to wood-frame houses; "Heavy equipment" denoted the tossing or toppling of automobiles, railway boxcars, or massive industrial equipment; "Roof repair" denoted the removal or denting of shingles or chimneys; "Auto" required that automobiles be damaged but not thrown; "Building" represented non-structural damage to buildings, including broken windows and dented siding, but excluding roof damage; "Garden" included damage to gardens, lawn furniture, lawns, fences, and garbage cans; "Trees" required the loss of tree limbs or branches or the fracturing of trunks, but did not include the loss of twigs or leaves.

When respondents noted damaged objects but failed to give the locations their damage reports were ignored. If a respondent did not mention whether wind or hail caused the damage, it was assumed to have been caused by hail provided that hail of golfball size or larger was reported. Conversely, if the Hail Report (Fig. 1b) was ignored, or deemed not applicable (N/A), or indicated only walnut-size or smaller, the damage was assumed to have been caused by wind.

All industrial damage was caused by wind ('I'), and all lay either in the regions of considerable or greater damage, determined by the field study, or within 0.5 km of these regions (Fig. 15). This damage implied winds of F2 to F4 intensity. Respondents reported structural damage due to wind to 4 houses ('H') in Mill Woods (Fig. 15), where the roofs of at least 9 houses were fully (F2) or partially removed (Tower, 1989). This damage could not be confirmed using the black and white air photographs borrowed from the City or the colour air photographs, which showed only a small portion of the northeastern edge of Mill Woods. Sixteen houses in Clareview had their roofs and, in some instances, parts of their walls removed; another house had even more damage: it was left with only the floor and part of one wall (F3 to F4). The structural damage to these 17 Clareview homes (Lux, 1990) was confirmed by the colour air photographs and by 2 homeowners who responded to the survey. Their 2 'H's are plotted in Fig. 15.

Four respondents knew of roofs that were pierced by hail, but only 3 of them noted the locations; each is plotted as an 'h' in Fig. 15. The records of a roofing firm provided additional examples of roofs pierced by hail; this will be discussed in Section 7. Most of the reports of non-structural roof damage and automobile damage due to hail, plotted as 'r' and 'a', respectively, were confined to the golfball and tennis ball areas. Many respondents who recorded garden and tree damage also recorded higher priority damage types; therefore, garden and tree damage, due to hail and wind, were much more common than is suggested by Fig. 15. The number and distribution of reports of wind damage suggested that strong wind gusts buffeted nearly all of Greater Edmonton.

c. The wind and hail of the evening storm

Numerous reports of wind damage to trees, roofs, gardens, and buildings came from west and northwest Edmonton, as well as St. Albert (Figure 15). The times of occurrence accompanying these reports suggested that a storm traversed this region at approximately 1800 MDT. Weather observations taken at the Municipal and Namao Airports, the locations of which are shown in Fig. 2, attest to the ferocity of the evening storm. At 1800 MDT, the weather observer at the Municipal Airport (7.2 E, 12.0 N) experienced the strongest measured winds of the day, 83 km/h, accompanied by small hail. At 1812 MDT, the strongest winds of the day at the Namao Airport (9.2 E, 18.5 N), 97 km/h, were reported as a squall, that is, a prolonged gust. According to the Beaufort Wind Scale, which states that such speeds are seldom experienced over land, these speeds are sufficient to uproot some trees and cause incidents of structural damage. The speed measured at the Municipal Airport, 83 km/h, was in the range for strong gales but close to the minimum for storms. The speed measured at the Namao Airport, 97 km/h, was in the Beaufort range for storms. A heavy hailstorm and an intense thunderstorm were recorded by the observer at the Namao Airport between 1812 and 1821 MDT, but the size of the hailstones was not recorded. Earlier in the day, as the tornado ravaged northeast Edmonton, 2.5 cm hail had fallen at the Namao Airport, and "marble size" hail had been observed at the Municipal Airport.

The severe winds from the evening storm proceeded north of the Namao Airport and beyond the northern boundary of the figures. This was confirmed by 2 survey respondents. One noted that part of the gymnasium roof of the Sturgeon Composite High School (8.0 E, 22.0 N), located 5 km north of the Namao Airport, was lifted; he also knew of a site 3 km northeast of the high school where more than 100 trees were blown down. The second participant, located 4 km north of the high school, reported experiencing strong winds at 1825 MDT. In the evening, damaging winds were not restricted to west and northwest Edmonton; a survey participant, who was a trained weather observer, reported a "downburst" which flattened a wooden fence at his home (9.8 E, 8.5 N) southeast of the city centre. Although the most intensive rainfall had passed with the tornado, these strong, widespread winds hampered the provision of emergency services (Alberta Public Safety Services, 1990).

Apparently no mention of the damage to the Sturgeon Composite High School was made in the daily newspapers or other literature documenting the storms of July 31, 1987. Confirmation was obtained from Alf Sadae, an operations supervisor with the Sturgeon School Division, who stated that one half of the gymnasium roof lifted and folded over the remaining roof. Repairs were completed on August 3, just 4 days after the tornado. Locations where windstorms had damaged schools in Alberta, and the dates of these events, were found in **Alberta Tornados, Other Destructive Windstorms and Lightning Fatalities, 1879-1984,** by K.D. Hage (1994). In the 106 years before 1985, tornadoes destroyed or badly damaged 11 schools and removed roofs from 6 others; non-tornadic windstorms destroyed or badly damaged 9 schools and removed roofs from 9 others. There were no fatalities at any of these destroyed or damaged schools; nearly all of the incidents occurred in the normal period for summer holidays when the schools would have been unoccupied. The **Annual Summer Severe Weather Reports** from the Alberta Weather Centre (1984-1996) do not have consistently organized summaries of the types or numbers of buildings damaged by windstorms. No incident of school damage was found in these reports. The reference book by Hage (1994) is a valuable and unique source of historical information about damaging windstorms. It confirmed the rarity of the lifting of school roofs by winds in Alberta.

d. Interpretation of the reported damage

As expected, numerous reports of hail damage to automobiles and roofs ('a' and 'r', respectively, in Fig. 15) came from the 2 communities where reshinglings were common (Fig. 5). The areas of cross-hatching in Fig. 15 are regions where numerous respondents observed large hail (see Fig. 12) but did not report any damage. These regions consist principally of light commercial buildings or parkland. Reports of wind damage from east Edmonton and Strathcona County denoted, to a reasonable degree, the path of the tornado; these reports corresponded to local values of the FTIS (Fig. 15) reported by Wallace (1987). Numerous reports of damage in the industrial area, however, came from locations east of Wallace's damage path. The damage path was wider in some places than depicted by Wallace (1987), or the spin-off tornado that passed Maple Ridge (Fig. 2) caused the wreckage east of the damage path.

An informed examination of buildings damaged by a tornado requires some knowledge of both meteorology and structural engineering. Marshall (1993) concluded that variations in the construction of wood-framed buildings might lead to an F scale number with a confidence, at best, of plus or minus one F scale. Grazulis (1993) noted that the FTIS neither discriminates between types of house construction, nor does it define descriptive terms like "destroyed". For example, a tornado that removes the roof of a house is rated F2, but the FTIS does not state the minimum percentage of the roof which must be removed to warrant the F2 rating. Furthermore, Grazulis listed 29 types of property damage which should be attributed to F1 winds but are usually classified F2. Using his criteria, he found that 2567 of 8273 F2-F5 ratings contained in the National Severe Storms Forecast Center's records (1950-1989) should have been rated F1. The destruction of steel-framed buildings is classified as an F4 event (Fujita, 1971), but the annihilation of such structures in the industrial area of east Edmonton and Strathcona County suggested that the anchorage of a building to its foundation and the connection of its components to one another are vital factors in its resistance to wind (Lux, 1990). David Ungstad (see subsection 3g) noted that sections of numerous concrete-block buildings in the industrial area collapsed because the roofs were not adequately connected to the floors through the walls. Moreover, he stated that the quality of the welds joining components in some steel-framed buildings was poor, and, consequently, the welds were not sufficiently strong to prevent winds from twisting these buildings apart. Ungstad also shared his opinions with Barrett (1995), who interviewed him for the Edmonton Journal. Warehouses without internal walls to assist in bracing the building seemed to be particularly vulnerable to the winds of the Edmonton tornado. Perhaps the demolition of steel-framed buildings should not be assumed to be an F4 event.

Tornadoes are often said to 'skip' when some houses in a block are severely damaged while others are nearly unaffected; this pattern of damage is more likely caused by inconsistencies in the quality of the houses (Rosenfeld, 1994) or suction vortices (Fujita and Smith, 1993). A row of 17 houses in Clareview was severely damaged, including one house which was practically levelled. To the east of these houses, approximately 100 m, were some twisted, steel transmission towers, but to the west of these houses, across the street, was a row of houses that, with the exception of a few which lost sections of their roof sheathings, suffered little more than shingle and missile damage (Lux, 1990). Perhaps the difference in wind speeds between the 2 rows of houses was modest, but the wind along the row of badly damaged houses was just strong enough to weaken the houses' structural integrity and cause the loss of roofs and some walls.

The aerial photographs discussed in Section 3 could be used to reevaluate the tornado's path and FTIS values depicted in Fig. 15. This task should employ the recent research compiled in **The Tornado: Its Structure, Dynamics, Prediction and Hazards** (Church et al., 1993) and the techniques for damage evaluation developed by Bunting and Smith (1993) for use by the National Weather Service in the United States.

7. SURVEY OF SHINGLE REPLACEMENTS

The frequencies of shingle replacements in the hail areas depicted in Fig. 12 were investigated. Asking an insurance company for a list of clients who submitted claims for roof damage was considered, but no insurance company was likely to provide this confidential information; consequently, the records of 2 local roofing companies were perused.

a. Motivation for studying reshinglings

Insurance and reinsurance firms are greatly interested in the frequency of severe, and thus costly, urban hailstorms (Armstrong, 1993). For instance, BEP International in Toronto and Sedgwick Payne Insurance Strategy, Inc. in Seattle are involved with in-house hailstorm research programs. The Alberta Severe Weather Management Society, formed by a group of insurance firms operating in Alberta, was created in response to the loss caused by the 1991 Calgary hailstorm. In 1996, the group commenced a 5 year program of cloud seeding near Calgary and Red Deer (Rogers, 1996; Renick and Rogers, 1996). Furthermore, the Insurance Institute for Property Loss Reduction (currently named Institute for Business and Home Safety) in Boston commissioned Underwriters Laboratories Inc. to study the resistance of shingles to impacts (Insurance Institute for Property Loss Reduction, 1995; Laymon and Rhodes, 1995). Haag Engineering Company also tested the impact resistance of roofing products (Haag Engineering Co., 1997), though its experimental design was different than the one used by Underwriters Laboratories. Beginning in 1999, insurers will be required to offer premium credits, to a maximum of 46%, to Texas homeowners who install new roof coverings (Texas Department of Insurance, 1998). These credits will vary with the classification of the roofing material and the county. In the spring of 1996 at Bismark, North Dakota, representatives of the insurance industry met with cloud physicists and hail suppression experts to review the state of hail science (Boe, 1996).

The total insurance settlement for the July 31, 1987 storms was $250 million, then a record amount for a Canadian natural disaster. Figures deduced by Charlton et al. (1995) suggested that approximately $67 million was paid to 32000 homeowners, principally for hail damage to shingles. Commercial policy holders collected $150 million, mostly for wind damage along the tornado path, and most of the remaining $33 million was paid for hail damage to automobiles. The largest insurance loss in Canada, $400 million, was caused by the September 7, 1991 hailstorm in Calgary (Charlton et al., 1995), where $210 million was paid for hail damage to houses, and most of the remaining $190 million was paid for hail damage to automobiles. More detailed accounts of the insurance losses caused by this storm were given in Charlton et al. (1995) and Charlton and Kachman (1996).

Estimates provided by Alan Wood suggested that the insured loss caused by the floods in the Saguenay region of Quebec in July, 1996 may exceed the record set by the Calgary hailstorm. Many of the claims, however, are being disputed because some businesses may be held liable for some of the losses. The January, 1998 ice storms in Quebec and Ontario will exceed the Canadian record for insured loss because the collapse of the electricity delivery system and warm weather prompted more than 600 000 claims, most for food spoilage. The total insured loss is expected to reach $800 million.

During the summer of 1996, destructive hailstorms struck Calgary twice and Winnipeg once. Alan Wood estimated that the insurance losses in Calgary on July 16 and July 24 totalled $160 million, though the damage was apparently reduced by the cloud seeding program (Canadian Press, 1996; MacLean, 1996). Maps prepared by Dudley (1996) at the Calgary weather office showed that the 2 damage swaths overlapped in south Calgary. On July 16, a hailstorm buffeted Winnipeg and caused $100 million of insured damage (Chalmers, 1996). As Winnipeg was struck one-half hour before Calgary, the 2 cities were not struck by a typical weather system, which moves from west to east.

A detailed account of the hail suppression operations in the Calgary-Red Deer region during 1996 was prepared by Weather Modification Inc. (Krauss, 1996) for the Alberta Severe Weather Management Society. It indicated that the operation of the project was highly successful, Calgary hailstorms notwithstanding.

b. Determining the frequency of urban hailstorms

Cities are too small and widely separated to be frequently buffeted by large quantities of giant hail; therefore, a satisfactory climatology cannot be developed from such rare incidents. The average interval between severe hailstorms, however, is roughly one decade for each of the main cities in Alberta.

Throughout the world, agricultural regions where severe hailstorms are common usually have extensive records of crop insurance claims; these records cover many decades but, typically, do not include notes about the observed hail size or exact swath dimensions. For example, Willemse (1995) studied many years of records of crop damage for a region of Switzerland, but detailed tabulations of hailfall parameters did not exist. Furthermore, crop damage is, at best, weakly related to the fall of large hail (Summers and Wojtiw, 1971). Vast quantities of pea- and grape-size hail, in combination with strong wind, can devastate many types of crops, but hail of these sizes is unlikely to inflict substantial damage upon houses or automobiles. A crude relationship between reported hailstone sizes and shingle damage can be established from the field observations recorded in the present study or by laboratory experiments involving impacts to both new and weathered shingles. If available, local historical records of reported hail sizes and hail swath dimensions might then be employed to estimate the extent and frequency of future severe, urban hailstorms. Weather radar records may also be used to augment ground-based observations of hail (Al-Jumily et al., 1991; Balakrishman and Zrnic, 1990; Holt et al., 1994; Schiesser et al., 1995; Wrenshall, 1978), but the relationships between radar echo parameters and the sizes and quantities of hailstones need further investigation.

Some regional hail databases were developed by soliciting hail reports from farmers. These databases, augmented by studies of crop insurance, were usually assembled to evaluate the effectiveness of hail suppression programs like that of the Alberta Hail Project (Alberta Research Council, 1968-1985, 1986). For example, the Alberta Research Council collected more than 85000 hail reports from farmers located between Calgary and Edmonton in central Alberta (Wojtiw, 1987). These farmers' reports indicated that when hail had occurred, the frequency of maximum size was pea 44%, grape 37%, walnut 13%, golfball 5%, and larger than golfball 1.5% of the time. Reports of shot size hail have been removed from these percentages because shot size hail, at less than 0.5 cm diameter, is properly recorded as ice pellets or snow pellets, not hailstones (see subsection 5a). The reports are archived at the Department of Earth and

Atmospheric Sciences at the University of Alberta (Kochtubajda et al., 1996). Studies of the frequencies of hailstorms which produced large and giant hailstones in the United States were conducted by Kelly et al. (1985) and Sammler (1993), but similar studies have not been conducted for Canada.

c. Maps of shingle replacements

In the spring of 1994, the invoice records of the A Clark Shingle Company were examined for 1987, 1988, and 1990, with the permission of Doug Clark. Each invoice included the type of work performed and the address of the client. These records distinguished between minor repairs, installations of shingles on new houses, and replacements of shingles on houses, referred to as T & C's (Tear off the old shingles, install new shingles, and Clean the debris) on the invoices.

The dots on Fig. 16 mark the locations of 332 T & C's completed between August 1987 and July 1988. These 332 T & C's were a significant proportion of the total number of T & C's performed by the shingle company in that period. All T & C's completed in this period were counted and examined, but to maintain business confidentiality, the total will not be given. Furthermore, examination of the invoices and discussions with management at the A Clark Shingle Company were convincing: the company services roofs throughout Greater Edmonton and does not dominate in or exclude itself from some areas. Thus, the pattern of T & C's shown in Fig. 16 should be a reasonable facsimile of the spatial distribution of all reshinglings performed by roofing companies in Greater Edmonton. Also displayed in Fig. 16 are the maximum hail-size boundaries from Fig. 12 and the residential areas (shading) from Fig. 2.

Figure 17 shows the locations of 125 T & C's completed by the A Clark Shingle Company in 1990. The ALWC did not record an instance of large hail falling in Greater Edmonton in 1988, 1989, or 1990 (Alberta Weather Centre, 1984-1996). Figure 17 was included so that the distribution of reshinglings in 1990 could be compared with the distribution for the 12 months following the tornado ('87-'88). The fraction of 1990 T & C's plotted in Fig. 17 is the same as the fraction plotted in Fig. 16. Thus, the number of T & C's performed by the company in the 12 months following the tornado was 2.7 times larger than the number completed in 1990. The monthly average of reshinglings for the 7 months prior to the tornado and the 5 and 12 months following the tornado were also calculated. The ratios of the 5 and 12 post-tornado monthly averages to the average of the 7 pre-tornado months were 4.2 and 3.4, respectively: an impressive increase in business activity!

The increase in the number of T & C's that the shingle company could perform in the 12 months after the tornado might have been constrained by several factors: the availability of new roofing crews, the maximum number of hours that crews could work, the emergence of independent shingling crews in the city, and the number of new houses under construction that also required shingles. In the spring of 1995, Charlton spoke with a shingle installer in his late twenties who has spent most of his adult life working in cities which had been pummeled by severe hailstorms; the hailstorms in Greater Edmonton in 1987, Medicine Hat and Calgary in 1988, Calgary and Red Deer in 1991, Calgary in 1992, and Salmon Arm, British Columbia, on August 8, 1994, had been the man's principal source of employment. He reshingled roofs in Salmon Arm until the spring of 1995. These and other costly insurance events in Canada were listed in **Facts of the General Insurance Industry in Canada** (Insurance Bureau of Canada, 1996). In the spring of 1997, Charlton spoke with another shingle installer who laughed when he recalled his first hail-damaged roof; the hastily assembled crew had to read the installation instructions printed on the shingle bundles!

d. Tabulation of shingle replacements by maximum hail-size categories

Table 3 displays information about reshinglings derived from Figs. 16 and 17. The first and second columns of the table give the total and residential areas, respectively, of the walnut, golfball, tennis ball, and "Beyond Large Hail" areas in Greater Edmonton. These areas were first given in Section 5. The area of tennis-ball-size hail was sub-divided into 4 residential zones. Data for these sub-regions are also provided in Table 3. Kaskitayo is the residential region immediately to the west of Mill Woods, across the Calgary Trail commercial corridor (8 E), but its area given in Table 3 includes only that part of Kaskitayo within the tennis ball boundary. The residential areas of Greater Edmonton did not change significantly between 1987 and 1990, although the number of houses (detached, duplex, and multi-family) had increased by 9000. Thus, the residential areas were appropriate for both '87-'88 and 1990.

The third and fourth columns of Table 3 show the number of T & C's within each hail size boundary from Figs. 16 and 17, respectively. Only the areas within the tennis ball boundary had large differences in the numbers of T & C's between '87-'88 and 1990, particularly West Mill Woods and Kaskitayo. West Mill Woods was defined as the western part of Mill Woods which contained all but 6 of the T & C's plotted in that sub-division (Fig. 16).

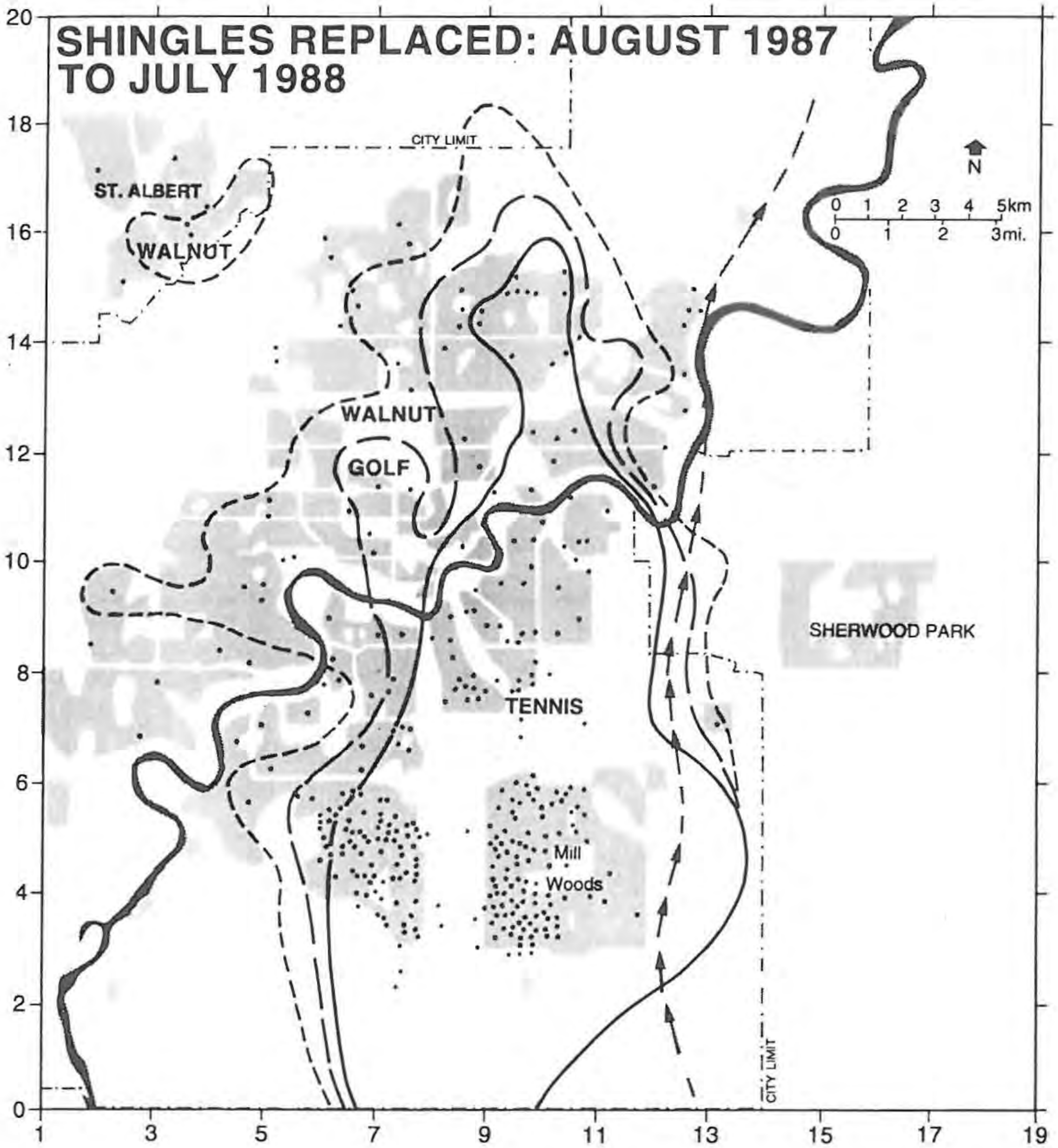


Fig. 16. Locations of 332 shingle replacements (T&C's) completed by the A. Clark Shingle Co. are compared with reported hail-size categories from Figure 12. The spatial concentration of T&C's is greatest where tennis-ball-size hail fell, particularly in west Mill Woods and, further west, in Kaskitayo. Walnut size hail resulted in only a few widely spaced T&C's.

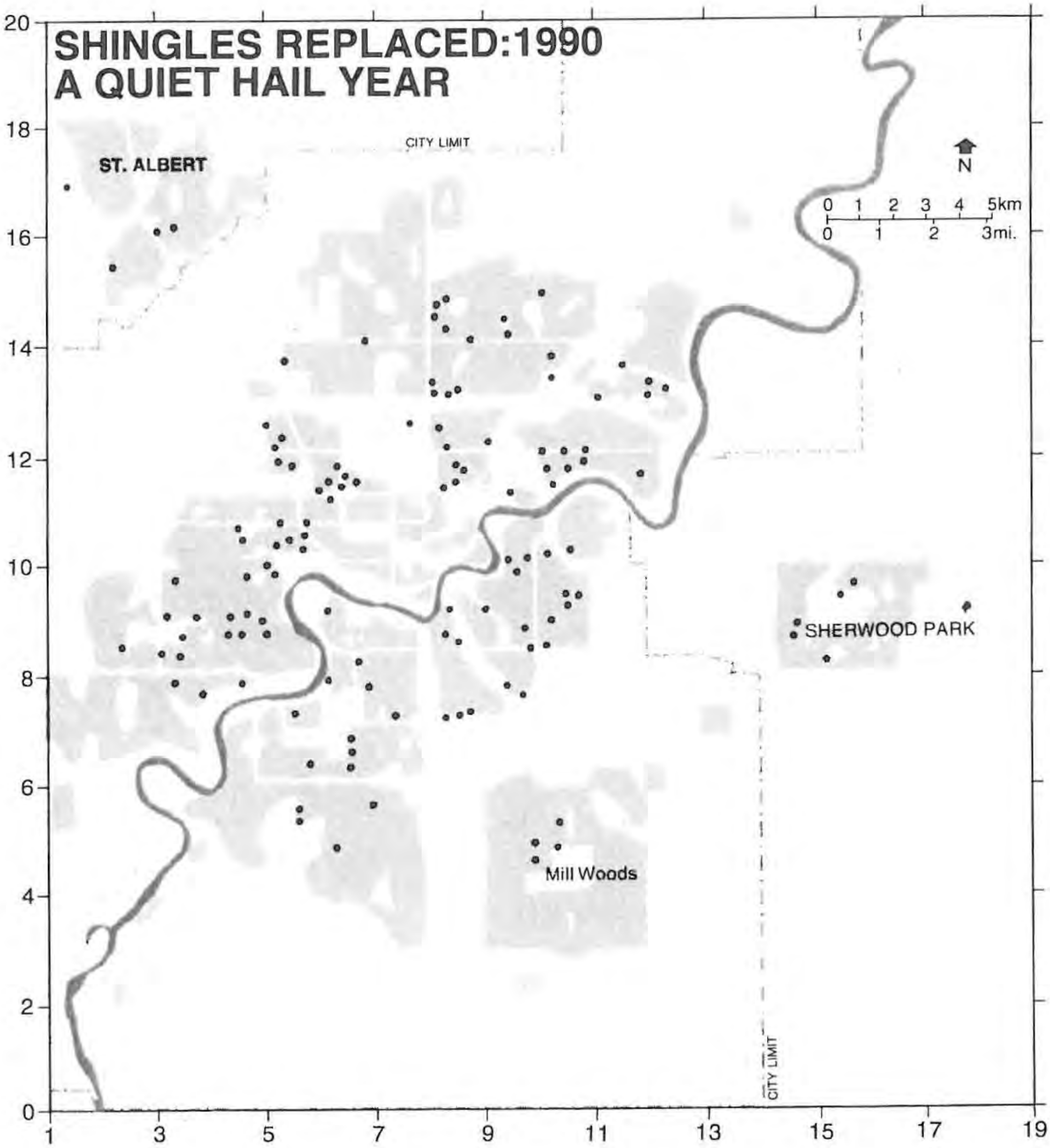


Fig. 17. Locations of 125 shingle replacements (T&C's) completed by the A. Clark Shingle Co. in 1990 are shown on a background of shaded areas depicting residential communities. During this nearly hail-free year, most T&C's were conducted in older communities. Residential communities near the city centre consist mainly of apartments. However, the estimates of the percentages of homes reshingled in 1990 in Table 3 also suggest that enhanced reshingling rates (6%) lingered in areas struck three years earlier by walnut and golfball size hail and in tennis ball areas other than the newer suburbs of Mill Woods and Kaskitayo.

Table 3. **Comparison of hail size with frequency of shingle replacements (T&C's).**

Large Hail Size - Category	'87 Hail Areas: Total (km²)	'87 Hail Areas: Residential (km²)	Annual T&C's Plotted: Fig. 16 '87-'88	Annual T&C's Plotted: Fig. 17 ('90)	T&C's Plotted Per Residential km²: '87-'88	T&C's Plotted Per Residential km²: ('90)	Estimated Percentage of Homes Reshingled: '87-'88	Estimated Percentage of Homes Reshingled: [Alf's]	Estimated Percentage of Homes Reshingled: ('90)
Walnut	92	39	22	(38)	0.6	(1.0)	6%	[6%]	(6%)
Golfball	53	23	32	(24)	1.4	(1.0)	13%	[15%]	(6%)
Tennis Ball (TB)									
Kaskitayo	-	9	67	(1)	7.4	(0.1)	77%	[84%]	(1%)
West Mill Woods	-	11	98	(4)	8.9	(0.4)	89%	[80%]	(2%)
East Mill Woods	-	9	6	(0)	0.7	(0.0)	7%	[15%]	(0%)
Other TB Areas	-	30	78	(35)	2.6	(1.2)	23%	[22%]	(6%)
All TB Areas	125	59	249	(40)	4.2	(0.7)	41%	[40%]	(4%)
All Large Hail Areas	270	121	303	(102)	2.5	(0.8)	24%	[25%]	(5%)
Beyond Large Hail	662	58	29	(23)	0.5	(0.4)	5%	[5%]	(2%)
Map Area	932	179	332	(125)	1.9	(0.7)	18%	≡18%	(4%)

e. Shingle replacement per unit of residential area

For each region, the number of plotted T & C's for '87-'88 was divided by the residential area, thus giving the spatial density of plotted T & C's; the results are shown in the fifth column of Table 3. For comparison, the figures for 1990 are provided in the sixth column.

For the 12 months following the storms ('87-'88), the density of T & C's (the number of plotted T & C's per square kilometre) within the walnut area, 0.6, was not substantially different from the density in the region outside the boundary of walnut size hail, 0.5. The density of reshinglings in the golfball area, 1.4, was more than twice that in the walnut area; in the region of tennis-ball-size hail, the density, 4.2, was 3 times larger than that in the golfball region.

In 1990, the range of T & C densities was far smaller than in the year following the tornado. The largest densities were in the regions of walnut (1.0), golfball (1.0), and the area of tennis ball outside of Mill Woods and Kaskitayo (1.2). This suggested that many homeowners not residing in Kaskitayo or West Mill Woods were beginning to find shingle damage caused by the storms of July 31, 1987, or that they had decided to spend their insurance settlements collected after the storms. In the 12 months following the storms, West Mill Woods and Kaskitayo had, by far, the highest rates of reshingling per unit residential area, but their rates were among the lowest in 1990. Apparently, repairs to roofs in these 2 regions were needed almost immediately.

f. Estimating the reshingling rates

The seventh column of Table 3 shows the estimated percentage of houses that were reshingled in each of the hail areas in '87-'88, that is, the real reshingling rates. To determine these rates, 4 assumptions were made.

1) All of the 32000 householder insurance claimants in Greater Edmonton had their houses reshingled in the 12 months following the tornado.

2) The 32000 reshinglings done for the insurance claimants were the only reshinglings performed in Greater Edmonton from August 1987 through July 1988.

3) For each area listed in Table 3, the number of houses reshingled was proportional to the number of T & C's plotted in it.

4) The spatial densities of houses within postal areas were constant.

The first assumption led to an exaggeration of the percentage of reshinglings in each region. The second assumption led to under- estimates, but the number of routine reshinglings performed in '87-'88 was probably much lower than if the storms had not occurred. The third assumption was based upon the belief, defended earlier, that A Clark Shingle Company's market share did not vary appreciably across the city.

A detailed explanation of the fourth assumption is warranted. Canada Post divided Greater Edmonton into 40 Forward Sortation Areas (FSA's) and tabulated the number of houses, farms, apartment units, and businesses in each. These data were used to estimate the number of houses in each hail area or part thereof. For most FSA's, the average number of houses per unit of residential area was between 800 and 1400 per km^2. The average for Greater Edmonton was 976 homes per km^2. Surprisingly, the differences among the averages for the hail areas (as opposed to FSA's) were small despite the residential density variations among FSA's. Thus, for '87-'88, reshingling rates in percent (column 7) were proportional, by a factor of approximately 10, to the numbers of T & C's per km^2 (column five). For 1990, reshingling rates (column nine) to one significant digit obscured the nearly constant factor of 5.7. Thus, the comparisons of the densities of T & C's, discussed in subsection 7e, also applied to the reshingling rates in percentage; still, reshingling rates of 77% in Kaskitayo and 89% in West Mill Woods are certainly remarkable.

g. Confirmation of the distribution of T & C's in '87-'88

The eighth column of Table 3, labelled Alf's, gives a second estimate of the percentage of reshinglings in each area in '87-'88. In 1995, when the analysis of T & C data from A Clark Shingle Company was nearly complete, Alf's Roofing was contacted. Surprisingly, the owner, Alfred Weimann, had retained the on-site estimates that his employees had completed in 1987. Unlike an invoice, an estimate usually included a description of the damage to the roof, the general condition of the roof, and the cause of the damage. An estimate provided other information as well: whether a repair or reshingling was recommended, the presence of structural damage, whether Alf's Roofing received the contract, and, occasionally, the comments of the homeowner. The locations where Alf's Roofing recommended a reshingling were used to supplement the information from A Clark Shingle Co. Only a modest fraction of the estimates was examined, and the locations of 319 "recommended reshinglings" were plotted on a map. Also recorded were the locations where only minor repairs were needed, where old and worn shingles were found, where hail caused structural damage to roofs, or where the estimator found no evidence of hail or wind damage. Alf's "recommended reshinglings" were used to determine the percentages of houses needing reshingling. Again, the 4 assumptions discussed in subsection f were used to determine the percentages.

Concern about the validity of using the distribution derived from A Clark Shingle Company's invoices to represent all reshinglings in Greater Edmonton was allayed by the strong similarities among the real reshingling rates and the recommended reshingling rates (columns seven and eight, respectively, of Table 3). Proportionately, the only large difference was for East Mill Woods, 7% from Clark's and 15% from Alf's. Possible reasons for this will be discussed in later subsections.

An examination of the damage reports (Fig. 15) from respondents to the newspaper survey was completed. In the tennis ball area the percentage reporting hail damage to roofs (labelled 'r' or 'h') was calculated for each sub-region: for Kaskitayo, 40%; for West Mill Woods, 44%; for East Mill Woods, 19%; and for "Other tennis ball area", 16%. Like the reshingling values derived from the records of the roofing firms, these values also suggest that reshinglings caused by hail damage were common in Kaskitayo and West Mill Woods but decidedly less frequent in East Mill Woods and the "Other tennis ball area". But reports of wind damage to roofs (labelled 'R' or 'H') were common from participants in East Mill Woods (28%). Respondents in East Mill Woods who lived near the path of the tornado might have been more inclined to examine their roofs and complete a newspaper survey than participants in the other 3 tennis ball areas. For the entire tennis ball area, the percentage of reports of damaged roofs (wind and hail) was 36%, a value similar to the percentages from A Clark Shingle Co. (41%) and Alf's Roofing (40%).

h. Reshinglings in 1990, a quiet hail year

The ninth column of Table 3 shows the estimated percentages of houses reshingled in Greater Edmonton in 1990. These percentages were calculated in the same way as those given for '87-'88, but there was one value which had to be estimated, namely, the percentage of homes reshingled in Greater Edmonton during 1990. Three methods were used to estimate the value appropriate to 1990.

If A Clark Shingle Co. had the same market share in 1990 as in '87-88, then 6.3% of homes were reshingled in 1990. Assuming that shingles were replaced every 20 years gave a value of 2.3% when statistics on the age of existing houses were consulted. Production figures from a major local shingle manufacturer, BPCO, were combined with regional sales information and an estimate that 70% of production is used for reshinglings. With these figures a value of 4.4% was obtained. Averaging the three estimates gave the city-wide value of 4% shown in Table 3.

Estimated reshingling rates for 1990, calculated for each area struck by hail in 1987, varied between 0% and 6% (column 9 of Table 3). Preliminary comparisons of these values are consistent with comments given in subsection 7e using the corresponding T & C densities.

i. Comparison of reshingling rates in Edmonton, 1987 with Calgary, 1991

As noted in subsection 5a, the estimated percentages of homeowners with insurance claims for hail damage were 18% for Edmonton and 28% for Calgary. In Calgary, one insurer, The Co-operators Insurance/Financial Services, settled claims with 34% of their policy holders (Charlton et al., 1995). Using Co-operators claims rates, derived from confidential, detailed data arranged by FSA, the total number of claims in Calgary would have been 70000. This is 20% larger than 58367, the actual number of claims according to Alan Wood of the Insurance Bureau of Canada.

In 4 of the 30 FSA's in Calgary, Co-operators had claims rates between 82% and 92%! Assuming that a claim is equivalent to a reshingling, the values from these 4 FSA's were similar to the percentages of reshinglings in West Mill Woods (89%) and the area of Kaskitayo buffeted by tennis-ball-size hail (77%). Charlton et al. (1995) found that the damage swath in Calgary, defined as areas designated as "many homes damaged" and "most homes damaged" by 2 Wawanesa Mutual Insurance Co. adjustors, had an areal extent of 130 km^2. This swath corresponded well to the area of large hail, that is, walnut size or larger. The area of large hail in Greater Edmonton, 270 km^2 (Table 3), was more than twice as large. The estimated number of houses exposed to large hail was 50% larger in Greater Edmonton — 120000 houses versus 80000 in Calgary. Furthermore, of the 638 participants from Greater Edmonton who recorded a maximum hail size, 73% reported hail of golfball size or larger, and 54% reported tennis ball or larger; but, in Calgary, only 58% of the 60 respondents to an informal survey reported golfball or larger, and 9% reported tennis ball or larger. Clearly, the area buffeted by giant hail and the number of houses in it were decidedly smaller in Calgary than in Edmonton. Was the record insurance loss in Calgary inflated by an increased willingness to file a claim?

The swath in Calgary encompassed 6 entire FSA's and portions of 7 others. Using information about claims from Co-operators and housing figures from Canada Post, the claims rate for Co-operators for these 13 FSA's was estimated to be 60%, assuming that damage was evenly distributed throughout the 13 affected FSA's, or 80%, assuming that damage was limited to the damage swath determined by the adjustors. Either of these values, if interpreted as the reshingling rate in the region of Calgary struck by large hail, greatly exceeded the 24% reshingling rate for the area of large hail in Greater Edmonton (Table 3). Apparently, the willingness of homeowners in Alberta to submit a claim for wind and hail damage had greatly increased between 1987 and 1991!

An exact comparison of the consequences of the Edmonton and Calgary hailstorms was difficult because insurance claims were not organized by FSA in 1987, and reshingling information from a roofing company in Calgary was not collected. Furthermore, the number of survey respondents from Calgary (60) is just 8% of the number from Greater Edmonton (755) and, thus, insufficient for delineating hail-size boundaries. Estimates of average shingle lifetimes in Edmonton and Calgary are given in section 8.

j. The anomalous reshingling rate in East Mill Woods

The reshingling rate in East Mill Woods, which lay entirely within the tennis ball boundary (Fig. 12), was a surprisingly low 7%. The "recommended reshingling" rate, 15%, was also curiously small. Meteorologists would be tempted to claim that "soft" hail, the kind that splatters when it strikes lawns and, thus, could not damage shingles, fell there. The survey forms from participants in this region were carefully read, but no comment about soft or splattered hailstones was found. The maps of hailstone measurements, Figs. 13 and 14, both suggest that the hailstones in East Mill Woods were, in general, smaller than those in West Mill Woods but of similar sizes to those in Kaskitayo, the residential community west of Mill Woods. But the reshingling rate in Kaskitayo, 77%, was 11 times greater than that in East Mill Woods!

The reports of the largest hail sizes were tabulated for each of the 4 areas within the tennis ball boundary. West Mill Woods, with 61% of the hail reports indicating larger-than-tennis-ball, apparently received the worst of the hailstorm, but its reshingling rates, real and recommended, were similar to those for Kaskitayo, where only 27% of respondents reported larger-than-tennis-ball. Surprisingly, East Mill Woods, with just one eleventh the reshingling rate of Kaskitayo, had a modestly larger proportion of reports of larger-than-tennis-ball (32%) than did Kaskitayo. The distribution of hail sizes in East Mill Woods was closest to that of "Other tennis ball areas", though the reshingling rates in these 2 areas were also substantially different, 7% versus 23%; but Alf's recommended reshinglings were quite similar, 15% in East Mill Woods versus 22% in "Other tennis ball areas."

The anomalies in the reshingling rates among the areas within the tennis ball boundary could not be adequately explained by variations in the maximum-hail-size categories. The possibility that the anomalies were caused, at least partially, by another hailfall parameter, namely the most common size, was also investigated. (The Hail Report (Fig. 1b) requested that respondents record the most common sizes.) The evidence was limited, but the average of the most common sizes for a region in the tennis ball area seemed to be a marginally better indicator of its reshingling rate than the average of the largest sizes, provided that East Mill Woods was ignored.

The Hail Report (Fig. 1b) also asked for an estimate of the duration of hailfall. Kaskitayo had an average duration of 29 minutes. For West Mill Woods, hailfall averaged 24 minutes. For East Mill Woods, the average was 12 minutes. The average of the durations from "Other tennis ball areas" was 25 minutes. Thus, for East Mill Woods, hailfall, and presumably the fall of tennis ball hail, lasted approximately one half as long as in the 3 other tennis ball areas. Within the "Other tennis ball areas" there was also a tendency toward shorter hailfalls in the east. Presumably, the probability of a roof being hit and, consequently, damaged by tennis ball hail increased as the duration of hail increases. Thus, the observations of hail duration explained, at least partly, the low reshingling rate in East Mill Woods.

k. Relating the age of housing with the resistance of shingles to hail, and roof penetration by hail

The average ages of houses in Mill Woods and Kaskitayo were determined by examining **Neighbourhood Fact Sheets**, published by the City of Edmonton's Planning Department. East Mill Woods is, on average, a newer community than West Mill Woods or Kaskitayo, although the difference in the average ages is modest. In 1987, north Kaskitayo was a little more than 15 years old and south Kaskitayo was 5 years old; West Mill Woods was 10 years old, and East Mill Woods was 5 years old, though a few neighbourhoods were nearly 10 years of age. All other communities struck by giant hail were more than 17 years old, with the exception of those at the northernmost tip of the golfball boundary. Perhaps East Mill Woods had a low reshingling rate, in part, because the community was relatively new; there were many reshinglings in south Kaskitayo (Fig. 16), however, even though houses there were about the same age as those in East Mill Woods.

Estimators from Alf's Roofing found roofs in every region of the city which showed no evidence of hail or wind damage, including a few in Kaskitayo and West Mill Woods. A list of the locations of 10 houses where hail penetrated the roofs was made; 7 locations were found in estimates from Alf's Roofing, and 3 came from survey participants. All but one penetration occurred in Mill Woods; 4 were in its extreme southwest corner. This district had the highest averages of both maximum and of most common hail sizes of any neighbourhood. The one penetration outside Mill Woods occurred at 10.5 E, 10.0 N (Fig. 15), approximately 6 km north of Mill Woods, and only 1 km southeast of the place where the second largest hailstone (264 g) was collected (Fig. 14).

l. Relating reshinglings with laboratory tests of shingles

The impact resistance of domestic roofing products has been determined by striking them with dropped steel balls (Laymon and Rhodes, 1995) and ice spheres (Greenfeld, 1969; Koontz, 1991) propelled by compressed air. These engineering studies contain only limited information about the effects of weathering on the resiliance of asphalt shingles. Nevertheless, they do suggest that new asphalt shingles are fractured by 5.1 cm (2 inch) spherical hailstones, and after 10 years of weathering, 3.5 cm (1.25 to 1.50 inch) ice spheres will cause fracturing. At 15 years, 1.9 cm (0.75 inch) will suffice. At these minimum sizes, the loss of granules on the upper surface is often minimal, and the fracturing of the shingle mat is often visible only on the lower surface. For each of these 3 ice spheres, the maximum dimension of a genuine hailstone with a kinetic energy at terminal fall speed equal to the sphere was calculated. The average shapes of large and giant hailstones reported by Barge and Isaac (1973) and Charlton et al. (1989) were used in these calculations. During the first 5 years, asphalt shingles of average quality should withstand a fall of real hailstones with maximum dimensions up to 6.4 cm (actual tennis balls). After 10 years of weathering, stones with maximum dimensions of 4.4 cm (actual golfballs) would fracture the shingles, and beyond 15 years, the blows of hailstones as small as 2.3 cm (small walnuts) could cause fracturing which, in time, would lead to leaking. The foregoing calculations, based on real hailstones, are unique to the literature about hail damaged shingles.

Both Randy Clark of A Clark Shingle Co. and Alf Weimann of Alf's Roofing noted that weathering is the principal factor determining the susceptibility of asphalt shingles to fracturing and granular loss. Dutt (1987) studied the adhesion of granules on both new and old asphalt shingles. Samples as old as 29 years were collected from roofs in Ottawa. He found that the exposed surfaces typically lost granules at a rate of 1% per year. Dutt did not test the resiliency of the shingles to impacts.

There are additional, secondary factors affecting the resilience of asphalt shingles to impacts: thickness, manufacturing techniques, variations among batches, and, no doubt, the pitch and orientation of the roof; but, if weathering is the key consideration, the tests conducted by Underwriters Laboratories should have been, at the very least, extended to include testing shingles which have been weathered for at least 10 years.

The retention of granular coatings and hidden fracturing might have been the reasons why the reshingling rates in 1990 (Table 3) were high in the walnut and golfball areas, relative to the area "Beyond Large Hail". Perhaps many homeowners inspected their roofs soon after the 1987 storms and failed to find any evidence of damage, but the mats of their shingles had cracked, and, within 3 years, their roofs began to leak. Greenfeld (1969) suggested that damage to shingles could be undetectable shortly after a hailstorm, but the fall of modest-sized hail months or years later or ice penetration during winter could make the damage noticeable.

In 1990, 18 of the 125 plotted T & C's (Fig. 17) were in communities that were less than 20 years old. Of these 18 seemingly premature reshinglings, 13 were in communities buffeted by large hail in 1987. Conversely, Alf Weimann noted that he had seen roofs with shingles that had suffered dents and granular losses in 1987 but remained functional in 1995. Many insured homeowners, however, will not accept the risk of developing leaks in the future, and, because policy holders have one year to proffer claims to their insurance companies, they will submit their claims, pressure their insurance companies for their settlements, and replace their shingles as soon as possible.

One variable has not been investigated to date; namely, the increasing popularity of oriented strand board (OSB) as a roof sheathing material. It is reported to be much harder and stronger than plywood. Dent-resistant OSB is believed to have been used extensively on the newer roofs in East Mill Woods. One source at A Clark Shingle Co. believed that all hail-penetrated roofs were sheathed in plywood, but an acquaintance living in central Mill Woods saw unshingled OSB penetrated on a nearby home under construction. After 10 years, the acquaintance had not replaced his dented shingles.

m. Summary of shingle replacements

Kaskitayo and West Mill Woods were buffeted by tennis-ball-size hail, and the reshingling rates in these 2 areas, derived from the examination of the invoices of A

Clark Shingle Co., were estimated to be 77% and 89%, respectively. Using estimates from Alf's Roofing, the rates of recommended reshinglings in these 2 areas were calculated to be 84% and 80%, respectively. The houses in both communities were, on average, 10 years old in 1987. The roofs of several houses in West Mill Woods were pierced, but there were apparently no roof penetrations in Kaskitayo. The distributions of reports of giant hailstones (golfball or larger) from East Mill Woods and Kaskitayo were quite similar. But in the newer community, East Mill Woods, the percentages of houses that were reshingled, 7%, and needed reshingling, 15%, were far smaller than in Kaskitayo. This discrepancy was explained, at least partially, by the averages of the reported hail durations in these 2 communities: 29 minutes in Kaskitayo and 12 minutes in East Mill Woods. Furthermore, the relatively new houses in East Mill Woods were probably less susceptible to shingle damage by tennis-ball-size hail than the houses in older communities, a possibility supported by laboratory experiments which implied that new asphalt shingles (produced in this decade) could withstand a blow from a small tennis-ball-size hailstone. Comparison of the laboratory experiments also suggested that the resistance of commonly-used asphalt shingles to impacts had increased between 1969 and 1995. Whether soft hail fell in East Mill Woods could not be confirmed.

For 4 FSA's in Calgary in 1991, The Co-operators Insurance/Financial Services had annual claims rates for wind and hail damage which exceeded 80% (Charlton et al., 1995). Assuming that every claimant had his house reshingled, the reshingling rates in these areas were similar to the reshingling rates in West Mill Woods and Kaskitayo. However, the hailstones that fell in Calgary on September 7, 1991 were, on average, decidedly smaller than the ones that fell in Edmonton on July 31, 1987.

8. THUNDERSTORMS IN EDMONTON AND CALGARY

In subsection 1c, data from Hage (1990) indicated that Edmonton had 12 tornadoes between 1890 and 1989 and Calgary had only 3 tornadoes during that period. Since 1989, Edmonton has had 3 more while Calgary has experienced no more tornadoes.

The number of times during the past 15 years that Calgary and Edmonton were struck by large hail, that is, at least walnut size, and thus damaging to weathered shingles, was carefully estimated. This was accomplished by perusing the list of insurance events compiled by the Insurance Bureau of Canada (1996) and the detailed tabulations of hail events in Alberta in the severe-summer-weather lists issued annually by Environment Canada for 1982 to 1996. From 1982 to 1996 Calgary had 17 storms with large hail while Edmonton had 14. During the summers of '91 through '96, however, Calgary had 12 of these hailstorms and Edmonton had only 6. The severe weather coordinator at the Southern Alberta Environmental Services Centre, Dennis Dudley, reported that the insurance industry believes that, for some undetermined meteorological reason, Calgary is being struck by damaging hail much more frequently in the 90's than in the 80's (Dudley, 1996). O'Dowd (1994, 1995) conducted research into the relationship between rainfall and production rates of cement plants located west of Calgary; these plants are a prodigious source of cloud-seeding ice nuclei. Perhaps this research, conducted at the University of Alberta, should be extended to include hailfall in the Calgary region. Devastating hailstorms with tennis-ball-size hailstones have struck both cities twice during recent decades: Calgary in '81 and '91 and Edmonton in '69 and '87 (Charlton et al., 1995).

Major hail swaths passing through Calgary during the period 1957-1973 were shown in maps contained in **Climatic Summaries of Hailfall in Central Alberta** (Wojtiw, 1975). During those 17 years, Calgary lay within the cloud seeding area of the Alberta Hail Project (AHP). An examination of the maps suggested that Calgary was struck by walnut size hail on between 13 and 20 occasions, or roughly once per year. The frequency of these events showed no trend during the 17 years. Edmonton was never within the jurisdiction of the AHP. Between 1974 and 1985, the final decade of the hail suppression project, Calgary also lay outside the project area: consequently, the hailstorms affecting Calgary were not depicted in the annual reports of the AHP (Alberta Research Council, 1968-1985). The **Climatic Summaries** for 1957 to 1973, however, gave further credence to the possibility that Calgary, with an average of 2 storms with large hail per year since 1991, has been experiencing twice its expected number of severe hailstorms.

Recently, Charlton and Kachman (1997) estimated the life expectancies of asphalt shingles exposed to weathering and a normal mix of hailstorms for both Edmonton and Calgary. They determined that typical asphalt shingles will last an average of 14 years in Edmonton and 11 years in Calgary. Improved asphalt shingles which would resist fracturing by golfball size hailstones even after 15 years of weathering were found to have hypothetical average lifetimes of 27 years in Edmonton and 17 years in Calgary. These lifetimes were calculated using official hail observations at the airports which, averaged over several decades, indicated that Edmonton airports averaged 2.0 hailfalls (pea size or larger) per year while Calgary Airport averaged 4.1 hailfalls per year. These estimates of shingle longevities employed the shape of genuine hailstones discussed in subsection 7l. Unfortunately, the distribution of hail size categories reported by farmers in central Alberta (see subsection 7b) had to be used in the estimates; the strong possibility that Calgary, because of its altitude, receives a high proportion of pea size hail, could not be taken into account.

A Severe Thunderstorm Climatology for Alberta (Paruk and Blackwell, 1994) was recently published by researchers at the Northern Alberta Environmental Services Centre (formerly, the Alberta Weather Centre). It used '82 through '91 reports from volunteer weather watchers and other members of the public. The objective of the research was to adjust the numbers of reports per county for population density to yield realistic provincial maps of various severe weather parameters. Direct comparisons of values for Calgary and Edmonton should not suffer from anomalies like those found in some sparsely monitored counties. For the ten year period, Edmonton had 2.3 severe thunderstorm events per year per 1000 km^2 while Calgary had 1.6. Similarly, Edmonton had 0.8 hail events (walnut or larger) per 1000 km^2 while Calgary had 0.7. Edmonton had 0.5 heavy rain events (30 mm in an hour) per year per 1000 km^2, while Calgary had 0.4. (The return period for 30 mm in an hour at a single location in Edmonton was given in subsection 3b as approximately 5 years; that is, 0.2 such events per year.) Severe wind events associated with thunderstorms were 0.3 per year per 1000 km^2 in both cities. Winter wind events associated with Chinooks in the foothills and cold frontal passages throughout the province were not considered. As expected, tornado sightings during the decade were much more frequent in Edmonton (0.8 per year per 1000 km^2) than in Calgary (0.1 per year 1000 km^2), but in both cities tornadoes seldom did damage to more than a few trees or one or two buildings, the exception being the Edmonton tornado.

Finally, the severe hailstorms in Calgary during the 90's may be a meteorological aberration like the Edmonton tornado appears to have been; if not, may Calgarians discover hail-resistant roofing before the insurance companies move to reduce the stupendous insured losses.

9. CONCLUSIONS AND DISCUSSIONS

Studies related to the Edmonton tornado and to the 1985 Ontario tornadoes had numerous similarities. Both events were documented by Environment Canada forecasters. Epidemiological reviews of the human injuries associated with both disasters were completed. The failures of buildings in Edmonton and Ontario were described by engineers. In homes, fatalities occurred when the ground floors were lifted. Substantial segments of the power grids in the 2 regions were destroyed. The loss of electricity in Ontario appeared to interfere with the dissemination of weather warnings to affected communities. The loss of power in Edmonton apparently had little effect upon the broadcasts of warnings. Two investigations were unique to the Edmonton storms: the newspaper survey and the Hage review of the weather warning system.

The newspaper survey provided an extraordinary opportunity to document the meteorological phenomena observed by the citizens of Greater Edmonton. To ensure that the information would be available to future generations, copies of the returned surveys were donated to the University and Provincial Archives. Information derived from the survey was supplemented with data from unusual sources. A map displaying this non-survey information (Fig. 5) indicated that nearly all of Edmonton was affected by the storms of July 31, 1987: most floods occurred in the northern half of Edmonton; claims for disaster assistance submitted by businesses denoted the tornado path; reshinglings were common in central Edmonton and prodigious in the suburbs of south Edmonton. Information about particular damage sites, both residential and commercial, illustrated the breadth and severity of the Edmonton tornado.

The existence of one of the 2 spin-off tornadoes in east Edmonton seemed to be confirmed by the numerous claims for disaster assistance made by businesses located east of the main tornado's path (Fig. 5). Apparently none of the survey respondents saw a spin-off tornado. Participants, however, saw numerous funnel clouds over west Edmonton during the afternoon and evening storms (Fig. 6), but none of the funnels seemed to touchdown. Video tapes and photographs taken from the air and the ground confirmed damage at many obscure sites. The reports of wind damage by respondents in west and northwest Edmonton were supported by official observations of violent winds at the airports.

The shape of the tornado varied considerably as it travelled northwards. Shapes reported by participants at various locations (Fig. 6) were in good agreement with those shown in photographs and video tapes. Many respondents reported seeing multiple funnels, a phenomenon associated with suction vortices and an indicator of a particularly severe storm. Video tapes of the tornado were used to calculate the wind speeds at 2 locations: the estimates were lower than the speeds implied by the damage. The shapes recorded in northeast Edmonton suggested that heavy rainfall obscured the approach of the tornado during its last few minutes.

As the tornado moved northward, there was an increase in the median warning times for viewers of the tornado (Fig. 10). This trend ended when the tornado became obscured by rainfall. At most locations, those who claimed to have been assisted by radio or television broadcasts had approximately 10 minutes more warning than those without such assistance. The additional warning time provided by broadcasts did not increase significantly as the tornado moved northward. The warning times reported in other surveys (Table 2) were not consistent with one another; these were not examined for relationships between the positions of the respondents and the locations of the tornadoes. The analysis of warning times recorded by participants in the newspaper survey should interest social scientists and meteorologists studying public responses to hazards.

Figure 15 depicts the highest-priority damage types recorded by respondents. It demonstrated, as did the map of non-survey information (Fig. 5), that most of Greater Edmonton was affected by severe wind, giant hailstones, or heavy rain on July 31, 1987.

The maximum hail sizes recorded by 638 participants were plotted and thoroughly analyzed. A record was established for the largest hailstone to fall in Alberta, 264 g. The total insured loss, $250 million, was a record for natural disasters in Canada, and 50000 of the 60000 insurance claims were for hail damage to houses and automobiles.

The maximum dimensions of the largest hailstones in the hail samples collected from 50 respondents were categorized. These categories were then compared with the categories recorded by respondents. For 90% of the hailstones, the 2 categorizations were the same, though one half of the measurements by participants were at least 20% larger than those taken in the laboratory. This measurement error was attributed to rounding-up by one half of an inch.

The enormous hailstones that buffeted Edmonton were much larger and more widespread than those which fell in Calgary on September 7, 1991. The insured loss caused by the Calgary storm, however, set the record for the most expensive natural disaster in Canadian history, $400 million.

Three Alberta thunderstorms (the Calgary hailstorm of 1981, the Edmonton tornado and hailstorm of 1987, and the Calgary hailstorm of 1991) set successive Canadian records for an insurance loss caused by a natural disaster, though insurance payments for plant and infrastructure repairs and for production losses caused by the July 1996 floods in the Saguenay region of Quebec may surpass the record. (It has been suggested that a significant portion of the insured loss in Saguenay may not be attributed to surface flooding claims but to lawsuits against the owners of some of the dams. Losses caused by surface flooding are usually covered by industrial insurance, but not by homeowner policies.) The ice storms in Quebec and Ontario in January, 1998 caused extensive and lengthy power interruptions. The insurance loss has set a new Canadian record, attributed to a large degree to food spoilage.

A summary of the relationship between various hail parameters and shingle damage was provided at the end of Section 7. Claims for roof repairs typically consumed more than one half of the total insurance settlement for urban hailstorms in Alberta (Charlton and Kachman, 1996). This provided the motivation to determine the relationship between field observations of shingle damage and hailstone size.

Although there was little difference between the frequencies of thunderstorm events in Edmonton and Calgary, Edmonton had many more tornado sightings, and Calgary had more hailstorms. However, hailstorm information for Calgary dating back to the 1950's suggested that severe events have been unusually frequent in Calgary during the 1990's.

The survey responses provided an exceptional source of information about the Edmonton tornado and hailstorm, perhaps the most violent thunderstorm to strike a major Canadian city this century. If a similar storm should strike another city, any researcher who wishes to study the event would do well to consider surveying the public through the local newspapers.

Finally, this study, with a decade of hindsight woven into it, should be useful to anyone who needs information about the Edmonton tornado and hailstorm.

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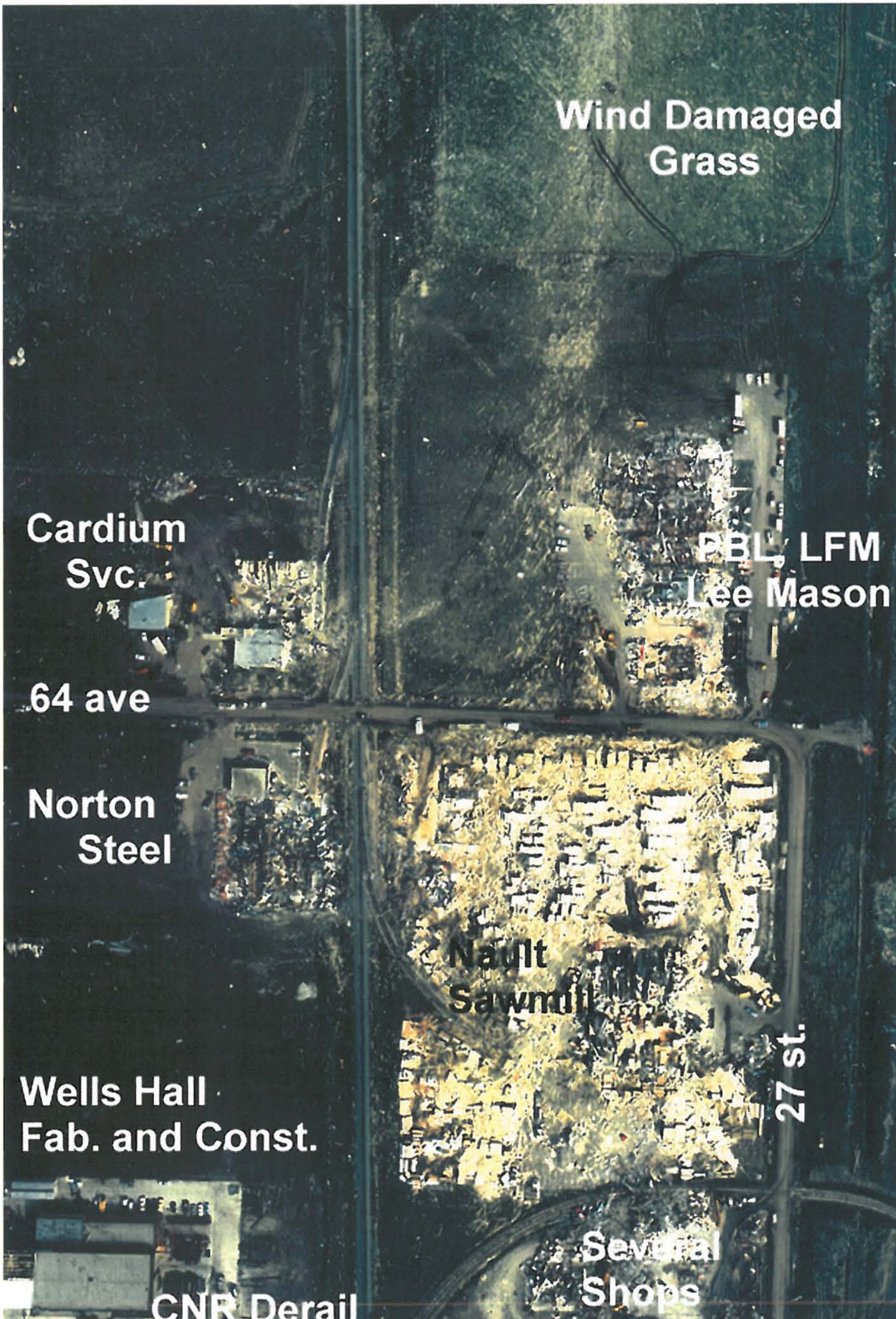
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