EUB/AGS Special Report 54

An Investigation of Geological Applications of Archival Lightning Strike Data in the Province of Alberta (North of Latitude 54° North)

Alberta Energy and Utilities Board
Alberta Geological Survey

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Contents

Figures

Appendices

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Abstract

Over the last two decades, the author has heard anecdotes recounted about mines, mineralized outcrops, hills, buildings and other objects that are repeatedly struck by lightning. As well, a search of ancient mining and exploration techniques implied that several high-grade mineral deposits were located by indigenous people observing specific hills or areas being hit more frequently than others by lightning strikes. Examples include the Lightning Ridge deposit discovered by an Aboriginal guide in Australia, the native copper and iron deposits of the Keewenaw Peninsula in Michigan, USA, that were originally found and worked by the Ojibway First Nations, and the Rammelsberg mine at Goslar, Germany, which was discovered prior to 938 AD and was in production from then until 1988.

The purpose of this study is to determine if any reliable geophysical or geological applications can be found for lightning detection networks. In the early 1960s, technology was developed that allowed the monitoring of electrical storm activity from a small number of fixed installations. Lightning detection instruments were initially deployed to protect aerospace launch vehicles and solid-state electronics. By the 1980s, lightning detection (LD) networks were being installed for the use of forestry fire protection branches. As the technology of the monitoring equipment and global positioning advanced the uses for lightning detection, LD networks expanded to provide predictive information for forest fire fighting, as well as insurance claims, storm warnings for sensitive industries and outdoor activities, such as sports events.

This study was launched to investigate whether the archived data from the Province of Alberta lightning detection network could be used to passively map geological features and more specifically assess if lightning strike lineaments might correspond to faults or major fractures in the subsurface bedrock. LD network data for northern Alberta north of about 55°N latitude were provided by Alberta Fire Protection Division. However, because of the large area involved in the study, interpretation of possible lightning strike linears was focused on the Peerless Lake map area (National Topographic System 84B), where a large number of possible linears had previously been identified by the Alberta Geological Survey (AGS). However, the contracted work herein did not provide for an extensive evaluation as to whether many, or even some, of these lightning strike linears are or may be related to underlying fault or fracture zones. This remains to be done under a separate study.

Regarding results, there is, unfortunately, a large location uncertainty associated with the interpreted lightning strike linears. That is, although Global Atmospherics Corporation specification literature indicates the lightning detection network should have a location accuracy of about ± 500 m, the scientists with the Alberta Fire Protection Division estimate the lightning detection network actually carries a positioning error of up to about ± 6.5 km, dependent on distance from the direction finder. As a result, although the inferred lightning strike linears from this study may be deemed somewhat inconclusive, enough evidence exists to suggest there may be some merit to the concept of using lightning strikes to infer subsurface faults. Having said this, although the lightning strike interpreted results for the Peerless Lake map area are interesting, because as yet no real verification has been done by AGS or others, the inferred linears in this report, and their underlying cause(s), should be treated with caution.

1 Introduction

This study is to determine if any sound geophysical or geological applications can be found for existing and future lightning detection networks. Most of the present geophysical methods date their origin to the Second World War or shortly thereafter. Remote sensing and airborne radiometrics are exceptions. Apart from large, relatively expensive reconnaissance airborne surveys (using magnetics, radiometrics and electromagnetics) and remote sensing in arid regions, (e.g., Chile, Arizona) there are no rapid and inexpensive regional geophysical surveys. The chance of success is low, but worth the risk because if there is an element of truth to the concept the rewards could be significant.

Occasionally, over the last two decades, I have heard various anecdotes about mines, mineralized outcrops, hills, buildings, et cetera that are repeatedly struck by lightning. Many geologists and prospectors can recount at least one story from first-hand experience or word of mouth. Anecdotes and folklore come from around the globe: from a South African mining engineer that worked on the Rhodesian copper belt in the 1950s; from Inuit guides in the Canadian Arctic; from gold miners in Nevada and tin miners in Cornwall; to German folklore and North American and Australian aboriginal legends.

In the early 1960s, technology began to develop that allowed the monitoring of electrical storm activity from a small number of fixed installations. Lightning detection instruments were initially intended to protect aerospace vehicles and solid-state electronics. By the 1980s, lightning detection networks (LDN) were being installed for the use of forestry fire protection branches. As the equipment evolved and positioning precision improved, uses for lightning detection networks expanded to cover insurance claims, storm warnings for sensitive industries and outdoor activities. This study was launched to investigate whether the archived data from the Province of Alberta lightning detection network could be used to passively map geological features.

A review of ancient mining and exploration techniques hinted that several high-grade mineral deposits were located by indigenous people observing specific hills or areas being hit more frequently than others by lightning strikes. Examples were found for Australia (Lightning Ridge discovered by an Aboriginal guide), the native copper and iron deposits of the Keewenaw Peninsula in Michigan that were worked by the Ojibway, and the Rammelsberg mine at Goslar, Germany (discovered prior to 938 AD and in production to 1988). Ancient prospecting methods were, in general, secretively protected by a small number of individuals, as also were metallurgy and mining techniques. Thus, early references to prospecting are often vague and contained in folklore and legends.

Preliminary studies of lightning strike data by the author have indicated interesting and unexpected observations that may relate to geological features. This field of research is not addressed in any of the geology or geophysical texts or publications that I have managed to review. If any papers or articles can be brought to my attention, I would be grateful for the knowledge. Volumes of information about atmospheric electricity can be referenced, but there seems to be a dearth of knowledge about atmospheric electricity as it may relate to whole earth geophysics. Many characteristics of atmospheric electricity remain a mystery after two centuries of study. Meteorologists and atmospheric physicists have advanced theories, but they are difficult to test and verify using existing technology.

Observations, stemming from this study, must be verified on the ground or supported by conventional scientific methods. The investigation should proceed in small increments until a basic level of understanding is attained with the data and the science. At this stage, both factors are largely unknown quantities. This project attempts to quantify repeatable observations or to identify 'pockets of predictability' in the huge volume of lightning strike data for northern Alberta. This has been a difficult study to complete because there are very few guidelines or established methods to follow. It may be a step in the wrong direction, but in the end, it was worth the risk.

Before delving into the study proper, it is important to provide the reader with some historical background and a brief introduction to the science of atmospheric electricity. There are dozens of Web sites and written summaries available to satisfy the needs of primary school children to graduate students. One of the most comprehensive articles was posted on the NASA Marshal Space Flight Center Web site, portions of which are quoted in the following section. Additional information has been included where it was considered appropriate.

2 Lightning Basics (excerpt from NASA Web site written by Dr. Hugh J. Christian)

Lightning, the thunderbolt from mythology, has long been feared as an atmospheric flash of supernatural origins: the great weapon of the gods. The Greeks both marvelled and feared lightning as it was hurled by Zeus. For the Vikings, lightning was produced by Thor as his hammer struck an anvil while riding his chariot across the clouds. In the East, early statues of Buddha show him carrying a thunderbolt with arrows at each end. Indian tribes in North America believed that lightning was due to the flashing feathers of a mystical bird whose flapping wings produced the sound of thunder.

2.1 History

Benjamin Franklin performed the first systematic, scientific study of lightning during the second half of the 18th century. Prior to that time, electrical science had developed to the point where positive and negative charges could be separated. Electrical instruments could, by rubbing together two different materials, store the charges in primitive capacitors called Leyden Jars from which sparks could be generated and observed.

Although others had previously noted the similarity between laboratory sparks and lightning, Franklin was the first to design an experiment that conclusively proved the electrical nature of lightning. In his experiment, he theorized that clouds are electrically charged; from which it follows that lightning must also be electrical. The experiment involved Franklin standing on an electrical stand, holding an iron rod with one hand to obtain an electrical discharge between the other hand and the ground. If the clouds were electrically charged then sparks would jump between the iron rod and a grounded wire, in this case, held by an insulating wax candle.

This experiment was successfully performed by Thomas Francois D'Alibard of France in May 1752 when sparks were observed to jump from the iron rod during a thunderstorm. G. W. Richmann, a Swedish physicist working in Russia during July 1753, proved that thunderclouds contain electrical charge, and was killed when lightning struck him.

Before Franklin accomplished his original experiment, he thought of a better way to prove his hypothesis through the use of a kite. The kite took the place of the iron rod, since it could reach a greater elevation and could be flown anywhere. During a Pennsylvania thunderstorm in 1752 the most famous kite in history flew with sparks jumping from a key tied to the bottom of damp kite string to an insulating silk ribbon tied to the knuckles of Franklin's hand. Franklin's grounded body provided a conducting path for the electrical currents responding to the strong electric field buildup in the storm clouds.

In addition to showing that thunderstorms contain electricity, by measuring the sign of the charge delivered through the kite apparatus, Franklin was able to infer that while the clouds were overhead, the lower part of the thunderstorm was generally negatively charged.

Little significant progress was made in understanding the properties of lightning until the late 19th century when photography and spectroscopic tools became available for lightning research.

Lightning current measurements were made in Germany by Pockels (1897-1900), who analyzed the magnetic field induced by lightning currents to estimate the current values. Many experimenters used time-resolved photography during the late 19th century to identify individual lightning strokes that make up a lightning discharge to the ground.

Lightning research in modern times dates from the work of C.T.R. Wilson, who was the first to use electric field measurements to estimate the structure of thunderstorm charges involved in lightning discharges. Wilson, who won the Nobel Prize for the invention of the Cloud Chamber, made major contributions to our present understanding of lightning.

Research continued at a steady pace until the late 1960s when lightning research became particularly active. This increased interest was motivated both by the danger of lightning to aerospace vehicles and solid state electronics used in computers and other devices as well as by the improved measurement and observational capabilities which were made possible by advancing technology.

3 Characteristics of a Storm

3.1 Lightning

As the particles within a cloud (called hydrometeors) grow and interact, some become charged, possibly through collisions. It is thought that the smaller particles tend to acquire positive charge, while the larger particles acquire more negative charge. These particles tend to separate under the influences of updrafts and gravity until the upper portion of the cloud acquires a net positive charge and the lower portion of the cloud becomes negatively charged. This separation of charge produces enormous electrical potential both within the cloud and between the cloud and ground. This can amount to millions of volts, and eventually the electrical resistance in the air breaks down and a flash begins. Lightning, then, is an electrical discharge between positive and negative regions of a thunderstorm.

A lightning flash is composed of a series of strokes with an average of about four. The length and duration of each lightning stroke varies, but they typically average about 30 microseconds.

3.2 Thunder

Sound is generated along the length of the lightning channel as the atmosphere is heated by the electrical discharge to the order of 20,000 degrees C (3 times the temperature of the surface of the sun). This compresses the surrounding clear air producing a shock wave, which then decays to an acoustic wave as it propagates away from the lightning channel.

Although the flash and resulting thunder occur at essentially the same time, light travels at 186,000 miles in a second, almost a million times the speed of sound. Sound travels at a relative snail's pace of 1100 feet per second. Thus the flash, if not obscured by clouds, is seen before the thunder is heard. By counting the seconds between the flash and the thunder and dividing by 5, an estimate of the distance to the strike (in miles) can be made.

4 Types of Lightning Discharges

4.1 Cloud-to-Ground Lightning

Cloud-to-ground lightning is the most damaging and dangerous form of lightning. Although not the most common type, it is the one that is best understood. Lightning from the negatively charged area of the cloud generally carries negative charge to Earth and is called a negative flash. A discharge from a positively charged area to Earth produces a positive flash. Most flashes originate near the lower-negative charge center and deliver negative charge to Earth. However, an appreciable minority of flashes carry positive charge to Earth. The ratio of positive to negative flashes in any given storm is approximately 1:10. These positive flashes often occur during the dissipating stage of a thunderstorm's life and are often the most powerful and destructive. They are thought to originate from the top of the thundercloud versus the base for the negative flashes. Positive flashes are also more common as a percentage of total ground strikes during the winter months.

4.2 Intra-Cloud Lightning

Intra-cloud lightning is the most common type of discharge. This occurs between oppositely charged centers within the same cloud. Usually the process takes place within the cloud and looks from the outside of the cloud like a diffuse brightening which flickers. However, the flash may exit the boundary of the cloud and a bright channel, similar to a cloud-to-ground flash, can be visible for many miles.

The ratio of cloud-to-ground and intra-cloud lightning can vary significantly from storm to storm. Storms with the greatest vertical development may produce intra-cloud lightning almost exclusively. Some suggest that the variations are latitude dependent, with a greater percentage of cloud-to-ground strikes occurring at higher latitudes. Others suggest that cloud-top height is a more important variable than latitude.

Details of why a discharge stays within a cloud or comes to ground are not understood. Perhaps a flash propagates toward the Earth when the electric field gradient in the lower regions of the cloud is stronger in the downward direction.

Depending upon cloud height above ground and changes in electric field strength between cloud and Earth, the discharge stays within the cloud or makes direct contact with the Earth. If the field strength is highest in the lower regions of the cloud a downward flash may occur from cloud to Earth.

4.3 Inter-Cloud Lightning

Inter-cloud lightning as the name implies, occurs between charge centers in two different clouds with the discharge bridging a gap of clear air between them.

The lower part of a thundercloud is usually negatively charged. The upper area is usually positively charged.

5 Description of Lightning Discharge Process

With the initial breakdown of the air in a region of strong electric fields, a streamer may begin to propagate downward toward the Earth. It moves in discrete steps of about 50 metres each and is called a stepped leader. As it grows, it creates an ionized path depositing charge along the channel, and as the stepped leader nears the Earth, a large potential difference is generated between the end of the leader and the Earth. Typically, a streamer is launched from the Earth and intercepts the descending stepped leader just before it reaches the ground. Once a connecting path is achieved, a return stroke flies up the already ionized path at close to the speed of light. This return stroke releases tremendous energy, bright light and thunder. Occasionally, where a thunderstorm grows over a tall Earth grounded object, such as a radio antenna, an upward leader may propagate from the object toward the cloud. This "ground-to-cloud" flash generally transfers a net positive charge to Earth and is characterized by upward pointing branches.

The initial breakdown and propagation are similar for intra-cloud lightning, but the discharge generally occurs between regions of opposite charge. Without the benefit of a connecting path to the Earth, intra-cloud lightning does not produce a return-stroke-like feature. Nevertheless, tremendous energy, bright light, and thunder are still produced by intra-cloud lightning.

6 The Global Electric Circuit

During fair weather, a potential difference of 200 to 500 kV exists between the Earth's surface and the ionosphere, with a fair weather current of about 2 pA/m2. It is widely believed that this potential difference is due to the worldwide distribution of thunderstorms.

Present measurements indicate that an average of almost 1 Ampere of current flows into the stratosphere during the active phase of a typical thunderstorm. Therefore, to maintain the fair weather global electric current flowing to the surface, one to two thousand thunderstorms must be active at any given time. The vast majority of these storms occur in the equatorial region. While present theory suggests that thunderstorms are responsible for the ionospheric potential and atmospheric current for fair weather, the details are not fully understood."

Credits for the above “Lightning Basics” to “The Global Electric Circuit” sections include: (a) Written by: Dr. Hugh J. Christian, Senior Scientist, Earth Science and Applications, NASA/Marshall Space Flight Center, AL, and Melanie A. McCook, Senior Research Project Coordinator, Chemistry Department, University of Alabama in Huntsville; (b) Edited by: Dr. George P. Miller, Assistant Research Professor, Chemistry Department, University of Alabama in Huntsville, and Morgan W. McCook, Consultant.

7 Scope of Study

The Alberta Fire Protection Branch generously contributed the lightning strike data for the 1992 through 2000 fire seasons for northern Alberta (54°N to 60°N and 110°E to 120°E). The master file was subdivided into individual databases for each year of collection. A one-page example of the data file format can be found in Appendix I. The data were further windowed to isolate the Peerless Lake map area (NTS 84B, 56°N to 57°N and 114°E to 116°E). The positive and negative strike results were studied both separately and in combination. The analysis of lightning strike data from other localities has shown that a preliminary visual review of the data is beneficial. Chronological (month by month) plots were generated and cross-referenced with each other. Plots of peak amplitude ranges were produced. Frequency plots, highlighting areas that are subject to repeated lightning strikes (multiplicity), appeared to show promise and were investigated.

If persistent trends and features were observed in the data (for any given year), their repeatability was compared with other years, screened for cultural interference and plotted on a digital terrain or geological base map.

8 Study Products

The earlier studies of lightning strike detection systems indicated several potentially informative diagnostic techniques; the ones completed for this report include

- plotting combined, negative and positive strikes;
- plotting frequency of strikes to establish areas or spots that are struck repeatedly, storm after storm and year after year;
- plotting intensity (amplitude) of strikes;
- plotting overlay on a geological base;
- plotting on topographic base to identify contributions from roads, pipelines, power lines, lakes, rivers and elevation;
- plotting overlay on regional aeromagnetic survey coverage;
- Fast Fourier Transform (FFT) the data to study and analyze power spectrum; and
- attempt to identify 'pockets of predictability,' where the statistical odds of repeat lightning strikes or higher intensities are observed.

9 Technical Objectives

The key technical objective of this proposal is to determine if information derived from specific lightning strikes can be used as a geophysical reconnaissance tool for the detection of mineralization or geological structures. The processed results are saved as ArcView geo-referenced TIF files that can be imported into a GIS database that includes topography, hydrology, geology, geochemistry, aeromagnetics, gravity and remote sensing. Deliverables include a structural interpretation and target priority map for the Peerless Lake map area (NTS 84B) and any pertinent GIS layers.

10 Background

The background to this proposal can be explained in detail. I cannot, however, refer the reader to current industry practice because I could not identify any prior applications of the concept or locate research in this area. Several industry colleagues were asked to inform me of any papers or articles that might touch on this area of research, but they also had negative results.

Most geophysical methods in current use are evolutions of technologies and concepts that date back to the Second World War. Remote sensing and airborne radiometrics are exceptions. Survey instruments, data recording and processing methods have seen tremendous technological improvements, especially in the last 15 years, but the underlying science remains the same. Apart from large, relatively expensive reconnaissance airborne surveys (using magnetics, radiometrics and electromagnetics) and remote sensing in arid regions (e.g., Chile, Arizona, Mongolia), there are no rapid and inexpensive regional geophysical surveys. The Geological Survey of Canada has collected aeromagnetic and gravity data over most of the country. The aeromagnetic program began in the late 1940s and early 1950s and still contains large gaps. I do not know if a precise dollar figure has ever been published for the combined cost of the National Gravity and Aeromagnetic programs, but it is undoubtedly in the millions of dollars.

I conjecture that a scientific basis for this study may involve four natural phenomena that can be measured and observed, but for which mechanisms and explanations remain ambiguous: spontaneous polarization (self potential), atmospheric electricity, telluric currents and electro-geochemistry. Spontaneous polarization has been known and measured since 1829; magnetotellurics since 1847; AFMAG since the late 1950s and modern electro-geochemistry since at least 1973. Lightning location networks have been in routine use since the early 1980s with first data routinely archived around 1984. Brief descriptions of the various processes that I think may be involved are listed below along with references for additional details.

10.1 Spontaneous Polarization

Spontaneous Polarization (Self Potential and Induced Polarization; Telford 1990; "The Electrochemical Mechanism of Sulfide Self-Potentials" Sato and Mooney, 1960)

"Mineralization potentials have usually been the main interest when prospecting with the self-potential method. They are associated with the sulphides of the metals, with graphite, and sometimes with the metal oxides such as magnetite. The most common mineralization potential anomalies occur over pyrite, chalcopyrite, pyrrhotite, sphalerite, galena and graphite.

The mechanism of spontaneous polarization in mineral zones is not completely understood, although several hypotheses have been developed to explain it.

Long period telluric currents (> 1 min) may produce background potentials, as large as several hundred millivolts per kilometre over resistive ground."

10.2 Induced Polarization

"The Induced Polarization method is based on the electro-chemical phenomenon of "over-voltage," that is, on the establishment and detection of double layers of electrical charge at the interface between ionic and electronic conducting material when an electrical current is caused to pass across the interface." (Telford 1990)

With the work of Dr. Harold O. Seigal (time-domain) and Dr. Philip G. Hallof (frequency domain) in the early 1950s, the Induced Polarization method developed into a much more reliable and repeatable survey technique than self-potential. Self-potential was subsequently considered a background noise and by various means removed from the data.

Frequently Induced Polarization surveys are disrupted by approaching thunderstorms. The lightning discharges are detected by the receiver and often give the operator ample advance warning to suspend the survey.

10.3 Telluric and Magnetotelluric Currents (Telford 1990)

"The existence of natural large-scale earth currents was first established by Barlow in 1847 in the course of studies on the first British telegraph system. Long-term records of telluric currents were made at Greenwich, Paris and Berlin in the late nineteenth century.

The source of these currents has been fairly definitely located outside the earth. Periodic and transient fluctuations can be correlated with diurnal variations in the Earth's magnetic field, caused by solar emission, aurora, and so forth. These activities have a direct influence on currents in the ionosphere; it is thought that the telluric currents are induced in the earth by ionospheric currents.

One source of higher-frequency current fluctuations is electric storms. Although their location is to some extent random, there are three major storm centers, all located in equatorial regions - Brazil, Central Africa and Malaya. Some of the thunderstorm energy is converted to electromagnetic fields that are propagated in the ionosphere-Earth interspace. The weak currents induced by these fields in the subsurface are useful in telluric and magnetotelluric prospecting, particularly because they have amplitude peaks at several distinct frequencies - 8, 14, 760 Hz, and so on. These same electromagnetic fields are also employed in the AFMAG method."

10.4 AFMAG (Ward et al., 1958)

"The initials denote audio frequency magnetic fields. This is a natural-source dip-angle method, presented by Ward in 1958 and published in 1959. The main origin of the primary field is lightning discharge (spherics) associated with worldwide thunderstorm activity as in audio frequency MT work. There are other minor sources of energy such as corpuscular radiation interaction with the Earth's magnetic field and manmade noise. The EM energy is propagated between the earth surface and the lower ionosphere as in a waveguide. The frequencies associated with AFMAG are in the ELF range, from 1 to 1,000 Hz, with the best reception apparently between 100 and 500 Hz. Over the ELF range an AFMAG record is quite similar to the telluric current record.

AFMAG has several real and potential advantages over the artificial source methods. No transmitter is required. The frequency is comparatively low and hence the depth of penetration is probably greater than for a local source. Because the primary field is uniform, at least instantaneously, over the survey area, all the conductors are energized uniformly. At times this may be a disadvantage, however, because it may emphasize large-scale, relatively poor conductors at the expense of smaller concentrated bodies.

There are two specific disadvantages with AFMAG. The first is the effect of large random changes in the amplitude and direction of the inducing field, that produce corresponding variations in the signal strength as well as changes in anomaly shape and size. The second is that the random fluctuations in direction may make it very difficult to locate the azimuth of the horizontal field."

10.5 Electrogeochemistry

"An Electrochemical Model for Element Distribution Around Sulphide Bodies"
B. Bolviken and O. Login, Geological Survey of Norway, 1974

"The existence of natural self potentials (SP) at certain ore deposits has been known for more than a century, and SP measurements are widely used in prospecting. The origin of these potentials is not completely understood, although largely explained by Sato and Mooney (1960) (Appendix II) who state that: "Self potentials associated with a sulphide ore body result from the ohmic potential drop within the country rocks. The electric current is produced by separate but simultaneous reduction of oxidizing agents near the surface and oxidation of reducing agents at depth."

11 How do the Previous Exploration Methods Relate to this Study?

Many massive sulphide orebodies and graphitic zones have measurable self-potential anomalies. Generally they are measured in millivolts to a volt or two. One deposit in Peru has a -12 volt response, but it is an exception. Could a negative self-potential anomaly of 1000 millivolts surrounded by a sea of positively charged host rock generate negatively charged streamers that could contact positive stepped-leaders, followed by high energy positive lightning strikes?

Because the primary field for AFMAG is uniform, at least instantaneously, over the survey area, all the conductors are energized uniformly. Some of the last AFMAG surveys completed in the late 1960s and early 1970s seemed to show promise for the mapping of faults and shear zones. If mineral deposits, faults, shear zones and other structures can be energized by telluric currents and/or audio frequency magnetic fields, might they be more likely to attract lightning strikes by sending out streamers as an electrical storm approaches?

If lightning strikes near an orebody, mineralized deposit or zone of higher conductivity and eddy currents are induced, will the secondary electromagnetic fields attract additional, concentrated lightning strikes? If lightning strikes an orebody directly, could the flow of galvanic currents attract additional strikes? Current flow should be maintained for a short time after the applied current ceases. If an electrical storm is in the immediate area, could the conductive body generate a higher number of streamers?

Is it realistic to believe that any of the above scenarios might have more influence on atmospheric electricity than elevated topography and distinct land-water boundaries?

12 Province of Alberta Lightning Detection Network

The Alberta Forest Protection Division operates a lightning detection system, developed by Lightning Location and Protection (LLP) of Tucson, Arizona. The system enables fire managers to monitor cloud-to-ground lightning activity on a provincial basis.

The LLP system uses a unique characteristic of cloud-to-ground lightning to accurately differentiate it from cloud-to-cloud discharges and calculate its location. The initiation of cloud-to-ground strike releases an intense, short burst of electrical energy. This rapid burst of energy propagates through the atmosphere in a manner similar to radio waves. The unique characteristic of the waveform is its extremely rapid rise to peak energy. This distinctive feature of cloud-to-ground lightning provides the means for real-time detection.

The following passage highlights the fact that for most engineering applications the intensity of the lightning strike is more significant than the polarity.

13 Mechanism of the Lightning Strike

"Characterization of the Electrical Environment," Bell Northern Research Ltd.,
D.W. Bodle, A.J. Ghazi, M. Syed, R.L. Woodside, U of T Press, 1976

"Photographic observations indicate that a lightning discharge may be initiated either from a cloud or from the peak of a tall structure on the ground. The polarity of the lightning discharge or stroke is of little practical concern to the protection engineer, because a surge propagated through an object in either direction has the same effect."

One object of this study is to examine whether the polarity of a lightning strike has any significance to reconnaissance exploration. If the answer is yes, the second is to determine if a practical exploration application is possible.

14 Principles of the Alberta Forest Protection Service Lightning Detection Network

(excerpt from Frequently Asked Question (FAQ) About Lightning by Kerry Anderson, Canadian Forest Service, Edmonton, Alberta, full article reproduced in Appendix II)

14.1 Lightning Detection

How is lightning detected? How are lightning maps made?

Most forest and weather services now use the wide band magnetic gate design lightning detector manufactured by Lightning Location and Protection Inc. of Tucson, AZ. The LLP lightning detection system determines the time and location of a lightning flash by triangulating information from direction-finder stations situated in the network. These data are stored on magnetic tape. Maps can be processed to show the location and polarity of lightning flashes that occur over a period of time.

The LLP lightning detection system has three components: the direction finder, the position analyzer and the remote display processor.

The direction finder senses the electromagnetic field radiated by a lightning flash using two erect, orthogonal wire loop antennas and a horizontal flat plate antenna. The antennas' bandwidths are from 1 kHz to 1 MHz. The radiated field of a lightning flash induces a current in the loops. The voltage signal measured in the loops is related to the flash's generated magnetic field strength by the cosine of the angle between the loop antenna and the direction to the flash. By comparing the voltage signals from the two loops, a direction to the flash can be determined. The flat plate antenna is used to resolve the 180-degree ambiguity associated with the calculations.

The direction finder can discriminate cloud-to-ground flash from other forms of lightning or noise by the electromagnetic signature. When the stepped leader reaches the ground, the return stroke is triggered producing a sharp voltage rise. This telling factor distinguishes a cloud-to-ground flash from other electromagnetic noise.

The direction finder sends the data of each registered lightning flash to the position analyzer. The position analyzer triangulates data from direction finders to locate the position of a lightning flash. If the flash is in line with or directly between two direction finders (called the baseline), the position analyzer uses the ratio of the signal strengths as well.

From the position analyzer, users can view a map of the lightning data on a remote display processor. The display can focus on desired time and location windows covered by the detection network and can show up to 30 000 flashes.

15 Observations and Results

The Alberta Fire Protection Division maintains a Web site where basic facts about the Province of Alberta Lightning Detection Network can be referenced. One image, posted on the site, is a map showing the cumulative lightning strike data for all of Alberta, grouped by the number of strikes per square kilometre per year (Figure 1). On the east side of the Rocky Mountain Foothills, a higher concentration of lightning strikes is apparent, spreading toward the northeast in the direction of Edmonton and the Swan Hills and less so toward Calgary in the south. The area of higher lightning strike is very roughly coincident with the buff-coloured Paleocene Paskapoo Formation shown on the accompanying geological map of Alberta (Figure 2).

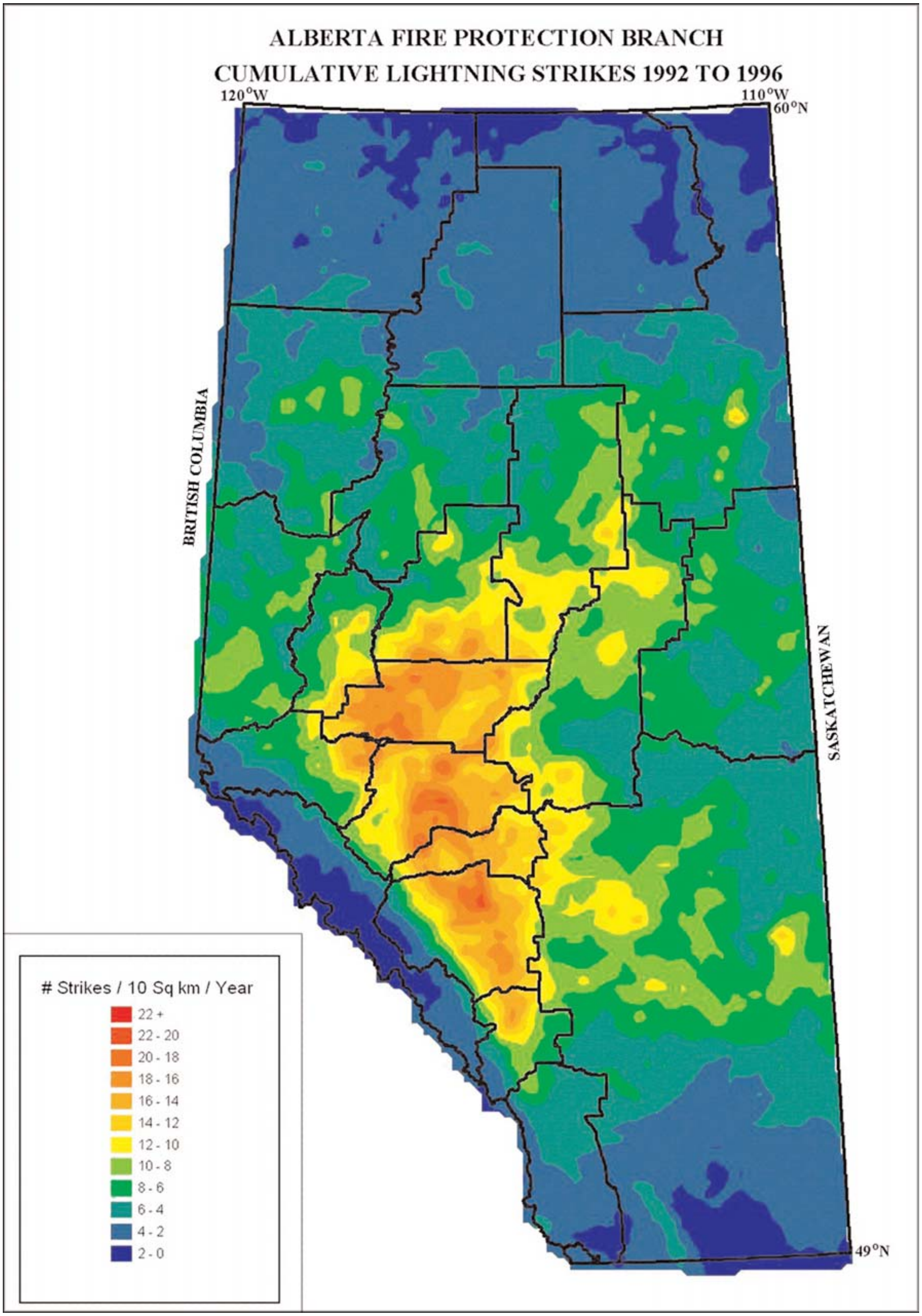

Figure 1. Province of alberta Fire Protection Branch Cumulative Lightning Strikes 1992 to 1996.

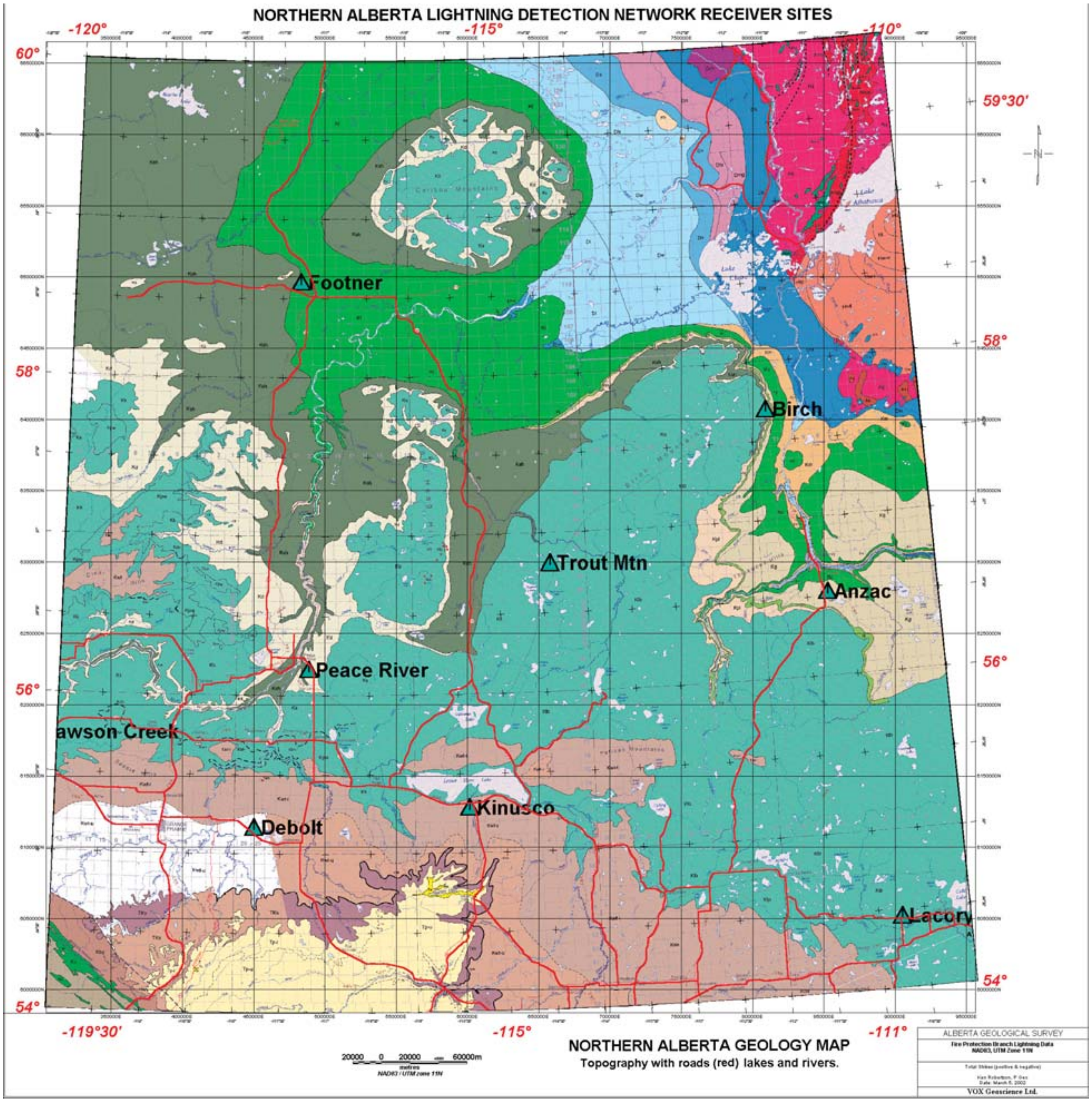

Figure 2. EUB/AGS Geological Map of Alberta.

Throughout the fire season, daily summaries of lightning activity are posted to the site. Two images from the 2000 season are shown (Figure 3) to illustrate the extreme changes in thunderstorm activity. The upper image shows the 49 cumulative lightning strikes recorded on August 15th, most of which were located in the Northwest Territories and Saskatchewan. Of the 49 lightning strikes, 32 carried a positive charge and 17 were negative. Statistically, the ratio of positive to negative lightning strikes is approximately 1:10. The lower panel records the lightning strikes from two weeks earlier on August 1st. The lightning strikes are colour-coded by time shown in the lower right portion of the legend column. Of the total 17 169 lightning strikes, 1333 were positive charge and 15 836 were negative (~1:12). Although these images were recorded two weeks apart, they are included to illustrate the rapid changes that can occur over a 24-hour period and to demonstrate how the Lightning Detection Network and Position Analyzer collect the data.

15.1 Northern Alberta Regional Area

The next section of the report will focus on the northern part of the province from latitude 54° north to 60° north and from 110° west to 120° west. A total of 20 direction finders transmit data to the position analyzer in the Edmonton Fire Centre (see Appendix III for a listing of LDN sites). The locations of the eight sensors in northern Alberta and a ninth located at Dawson Creek, B.C., are shown on the accompanying vector line and shaded topographic relief maps (Figures 4 and 5).

A series of maps has been compiled for the area mentioned above displaying the total lightning strikes recorded in any given fire season. The years 1992 through 2000 are all shown (Figures 6 through 14). The first observation to note is best illustrated on the 1998 map (Figure 12). Around some of the receiver sites, the lightning strikes show linear or arcuate fanning patterns. As mentioned previously, the position analyzer triangulates the data from the direction finders to determine the position of a lightning flash. Often, when the flash is in line with or between two direction finders, the position analyzer is unable to determine a unique solution. This artifact of the lightning detection network is called a baseline. Some direction finders show minimal baseline effects (e.g., Trout Lake), whereas others repeatedly exhibit severe effects (e.g., Birch and Debolt). The level of baseline 'fanning' also varies from season to season, probably in relation to the tracks of storms with respect to the direction finders and the number of lightning flashes.

The next set of maps (Figures 15 through 20) begins with the 1998 Total Lightning Strikes or Flashes plot, with the obvious baseline fans, then proceeds through the fire season, month by month. May 1998 (Figure 16) shows a moderate level of lightning activity over most of the study area with a higher concentration along the west side. The level of activity in June (Figure 17) is not much higher, but the greatest concentration of flashes has shifted toward the east. July (Figure 18) shows a strong cluster of strikes around the Kinusco direction finder in the south central portion of the area and minor baseline artifacts at the Peace River, Birch and Anzac sensors. In August (Figure 19), the overall level of lightning activity increases. Prominent baseline artifacts are recorded at Debolt, Peace River, Birch and Anzac. A strong concentration of flashes is observed in the northwest corner of the area. By September (Figure 20), the number of lightning flashes is very light throughout the entire study area. This serves to demonstrate what is essentially common knowledge: that the level of thunderstorm activity builds in the early summer, peaks in July and August and trails off dramatically in the early fall.

To provide reference against a well-studied and sound geophysical survey method, the available Geological Survey of Canada aeromagnetic coverage for the northern Alberta study area has been colour-shaded and contoured and overlain with the direction finder locations, roads and drainage (Figure 21). A datum of 58 000 nanoteslas (~gammas) is removed from the magnetic readings and the overall

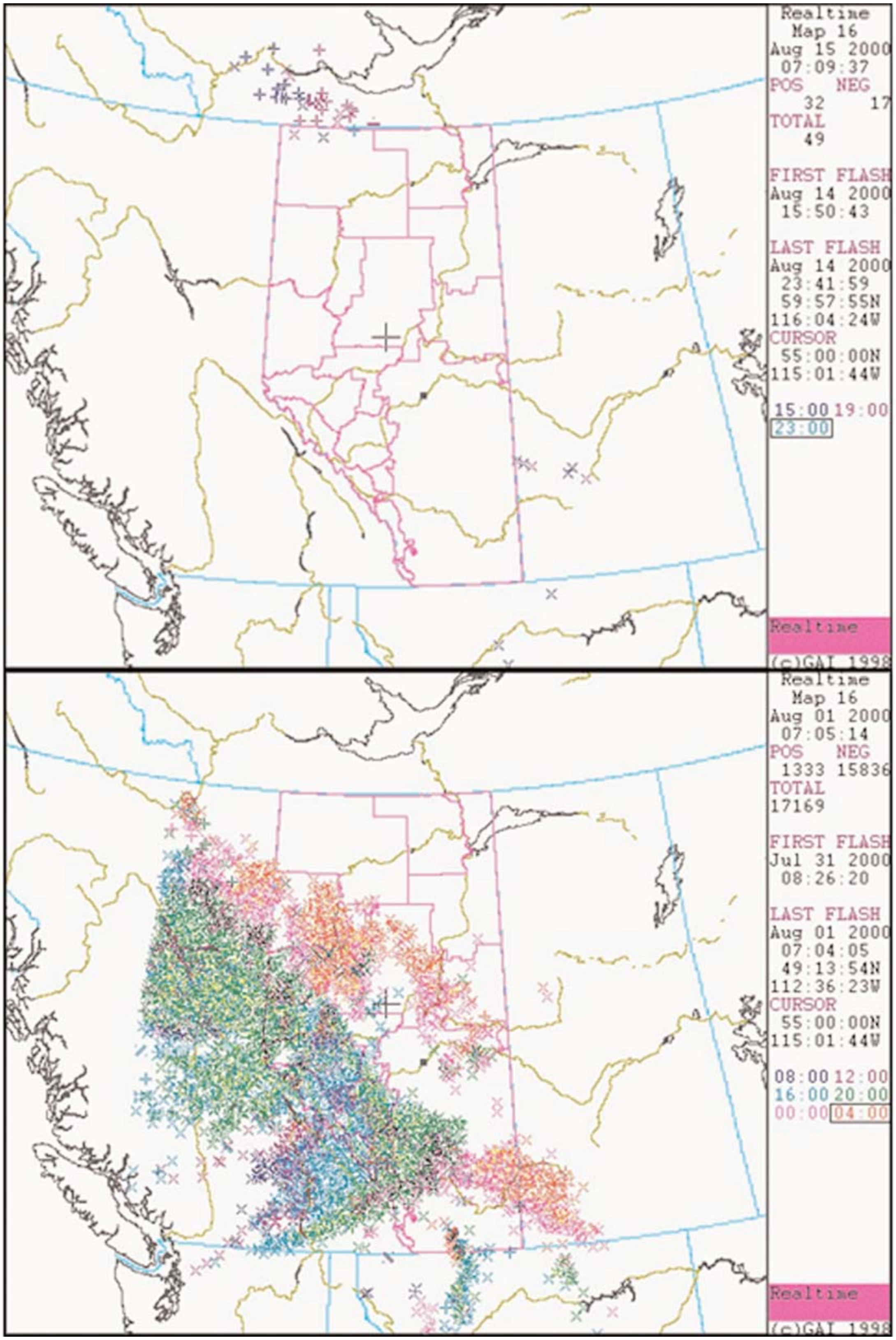

Figure 3. Screen output of the Remote Display Processor (RDP).

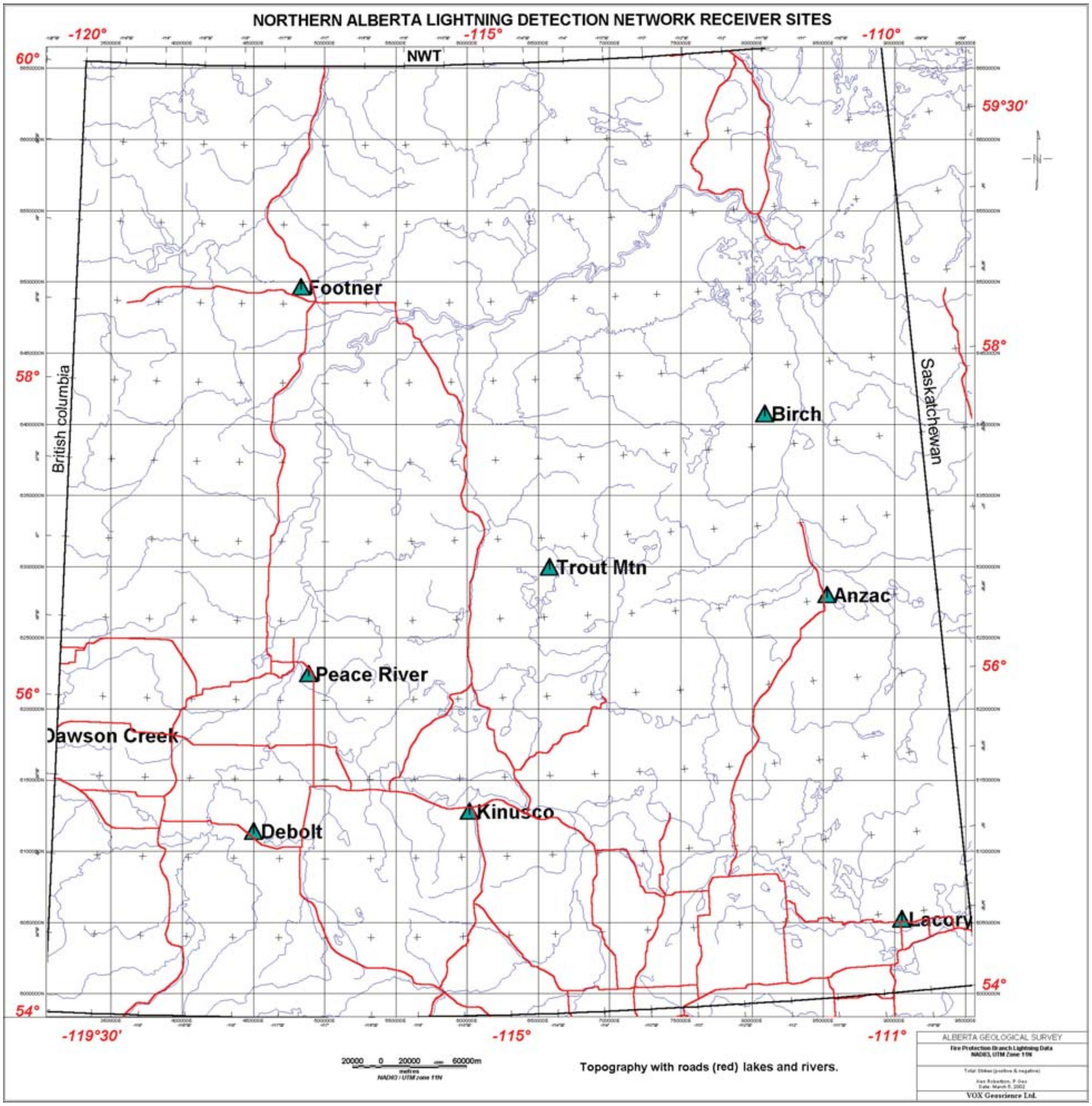

Figure 4. Locations of province of Alberta lightning detection network direction finders.

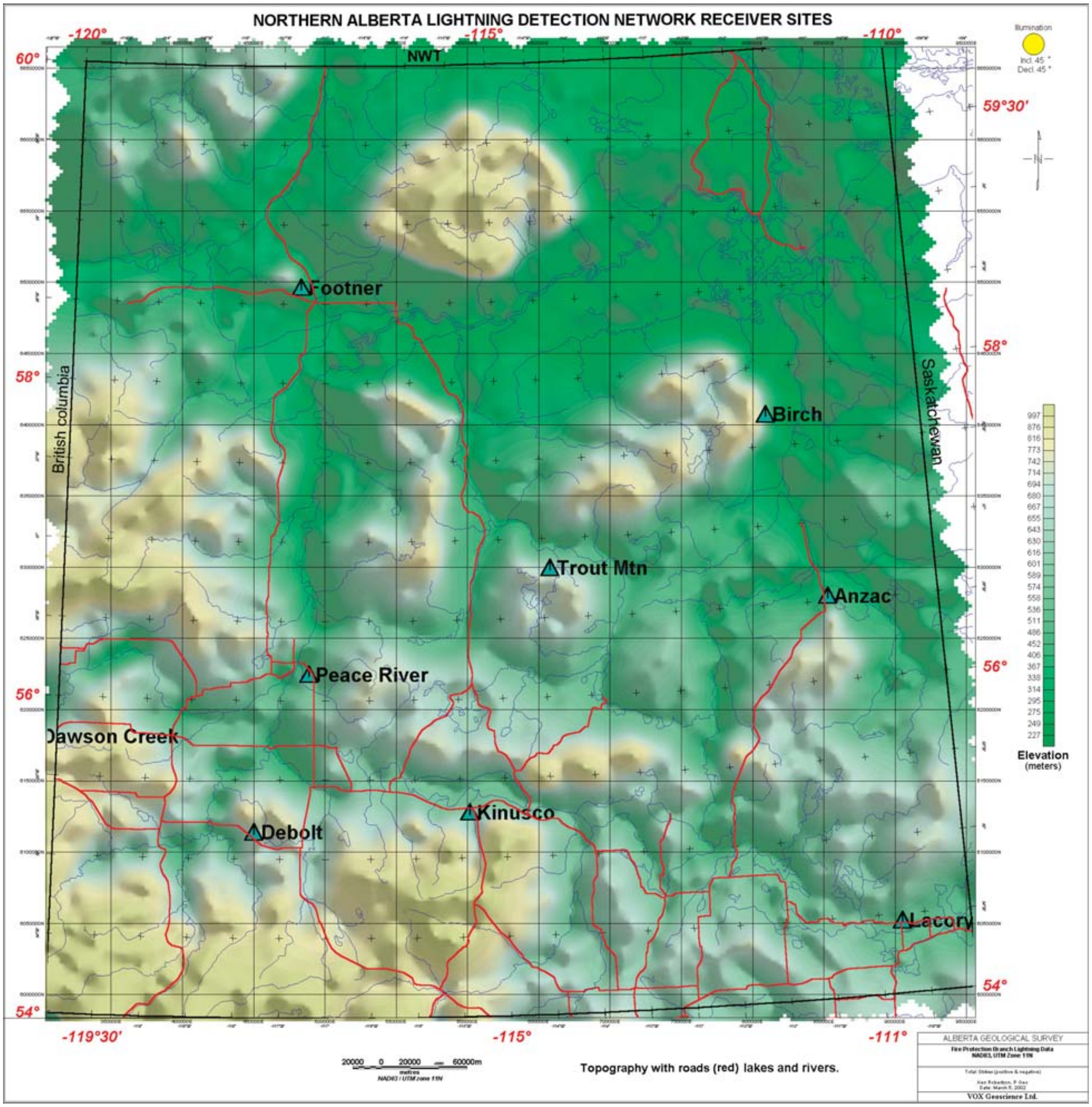

Figure 5. Alberta lightning detection network direction finders with shaded relief elevation.

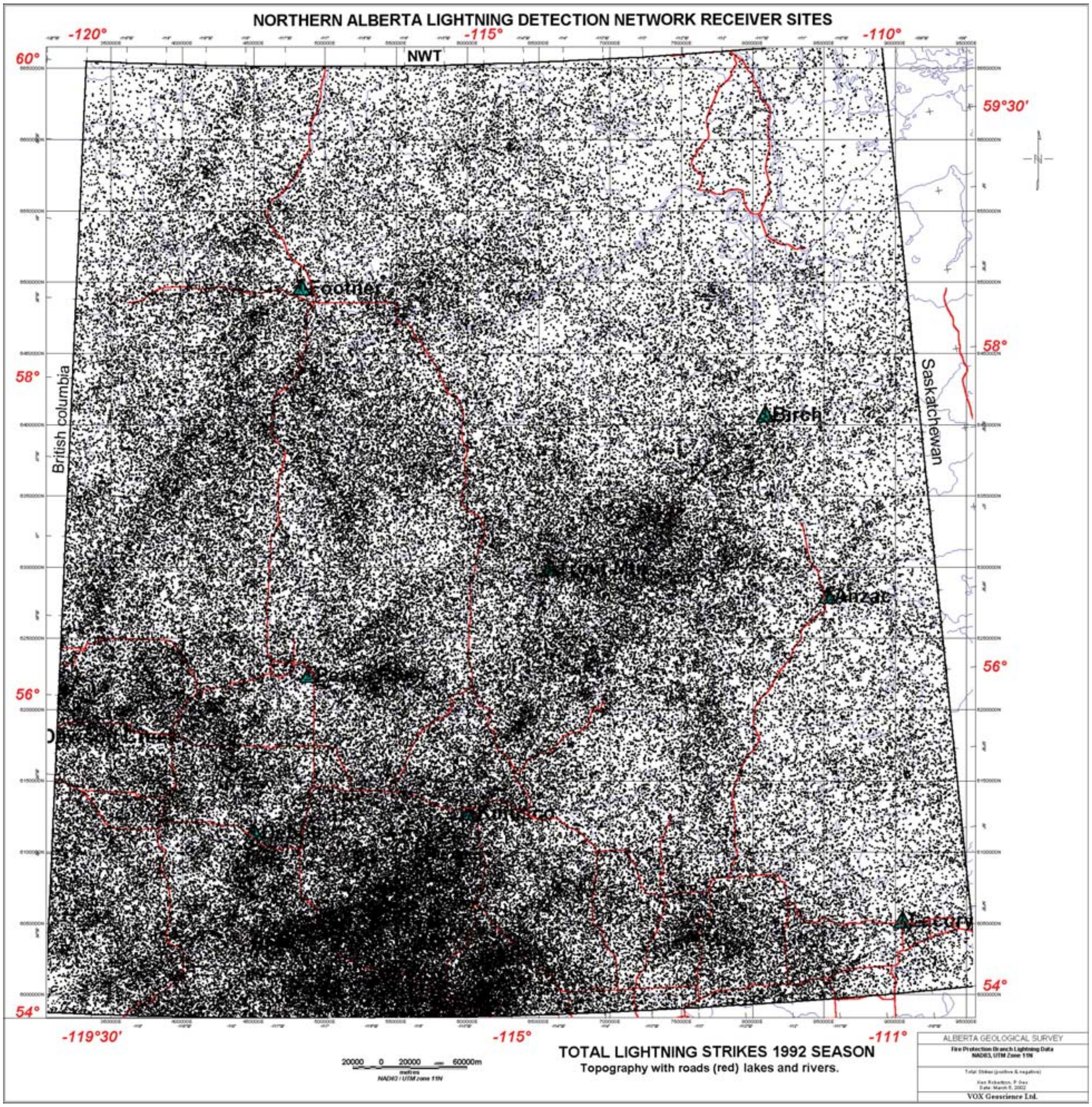

Figure 6. Total lightning strikes for the 1992 fire season.

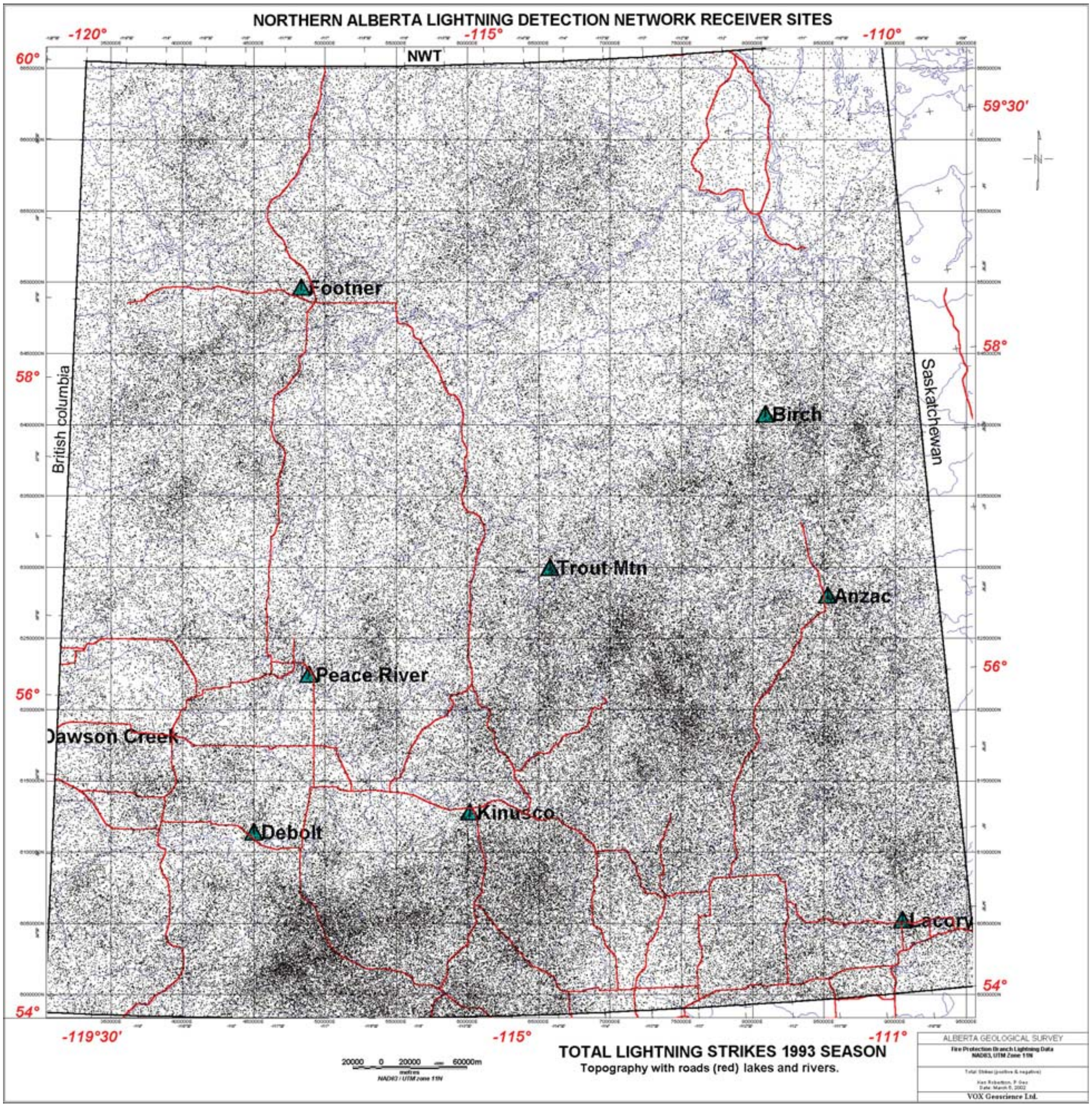

Figure 7. Total lightning strikes for the 1993 fire season.

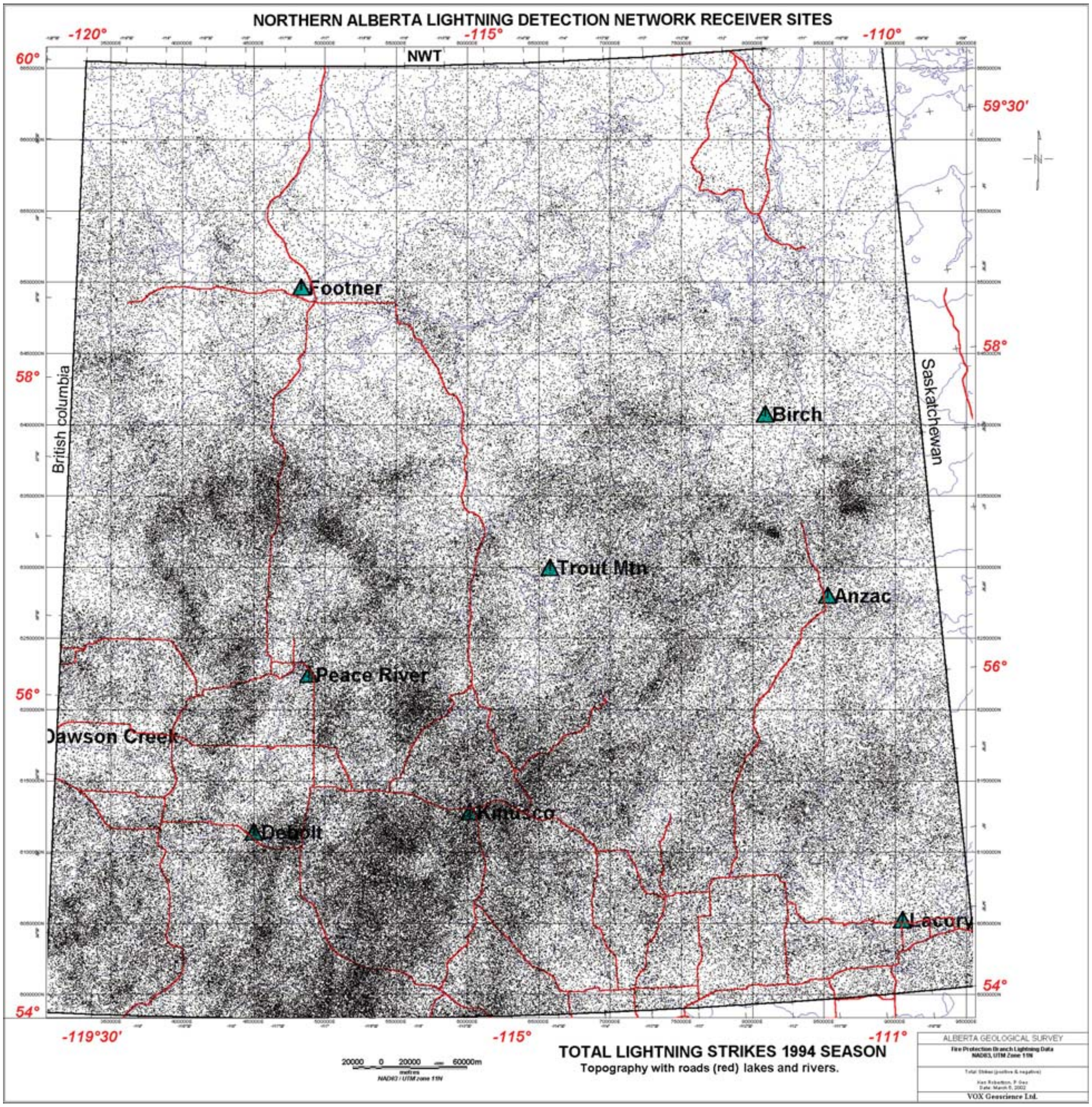

Figure 8. Total lightning strikes for the 1994 fire season.

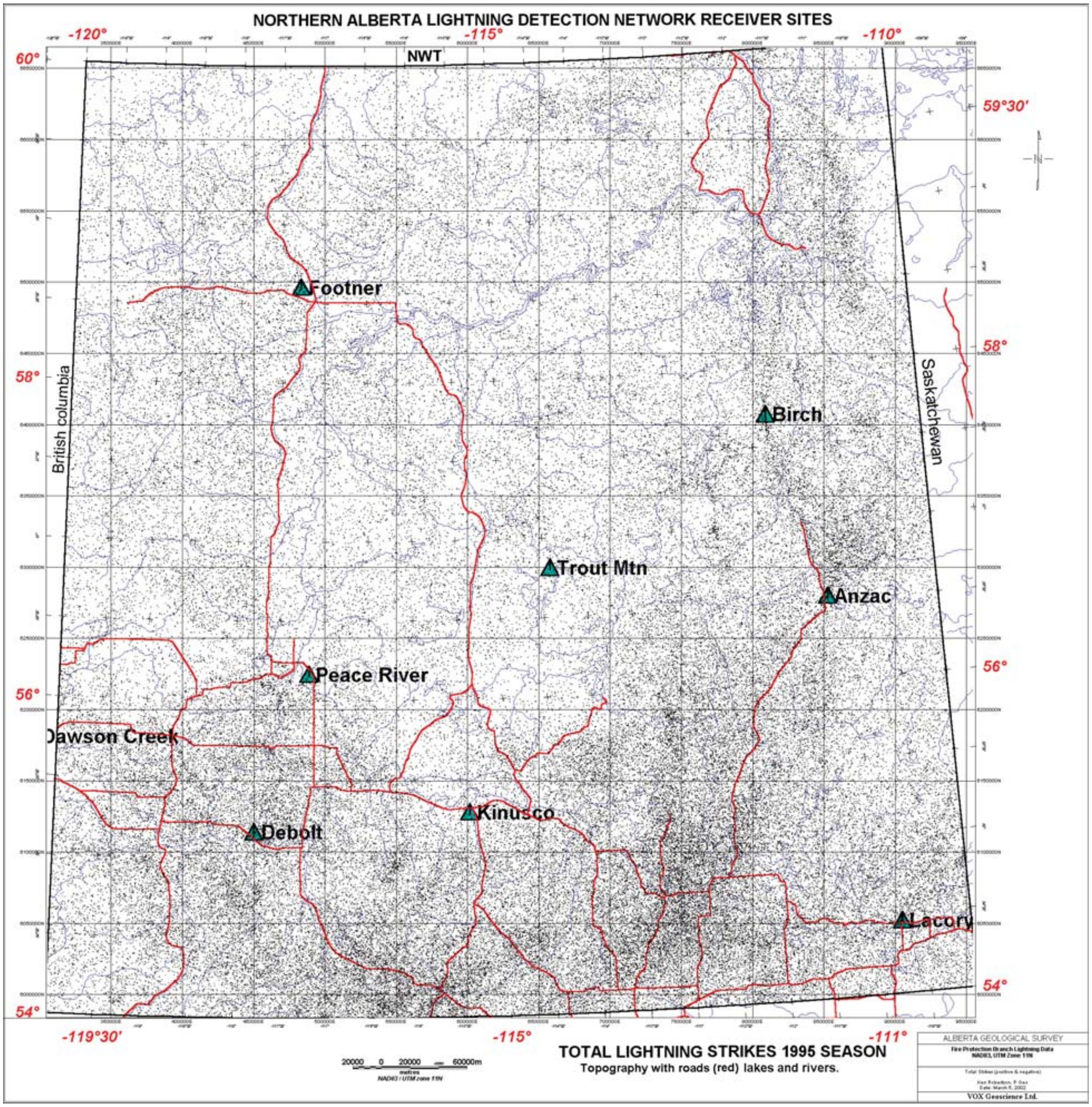

Figure 9. Total lightning strikes for the 1995 fire season.

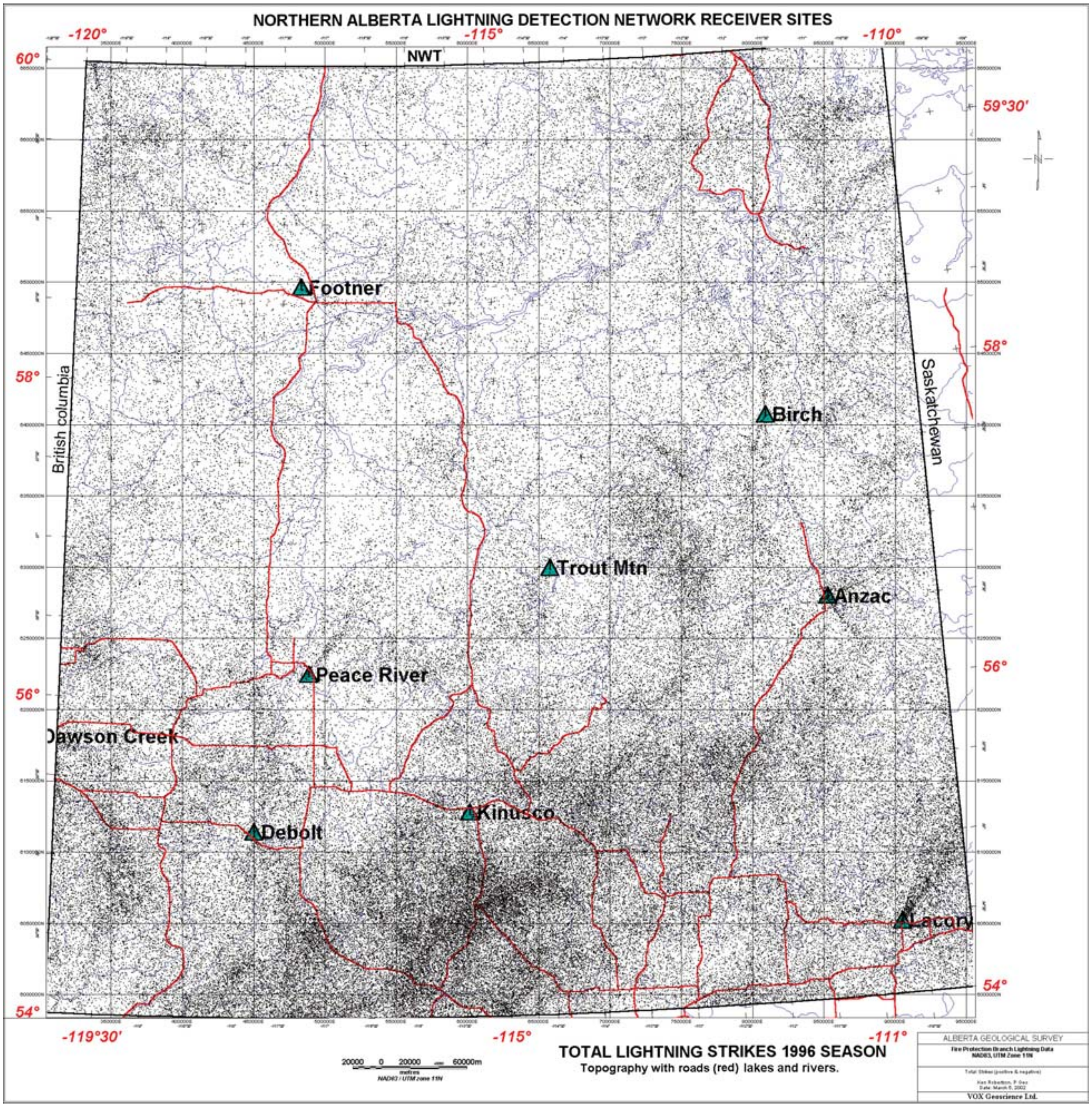

Figure 10. Total lightning strikes for the 1996 fire season.

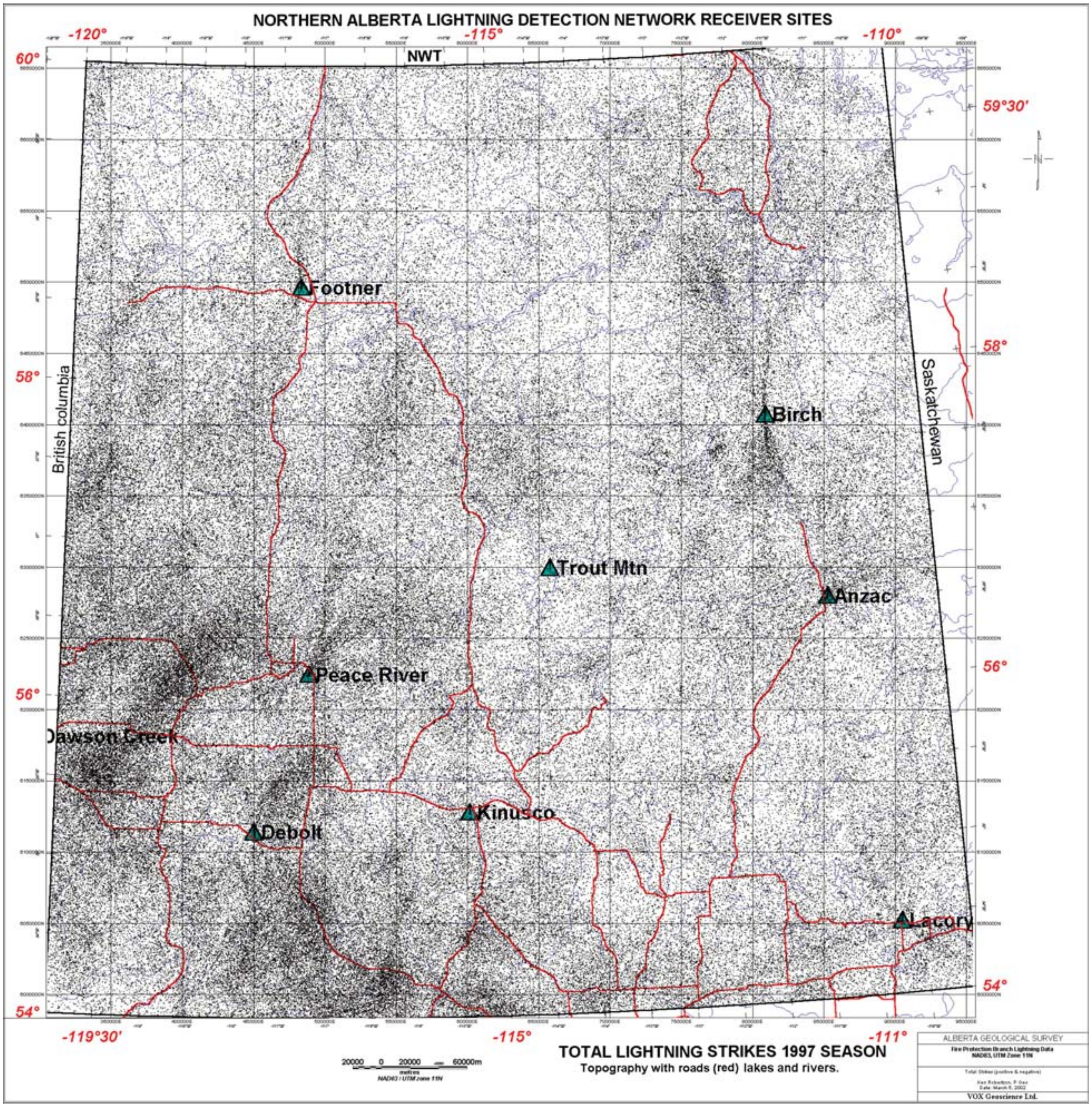

Figure 11. Total lightning strikes for the 1997 fire season.

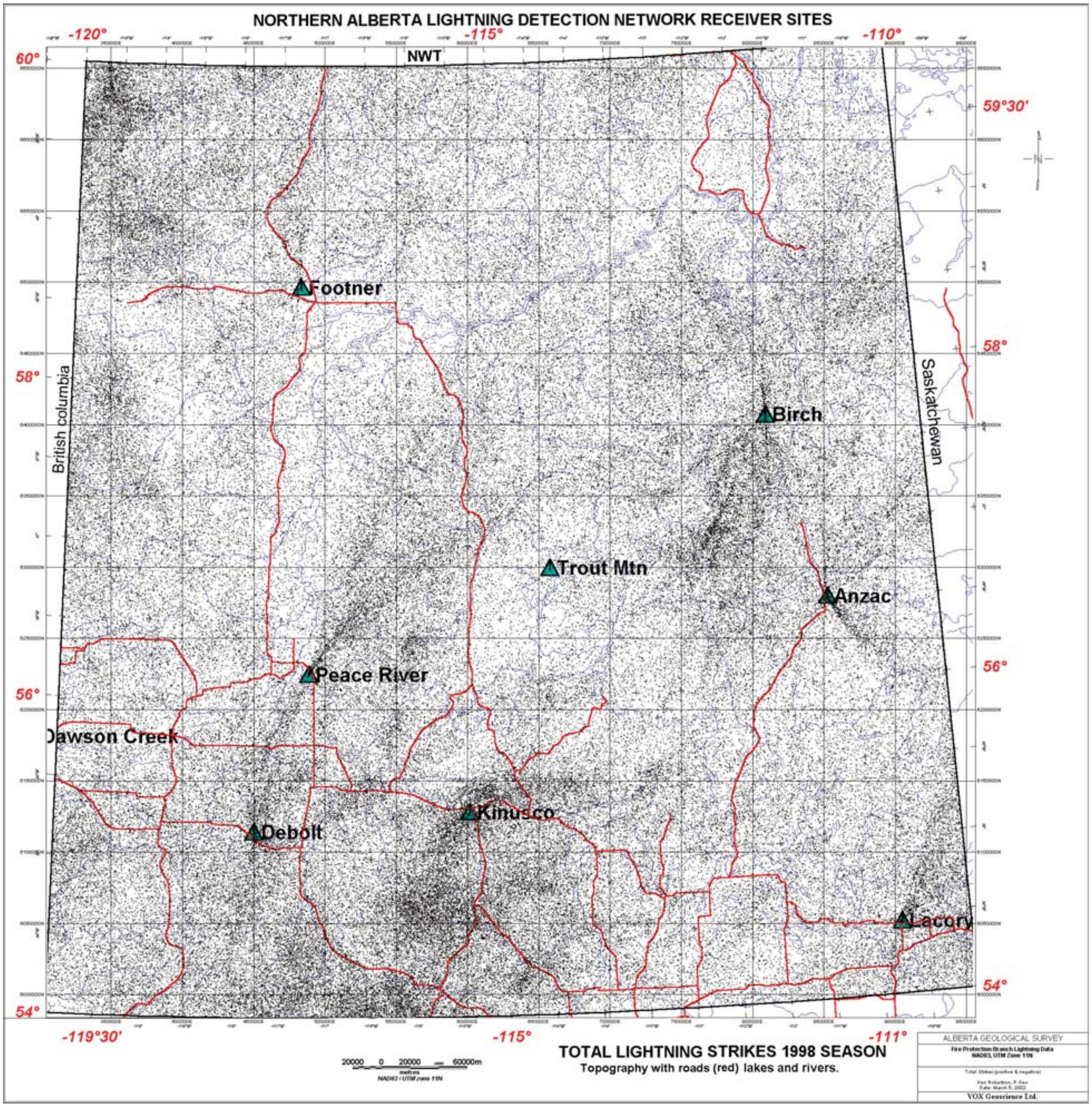

Figure 12. Total lightning strikes for the 1998 fire season.

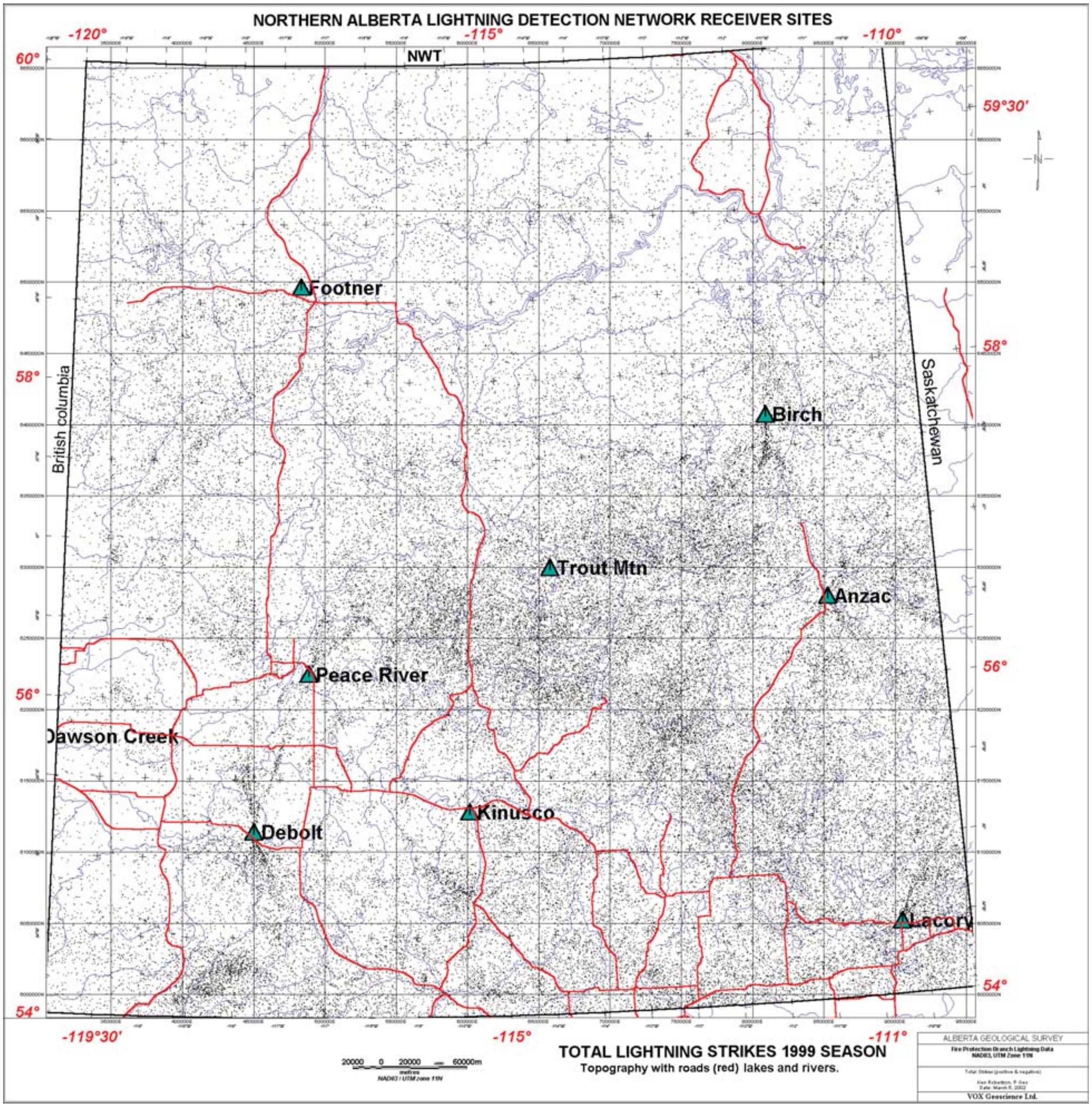

Figure 13. Total lightning strikes for the 1999 fire season.

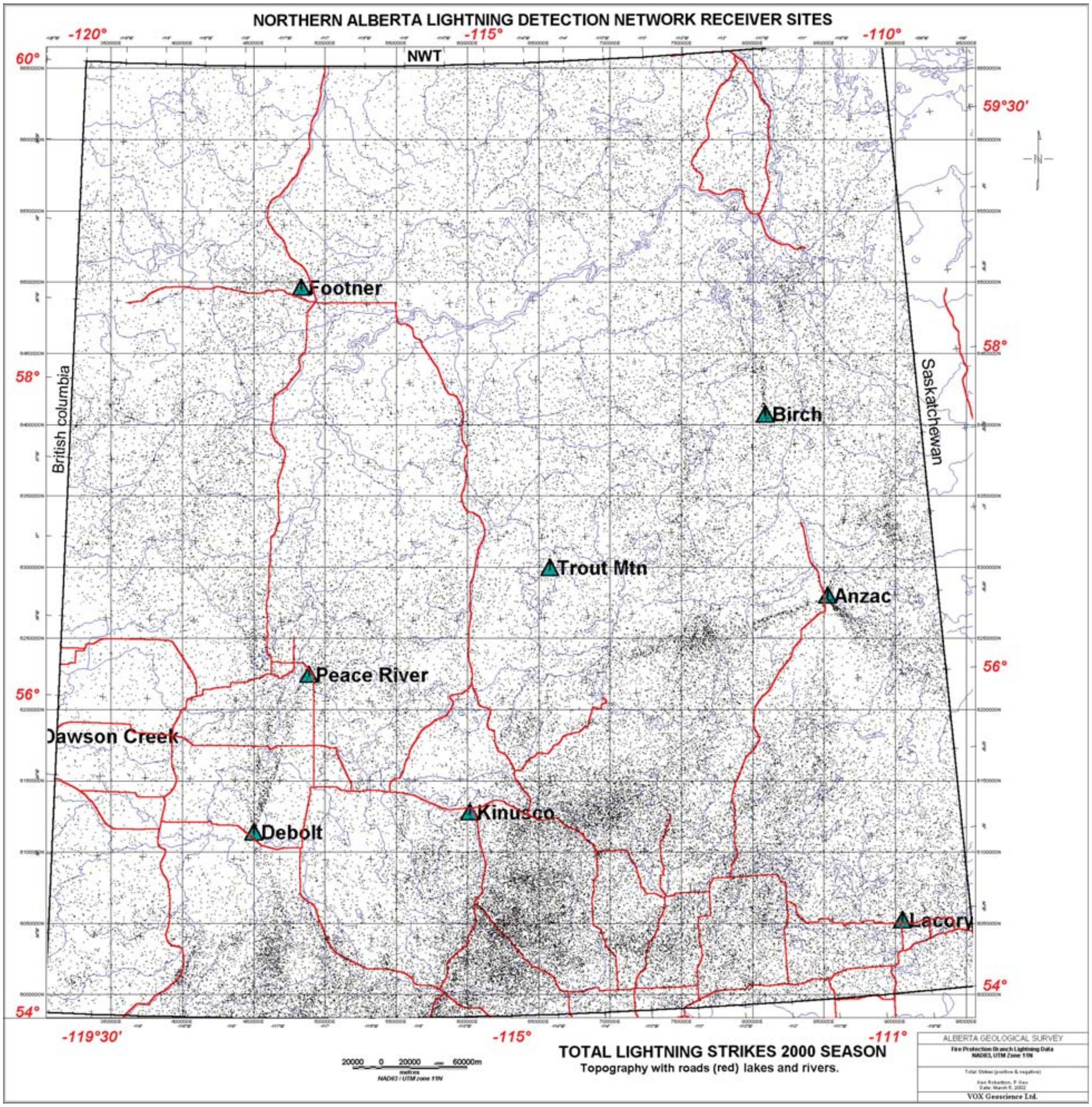

Figure 14. Total lightning strikes for the 2000 fire season.

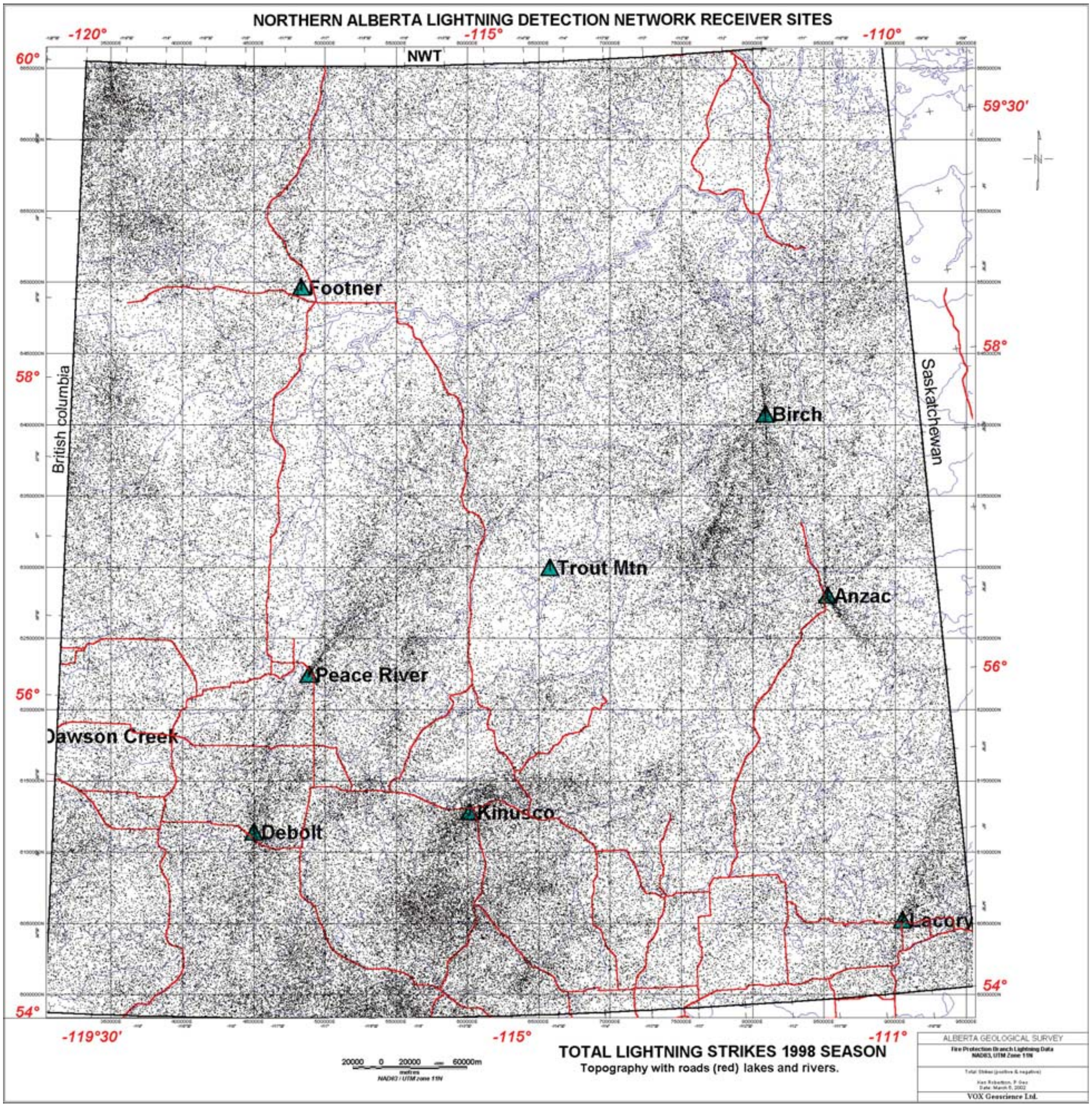

Figure 15. Total lightning strikes for the 1998 fire season (duplicate of Map 12).

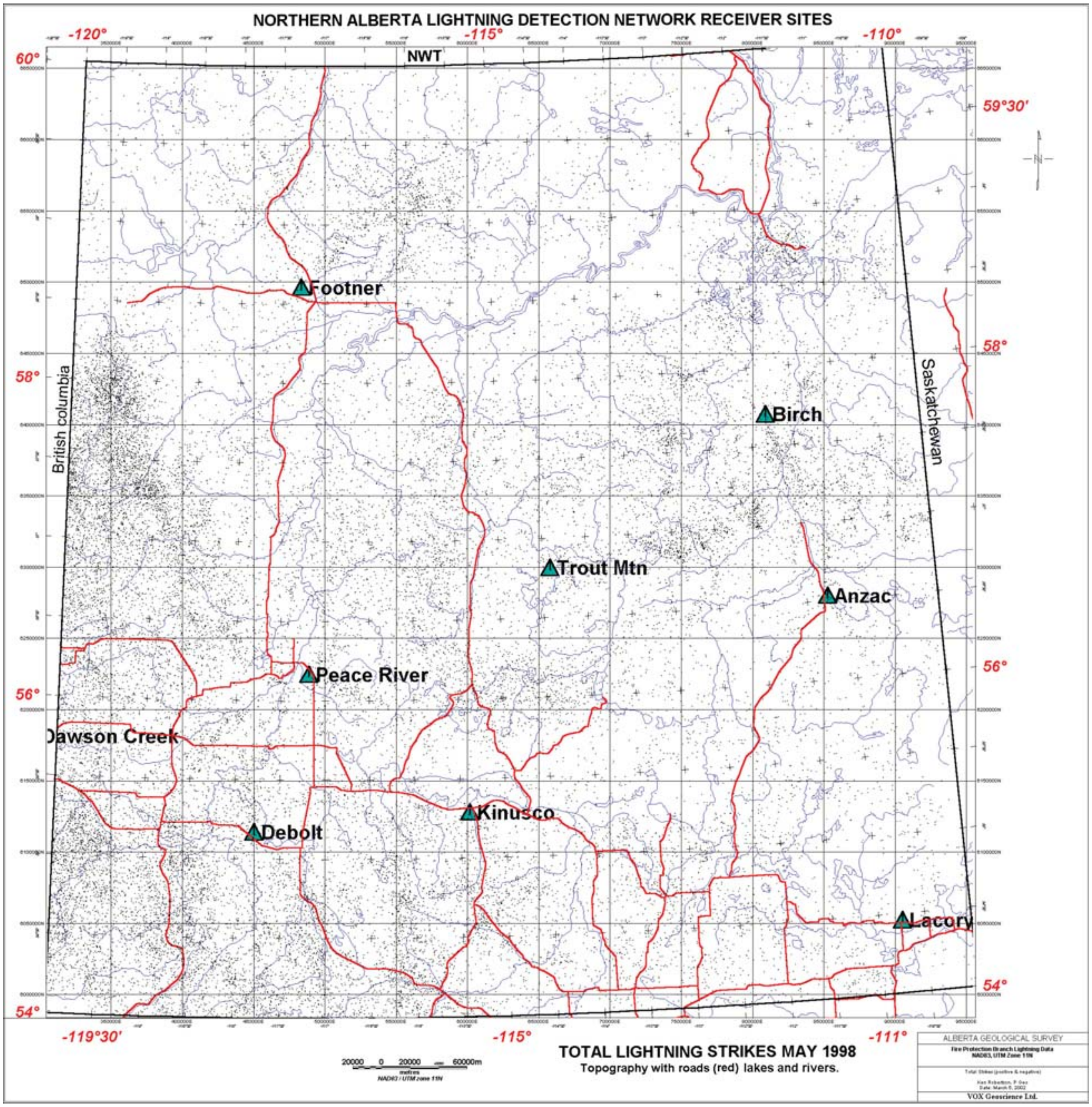

Figure 16. Total lightning strikes for May 1998 fire season.

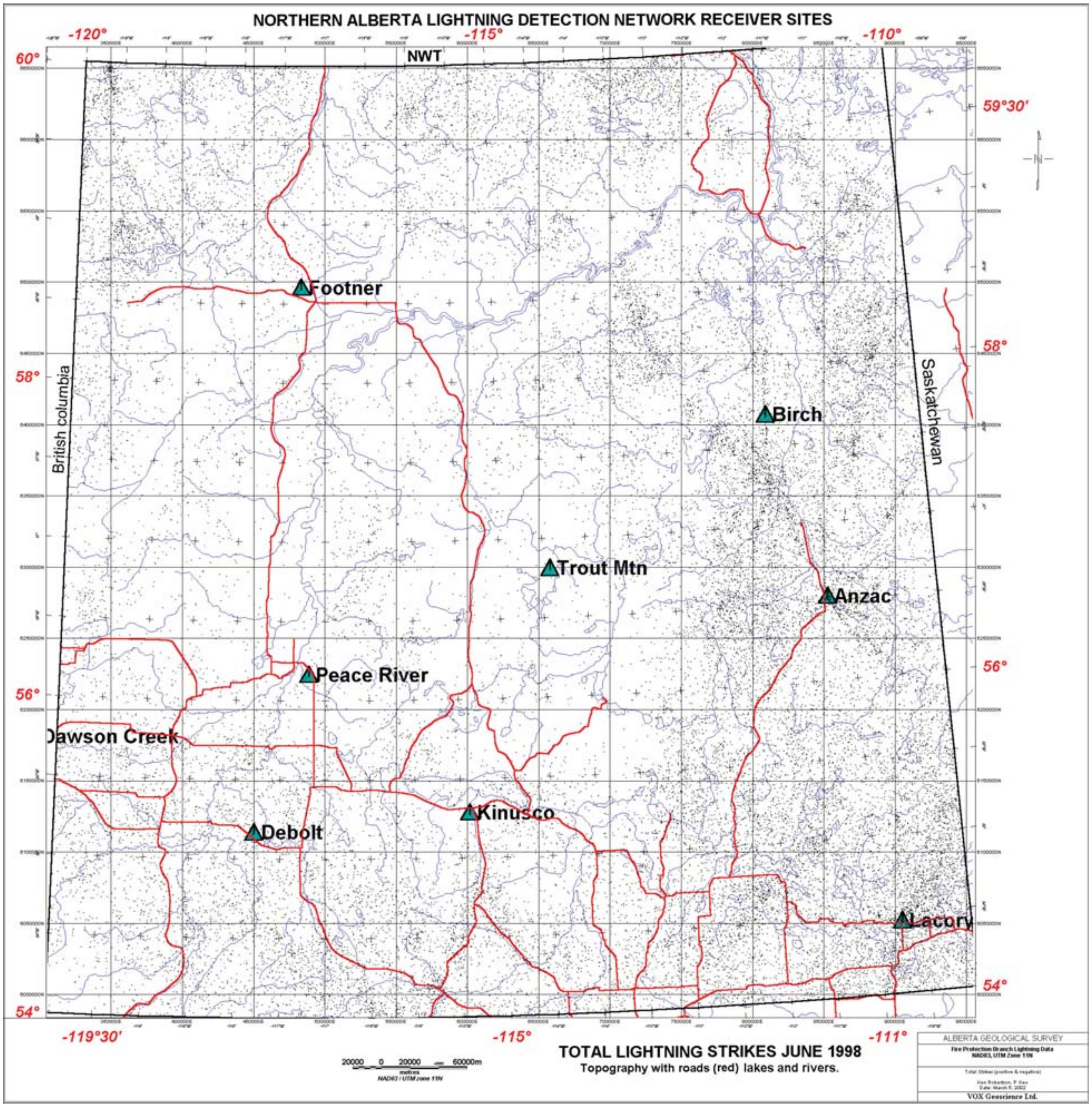

Figure 17. Total lightning strikes for June 1998 fire season.

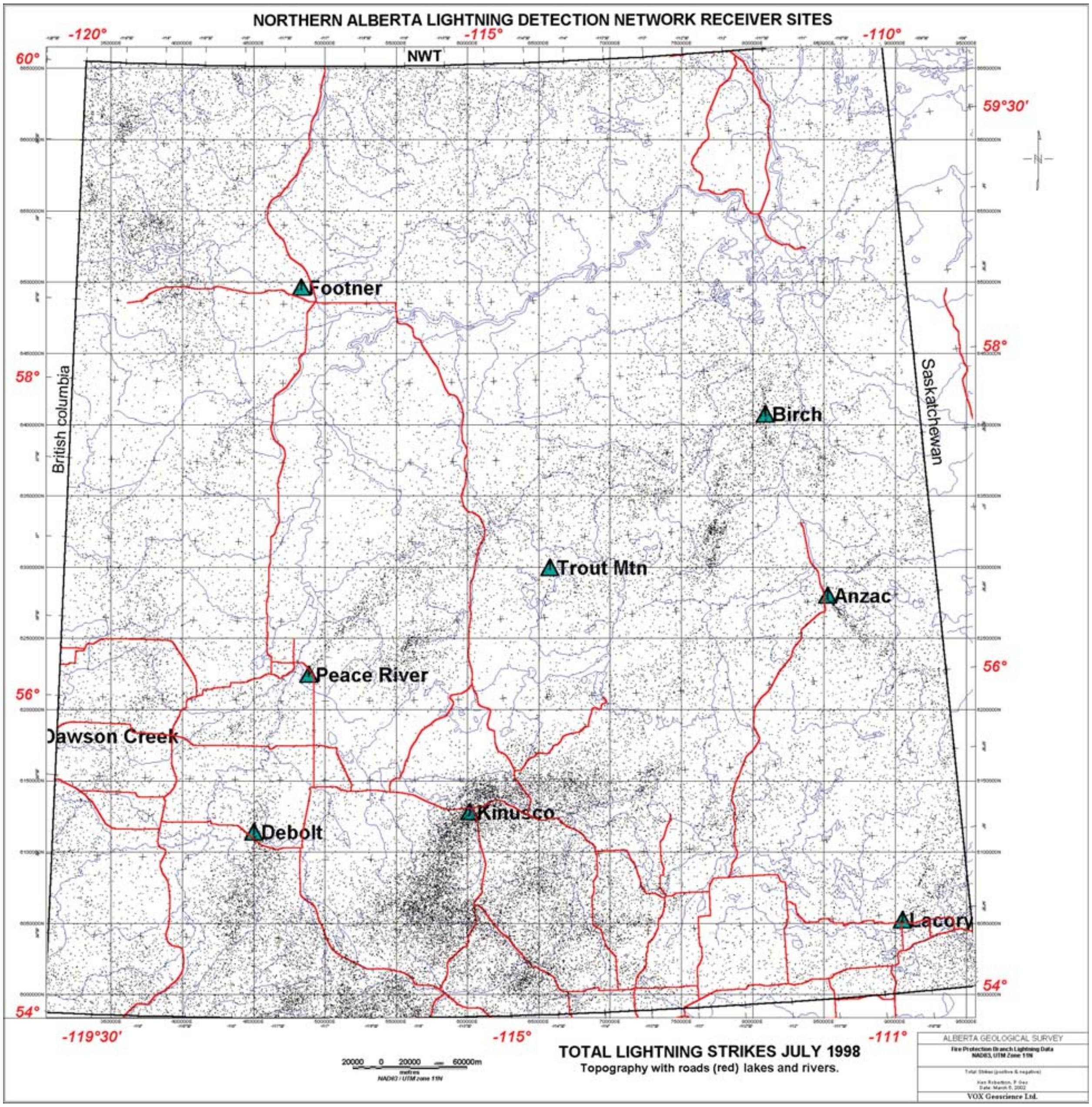

Figure 18. Total lightning strikes for July 1998 fire season.

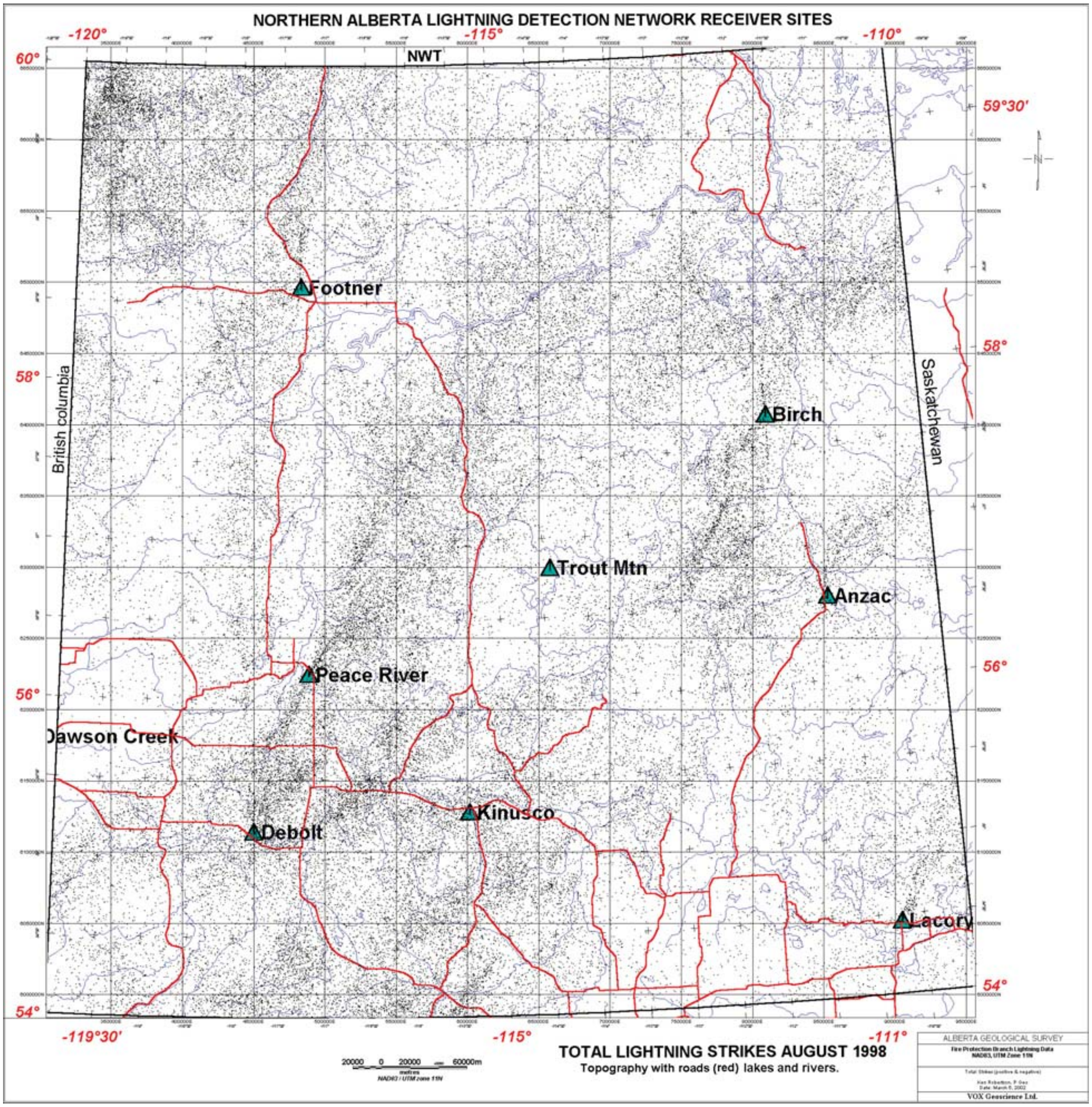

Figure 19. Total lightning strikes for August 1998 fire season.

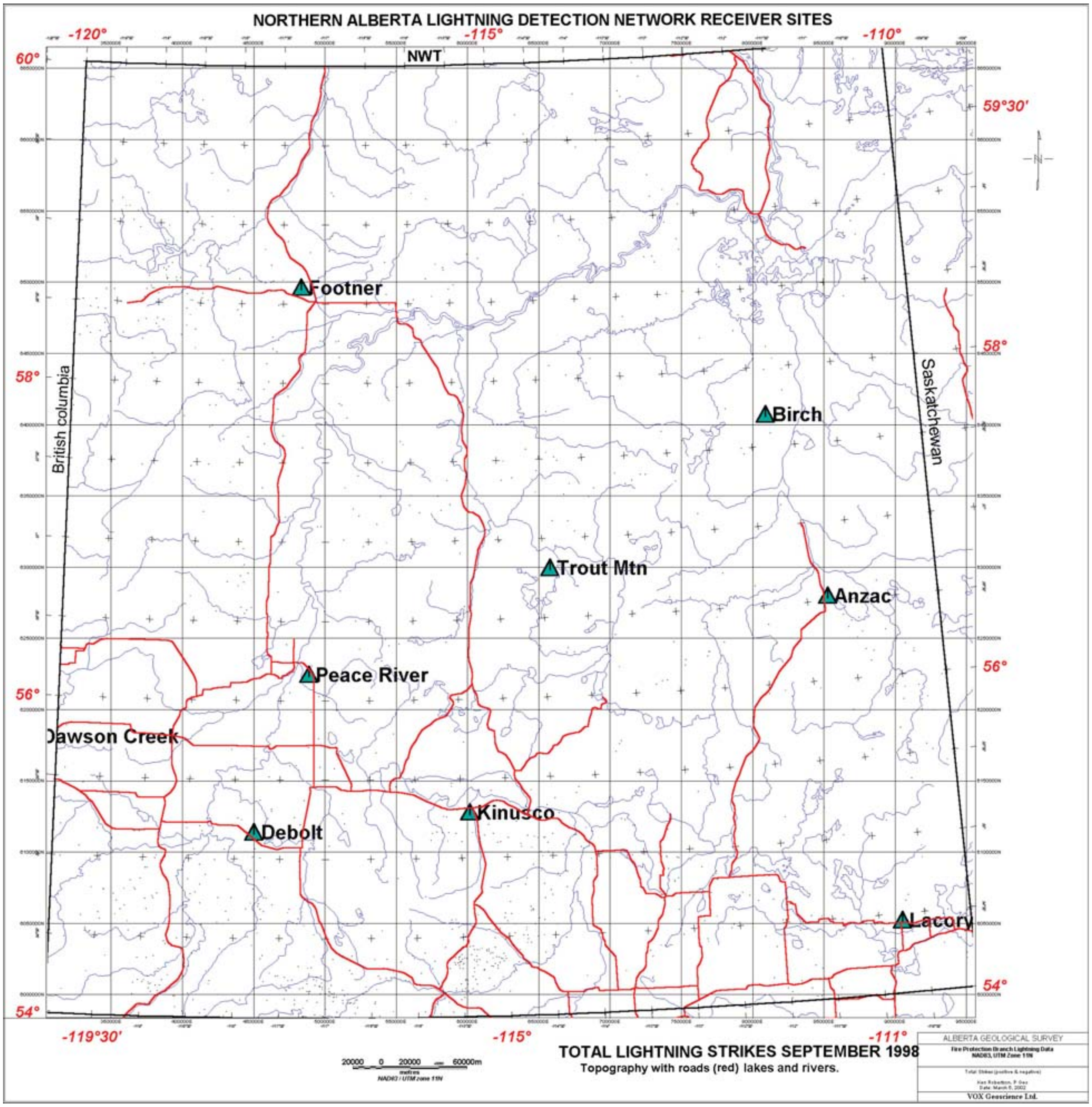

Figure 20. Total lightning strikes for September 1998 fire season.

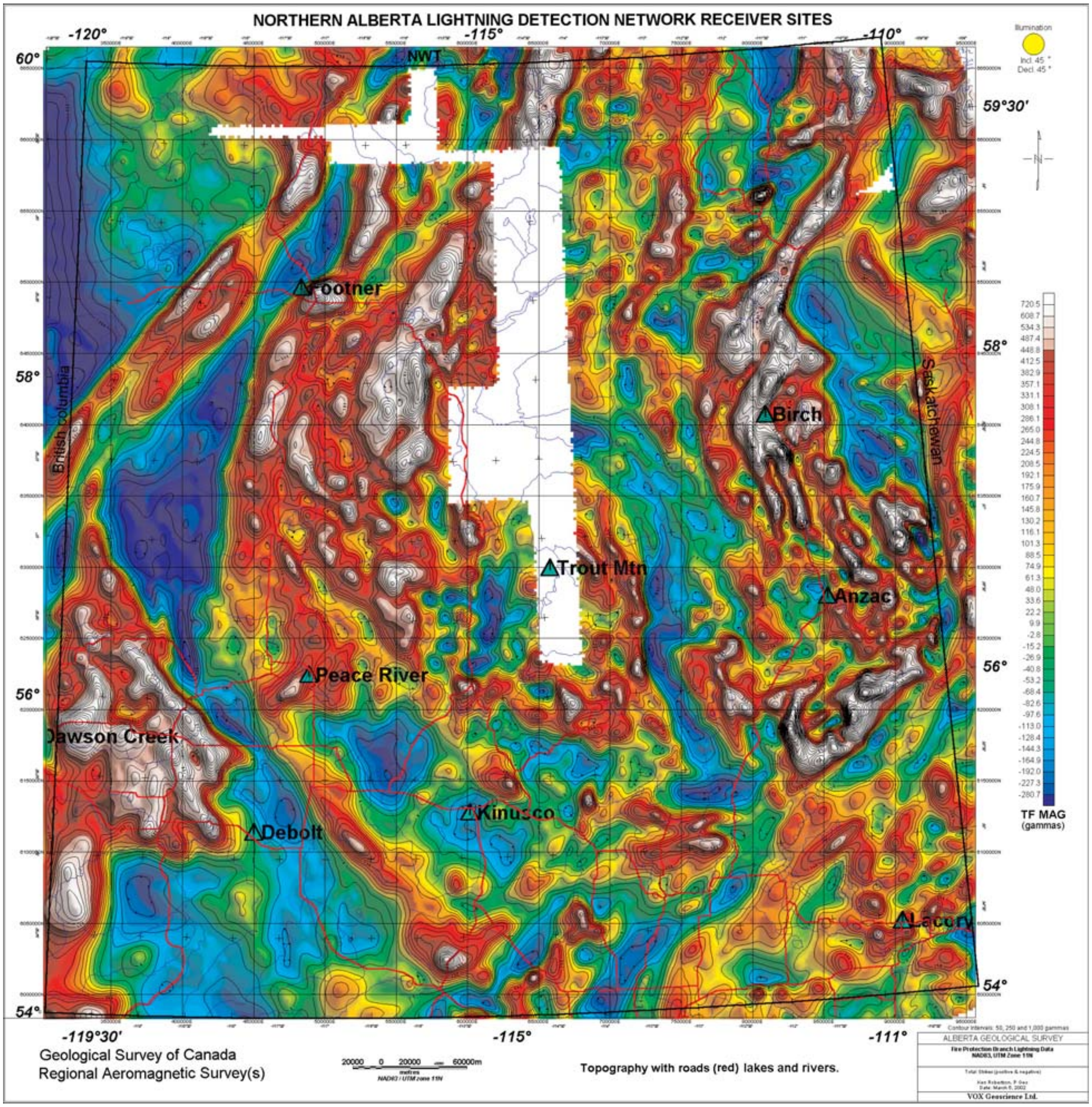

Figure 21. Colour contoured Geological Survey of Canada regional aeromagnetic coverage.

magnetic relief is approximately 1000 nanoteslas. The Great Slave Lake Shear Zone shows as a very prominent, linear, high susceptibility unit cutting diagonally (azimuth 40°) across the northwest corner of the map. Less obvious is the Snowbird Tectonic Zone that should lie south of the Kinusco direction finder and pass midway between Anzac and Lacory at an azimuth of approximately 50° to 60°. Not at all obvious is the Peace River Arch, the axis of which should lie roughly along a line connecting the Dawson Creek, Peace River, Trout Mountain and Birch direction finders.

The unshaded colour aeromagnetic coverage provides the background for the next three maps (Figures 22 to 24). The data from the 1999 fire season were selected because they appear to be the cleanest of the nine years collected. The negative lightning strikes were separated from the total and plotted as a series of weighted symbols that are almost impossible to discern on a page-sized plot. The strength of the detected lightning flashes is a function of their proximity to a sensor and decreases proportionally with distance. No attempt was made to compensate at this stage of the study. The intensity of the lightning strikes is roughly recorded in amperes. On this map, anything less than -100 is denoted by a small black dot. The remaining symbols are colour-coded circles from blue: -100 to -200, cyan: -200 to -500, green: -500 to -750, yellow: -750 to -1000, red: -1000 to -2000 and magenta: >-2000 amps. South of the Kinusco sensor, the June 1999 map (Figure 22) shows a grouping of high amplitude negative flashes over a cluster of high susceptibility magnetic units. Another grouping may be seen north of the Birch direction finder. A baseline trend is seen northeast of Peace River. No obvious trends of groups of lightning strikes are observed in the immediate vicinity of the Great Slave Lake Shear Zone or the Snowbird Tectonic Zone. By July (Figure 23), the grouping of strikes south of the Kinusco direction finder is much more diffuse. Baseline trends at Lacory and Anzac are readily apparent, but some groupings persist in the vicinity of the Trout Mountain and Birch sensors. In August (Figure 24), the level of activity in the centre of the study area has increased dramatically. The Debolt direction finder exhibits a well-defined baseline 'fan.' The small cluster of highs, more or less coincident with a small high susceptibility magnetic, south of Kinusco persists. Does this represent a 'pocket of predictability'? A weak linear trend of highs can be observed southeast of, but more or less parallel with, the Great Slave Lake Shear Zone. The trend, however, lies between the Footner and Dawson Creek direction finders and may be nothing more than a baseline artifact.

Windowing the area immediately to the south of the Kinusco direction finder (Figure 25) highlights the colour-shaded relief aeromagnetic survey. Superimposed on the magnetic grid are elevation contours (50-metre intervals) and the combined negative amplitude lightning strikes for June and July 1999. The clustering of high amplitude strikes (yellow and red circles) in the vicinity of the small magnetic high is easier to discern. The grouping lies close to a 1250-metre topographic high, but is displaced downslope toward the northeast. Groupings of lower amplitude strikes (blue and cyan circles), that do not appear to be coincident with high ground, are also evident on this map.

When the same symbols are superimposed on a window of the Geological Map of Alberta, it is clear the cluster of high amplitude negative strikes lies over the Swan Hills close to the contact between the Paleocene Paskapoo Formation and the underlying Upper Cretaceous basement (Figure 26). Whether or not the clustering of high amplitude negative strikes is related strictly to elevation is not known and requires further investigation.

15.2 Peerless Lake Map Area (NTS 84B)

The Peerless Lake area is covered by National Topographic System map area 84B and is located in north-central Alberta (latitude 56°N to 57°N and longitude 114°W to 116°W). The map area also encompasses the Buffalo Hills kimberlite province, discovered in 1997.

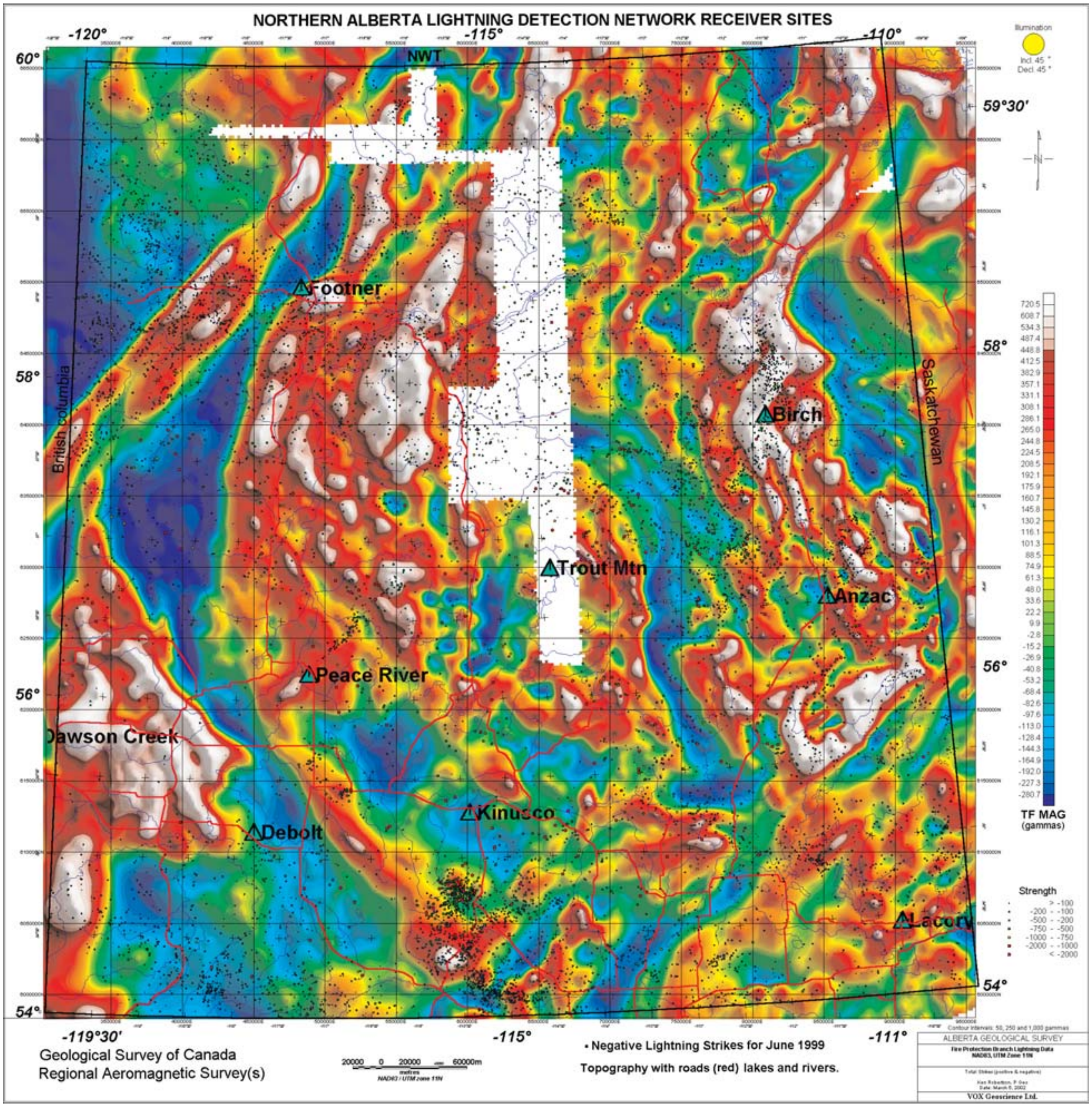

Figure 22. Colour contoured Geological Survey of Canada regional aeromagnetic coverage of northern Alberta with an overlay of all negative lightning strikes recorded in June 1999.

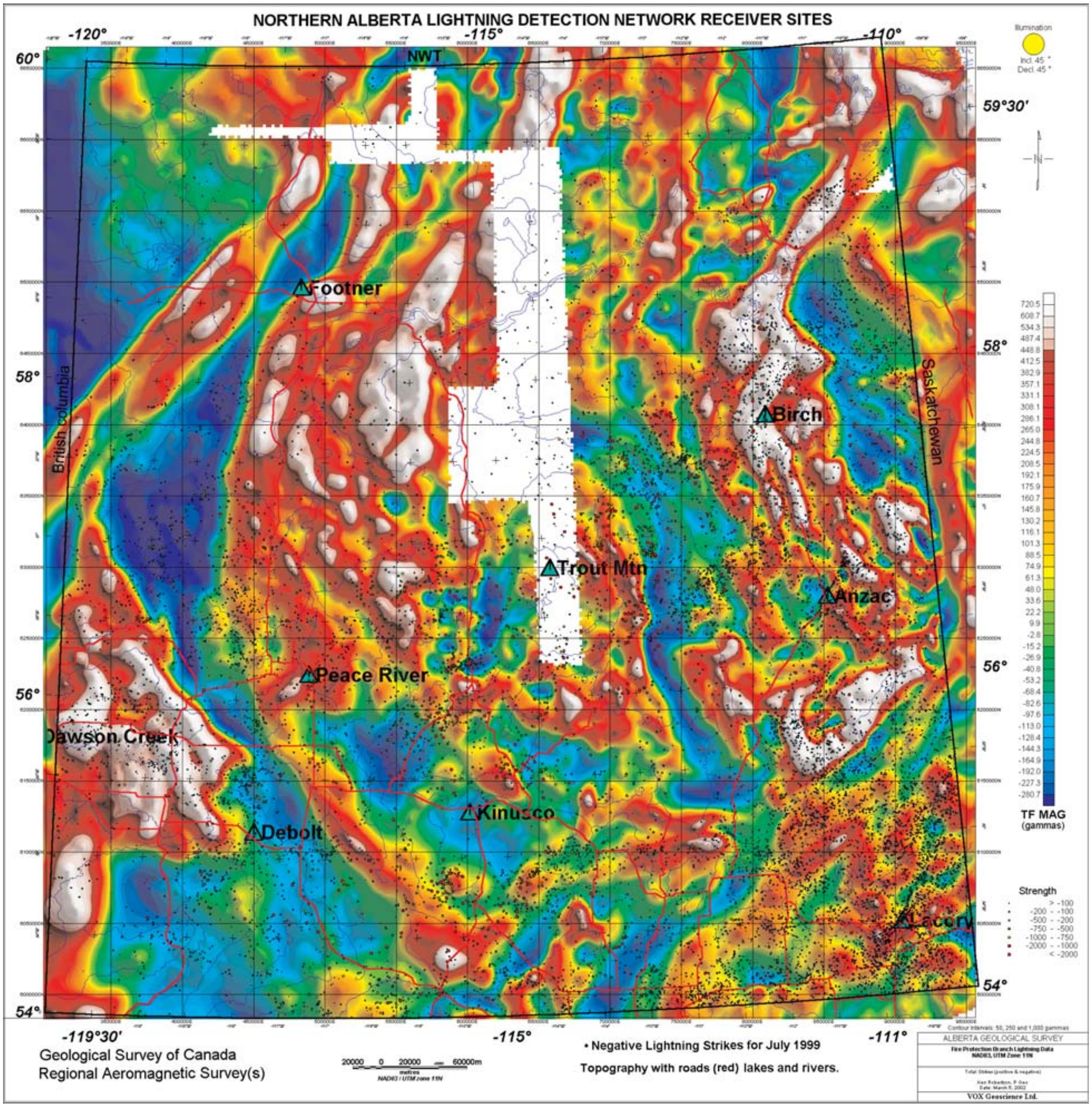

Figure 23. Colour contoured Geological Survey of Canada regional aeromagnetic coverage of northern Alberta with an overlay of all negative lightning strikes recorded in July 1999.

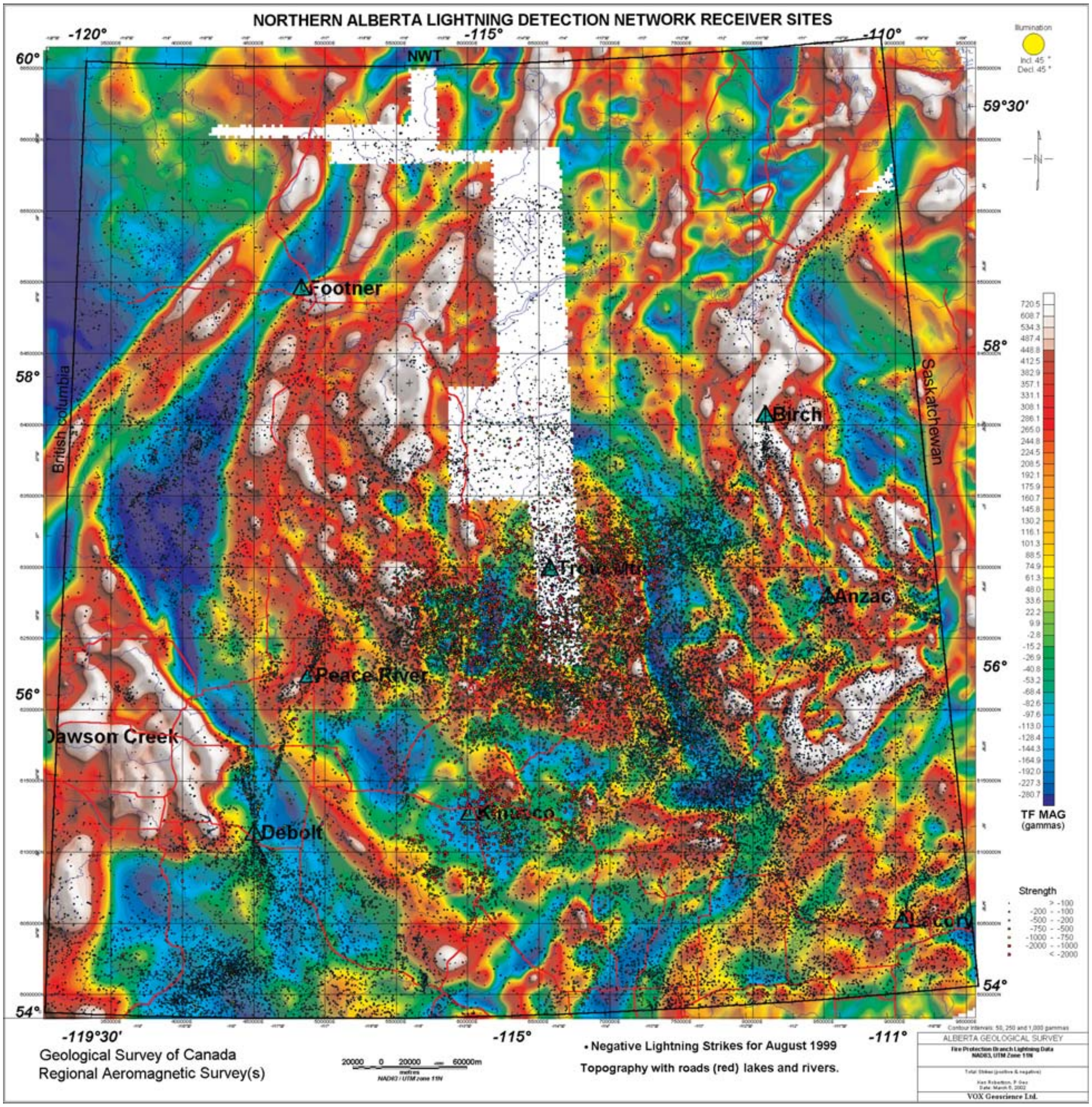

Figure 24. Colour contoured Geological Survey of Canada regional aeromagnetic coverage of northern Alberta with an overlay of all negative lightning strikes recorded in August 1999.

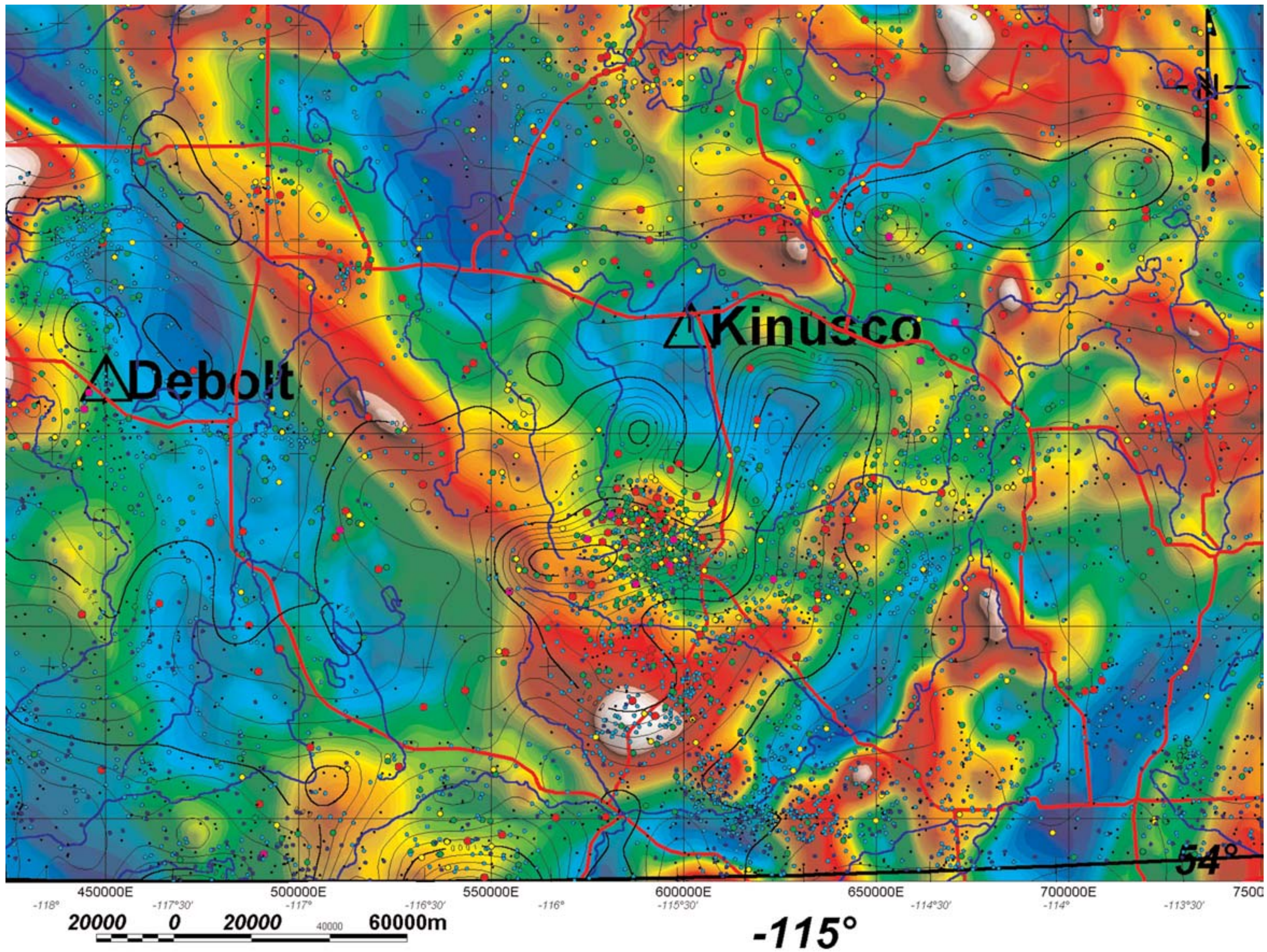

Figure 25. Colour contoured Geological Survey of Canada regional aeromagnetic coverage of the Swan Hills area of northern Alberta with an overlay of all negative lightning strikes recorded in June and July 1999.

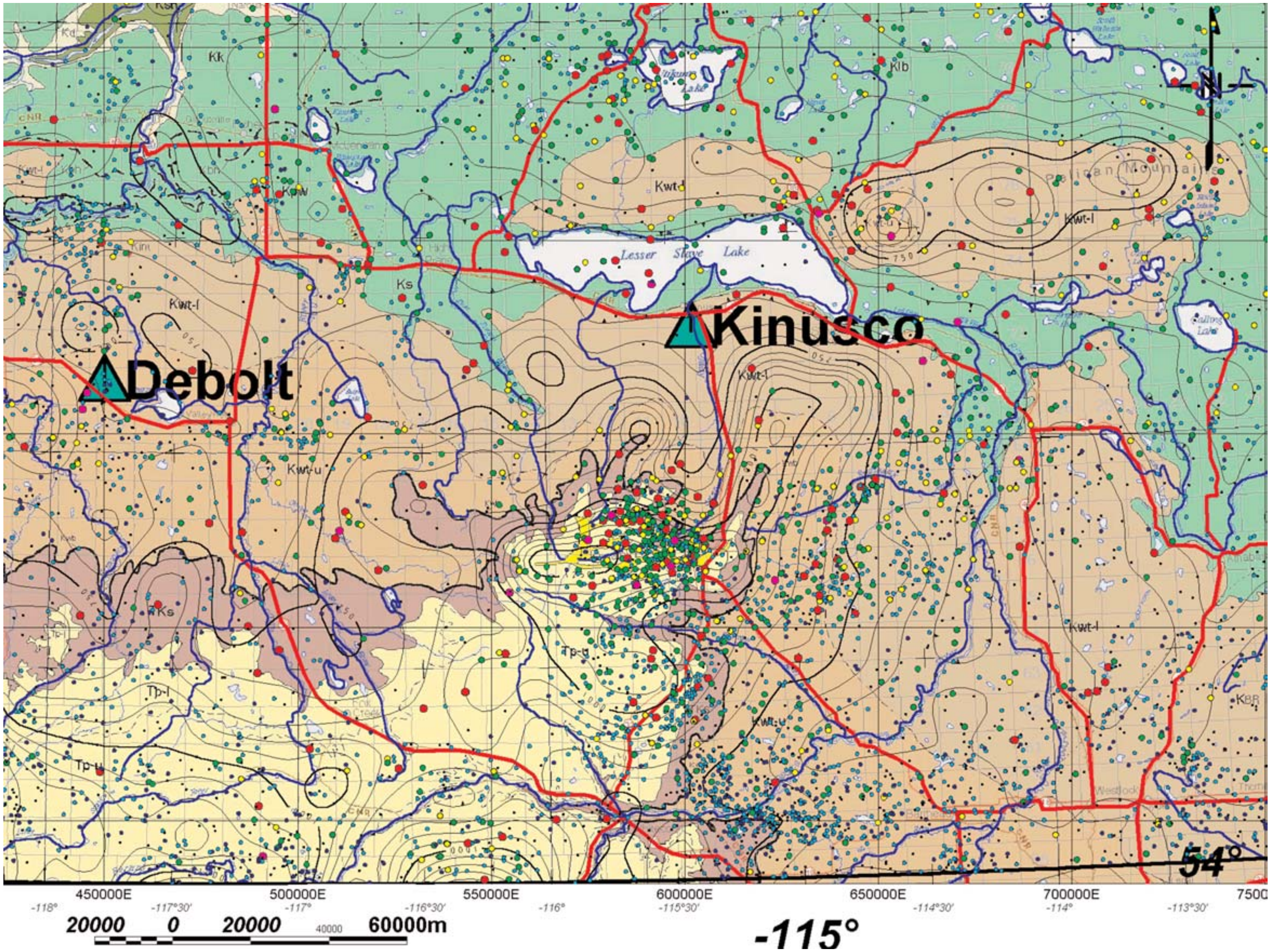

Figure 26. Window of the Geological Map of Alberta for the Swan Hills area of northern Alberta with an overlay of all negative lightning strikes recorded in June and July 1999.

"The Buffalo Hills kimberlites were first detected on a fixed-wing aeromagnetic survey conducted during February and March of 1995. The 600-m flight line data were acquired by Alberta Energy Company to assist in the interpretation of the Precambrian basement terrain for oil and gas exploration. The 64,000 km^2 of survey data were dominated by deep long-wavelength features, however 10 shallow high-frequency anomalies not related to culture were also observed in the data. An investigation of pre-existing seismic profiles in the vicinity of these anomalies revealed very strong diffractions and atypical reflections suggesting that the anomalies might be the result of disruptive volcanic intrusives. In May 1996 Alberta Energy acquired the mineral rights to 64,000 km^2 of land covering the original airborne survey area." - Ashton Mining of Canada Inc.

The regional topography of the Peerless Lake area is shown in Figure 27 by topographic contours superimposed on shaded relief elevation. Four red lines of latitude and longitude enclose the actual area of map area 84B. There are approximately 300 metres of relief in the area covered by this image. One lightning direction finder, Trout Mountain, is located in the study area slightly to the northeast of Peerless Lake.

A window of the Geological Survey of Canada aeromagnetic survey coverage is shown on the next image (Figure 28). The range of magnetic readings is roughly 750 gammas. The contour interval is 50 gammas. A large north-south gap in Geological Survey of Canada coverage still exists over Trout Mountain.

The lightning flash records from the 1999 season were selected for additional processing, as before. Multiplicity (number of repeat strikes from a single event) was selected from the database and plotted on the elevation contours represented by weighted and colour-coded circles ranging from black dots (<4 flashes) to magenta circles (>14 flashes) (Figure 29). Apart from a diffuse band of multiple strikes trending northwest to southeast across the map area, a discrete pattern is not observed. In general, the strikes appear to be on the flanks of topographic highs, roughly following river valleys.

A plot of negative amplitude strikes graded by strength (Figure 30) is not much clearer. In a few places the strikes look to be tracing short linear trends, but it may only be coincidence. The pattern of the lightning strikes is essentially random, but contrary to what might be expected, there does not seem to be a clustering of strikes with topographic highs.

In an attempt to identify any repeatable patterns or trends, the negative amplitude strikes, for each season from 1992 to 2000 (Figures 31 through 40), were randomly gridded with a 250-metre grid cell and shadow plotted with a northeast illumination direction. The plots are shown as is, without any overlays that might skew the observations. For the first three years, 1992 to 1994 (Figures 31 to 33), the patterns are quite similar; you might be able to trace a few southwest-northeast and northwest-southeast trends. In 1995, (Figure 34) the total number of recorded strikes was much lower. Using essentially the same approach as is used to interpret gridded magnetic and gravity maps, a number of trends, breaks and lineaments can be observed in the 1995 map and traced (Figure 35). The interpretation overlays will be exported and saved so a comparison can be made against established geological mapping, structural geology interpretations and remote sensing interpretations. From 1996 to 1999 (Figures 36 to 39), the patterns are similar to those of the first three years. In 2000 (Figure 40), the number of total recorded strikes was again lower than previous years.

As mentioned above, the 1999 negative amplitude strike plot was selected for interpretation (Figure 41). A large number of linear trends, which can be grouped in four general orientations, were sketched on the map. The next map (Figure 42) shows the grey shaded and contoured topography of the Peerless Lake

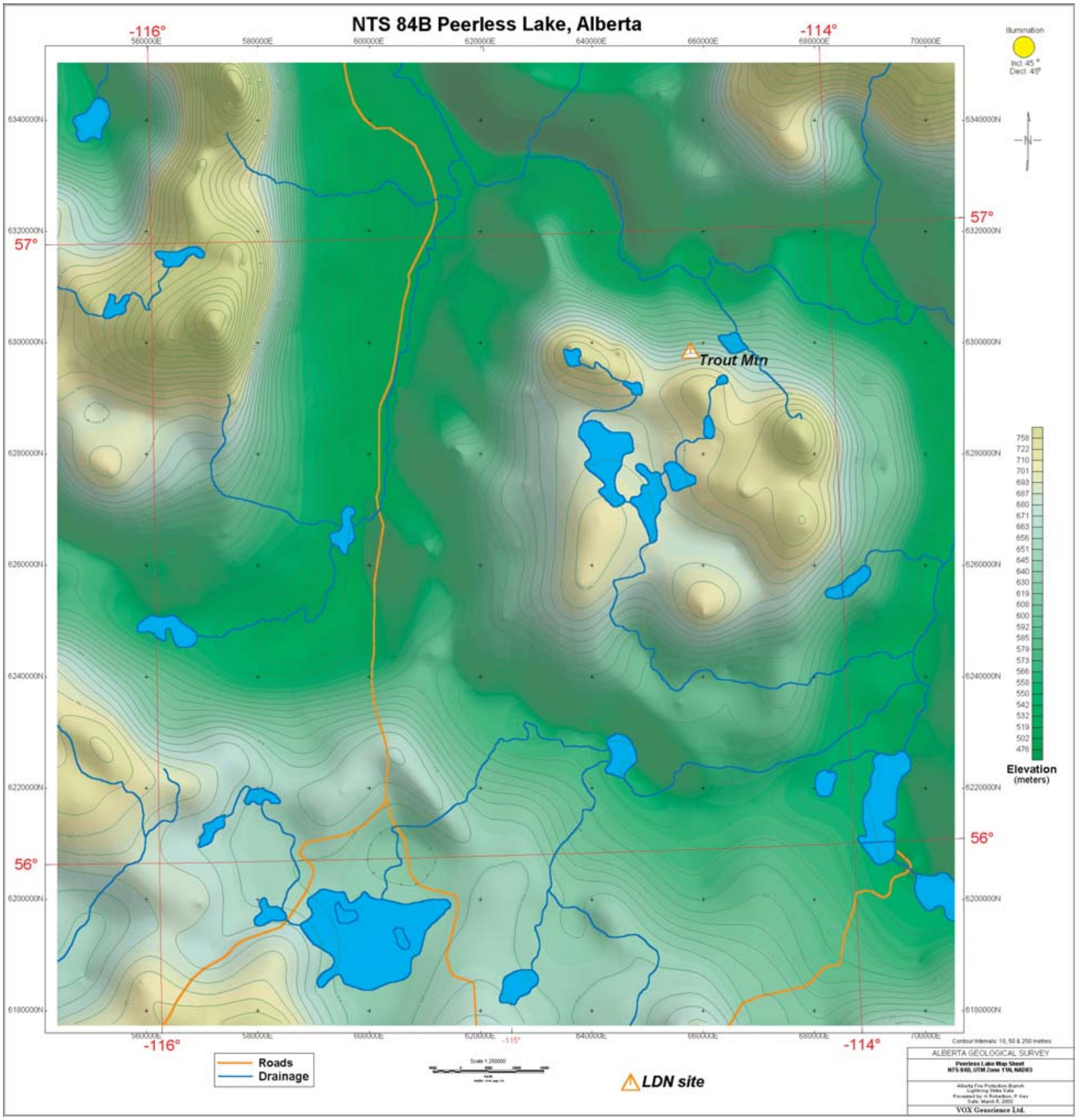

Figure 27. Shaded relief topography for the Peerless Lake area, NTS 84B.

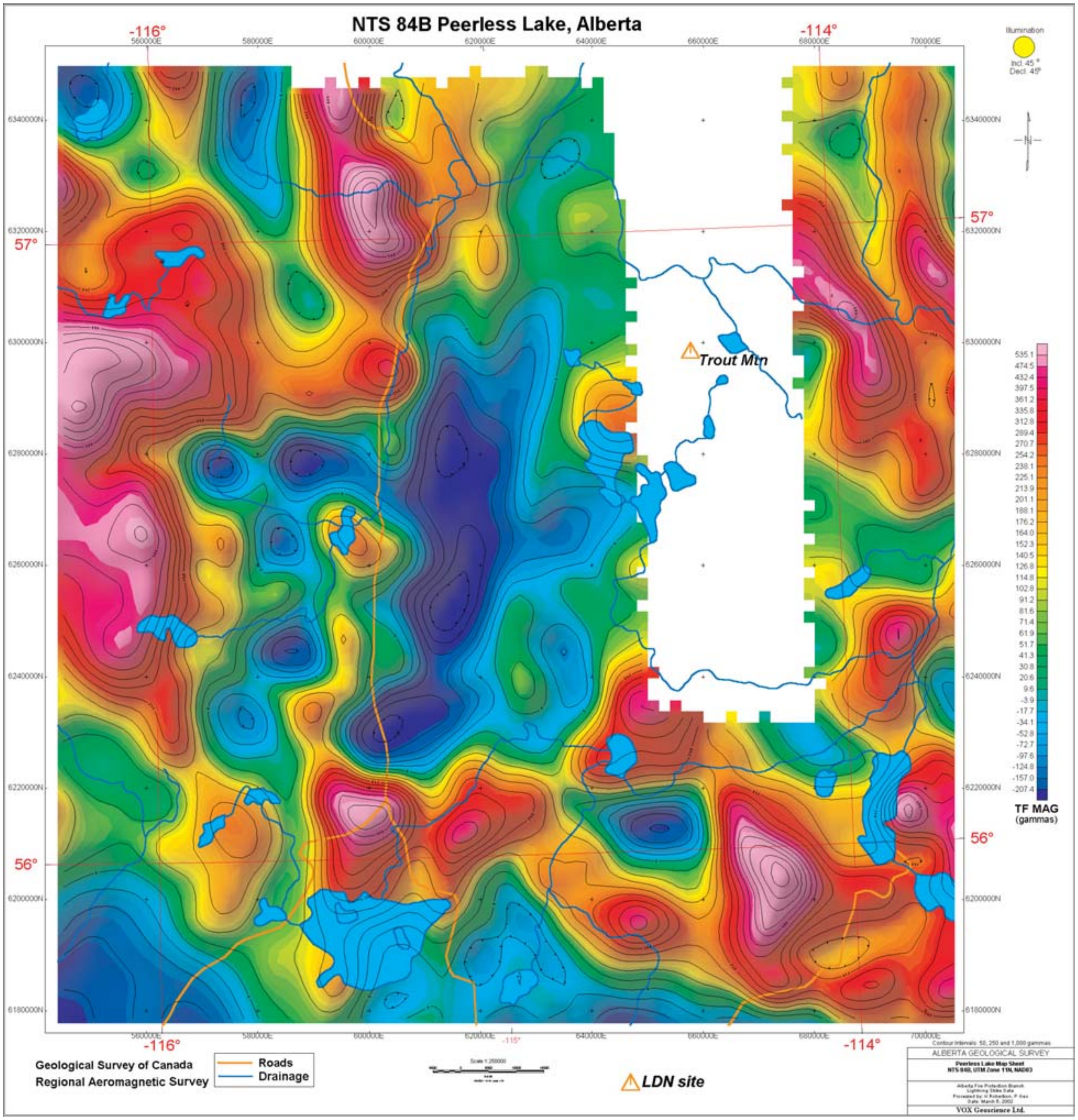

Figure 28. Colour contoured Geological Survey of Canada regional aeromagnetic coverage for the Peerless Lake area NTS 84B.

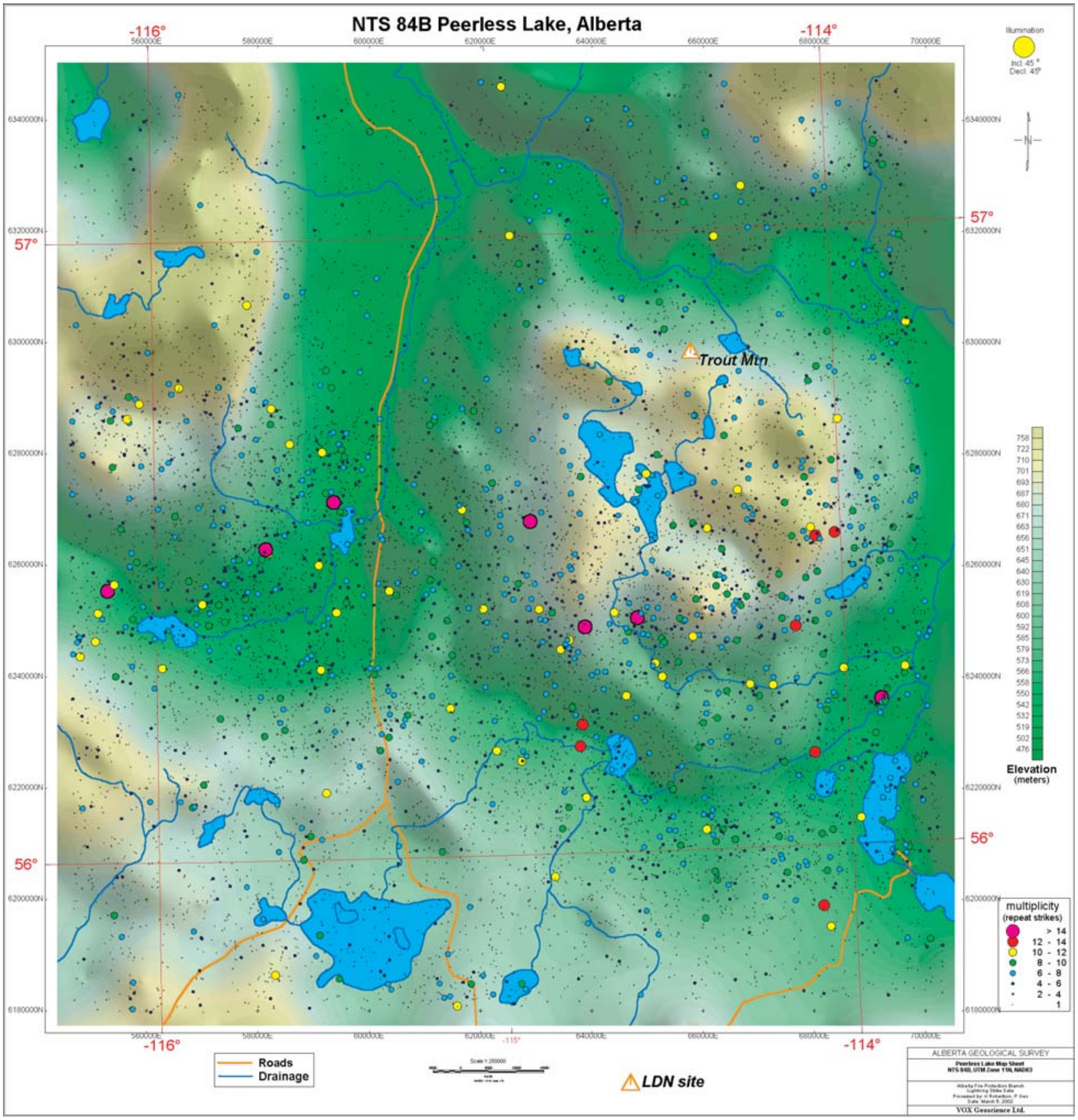

Figure 29. Peerless Lake area NTS 84B topographic contours with an overlay of 1999 multiplicity of total lightning strikes.

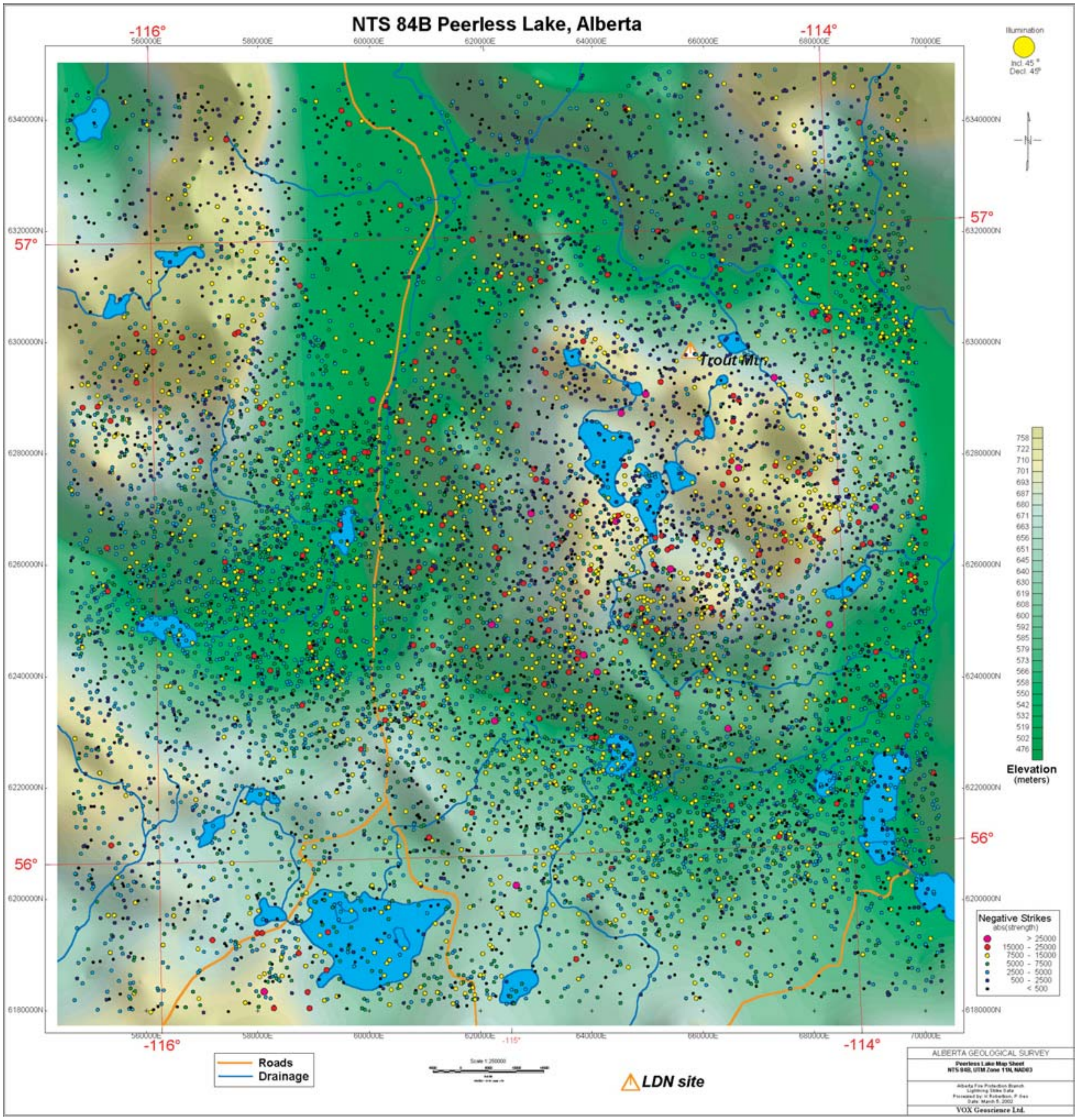

Figure 30. Peerless Lake area NTS 84B topographic contours with an overlay of range-classified 1999 negative lightning strikes.

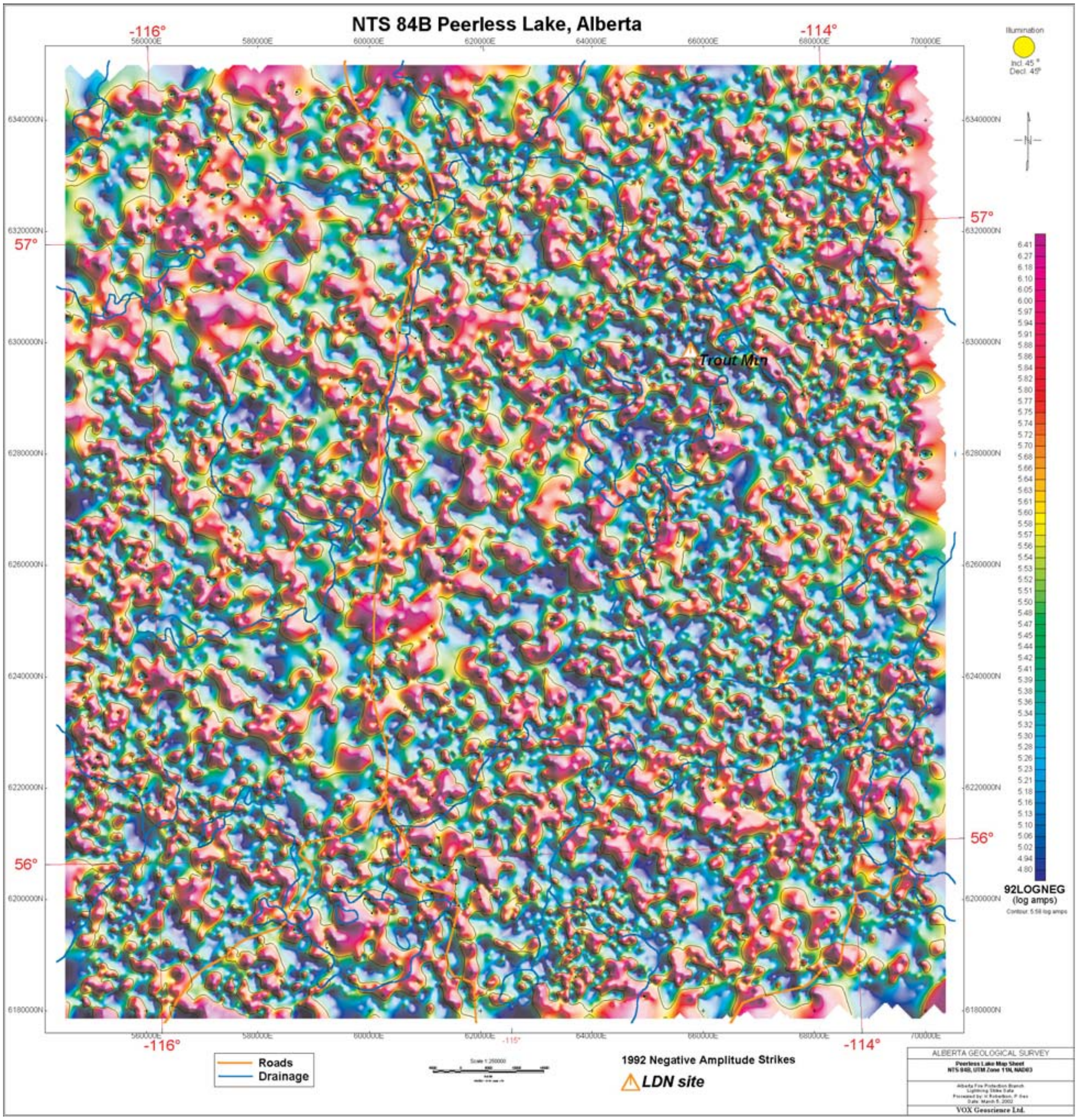

Figure 31. Peerless Lake area NTS 84B random gridded negative amplitude lightning strikes for the 1992 fire season.

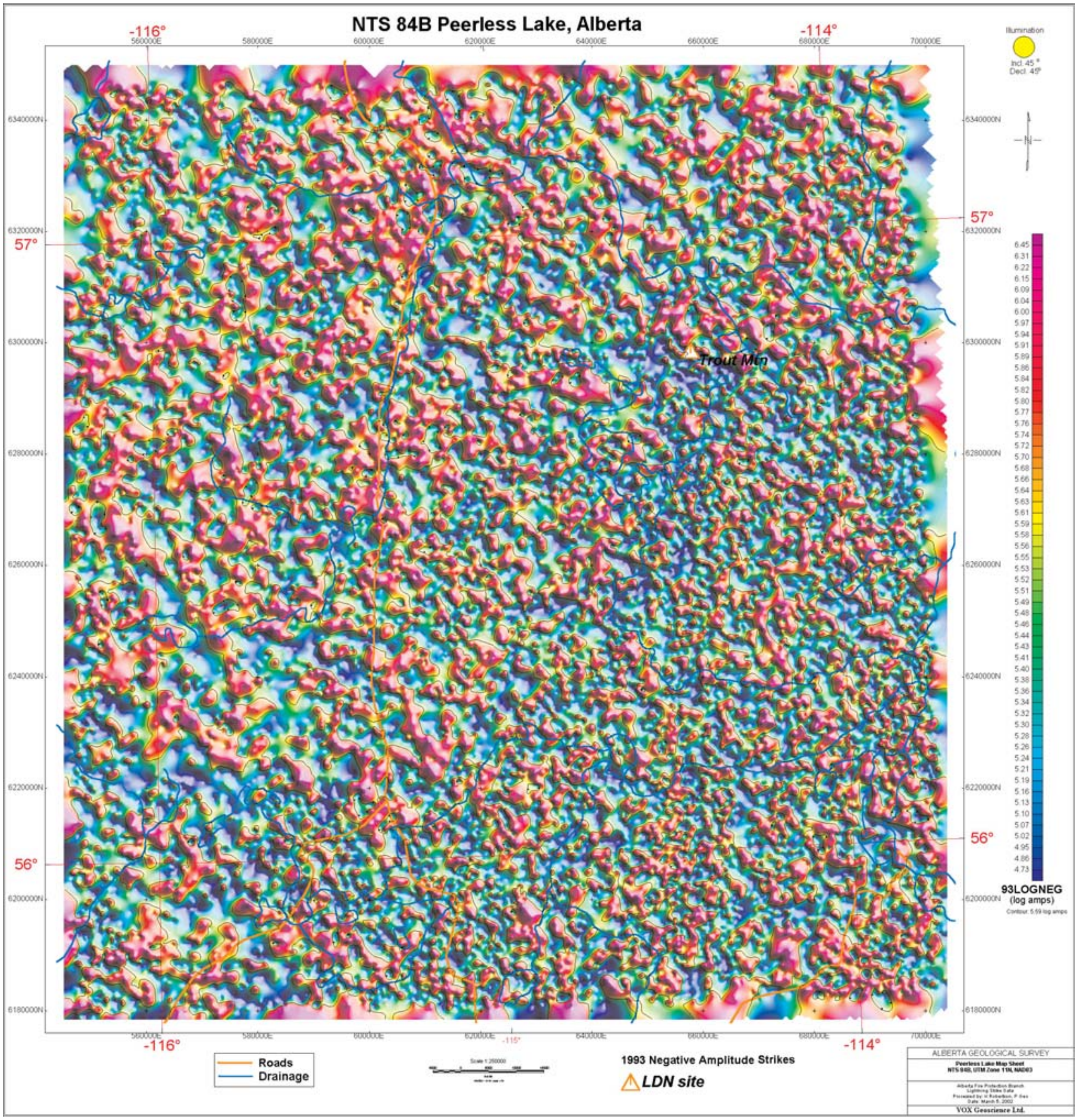

Figure 32. Peerless Lake area NTS 84B random gridded negative amplitude lightning strikes for the 1993 fire season.

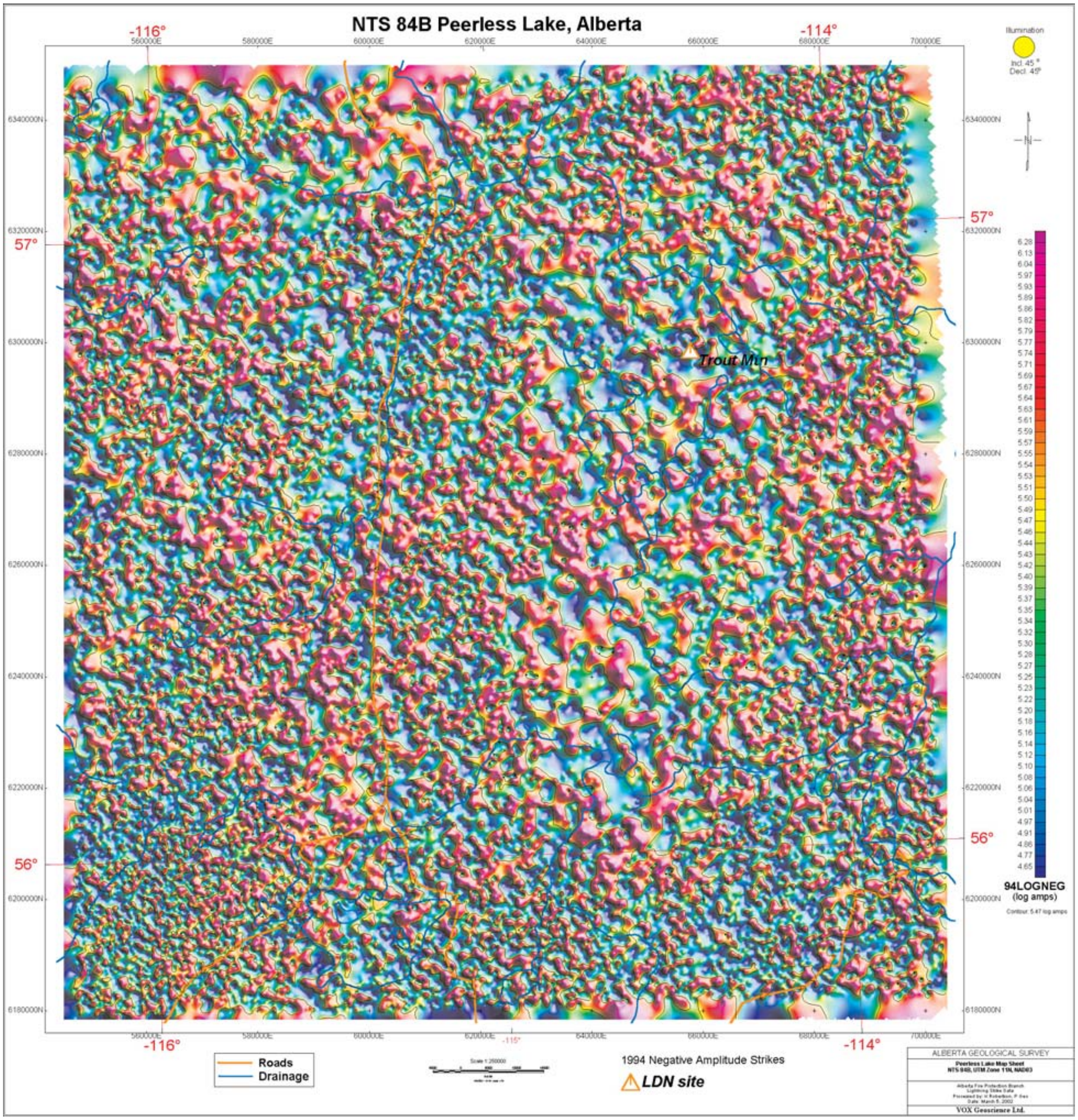

Figure 33. Peerless Lake area NTS 84B random gridded negative amplitude lightning strikes for the 1994 fire season.

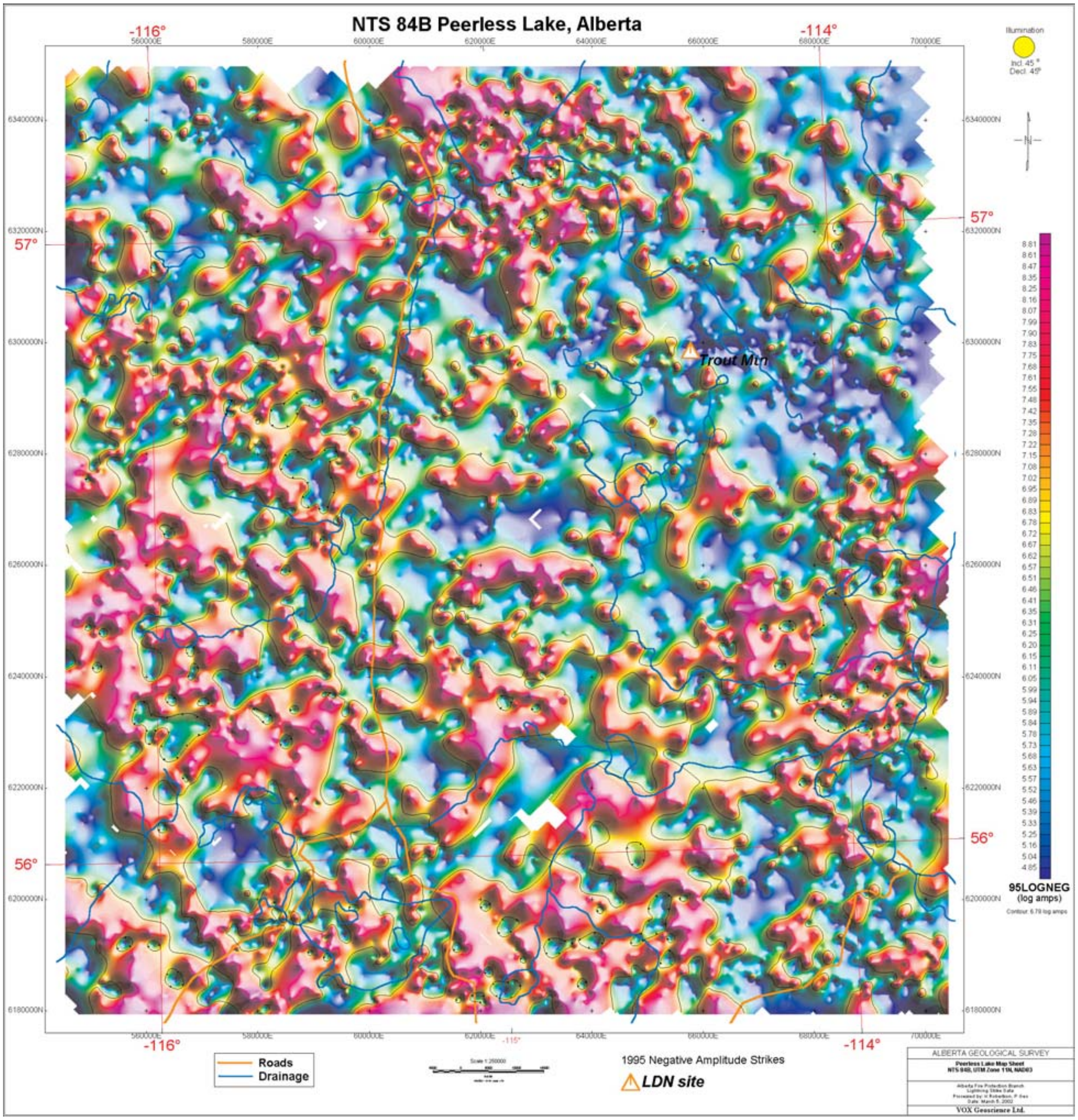

Figure 34. Peerless Lake area NTS 84B random gridded negative amplitude lightning strikes for the 1995 fire season.

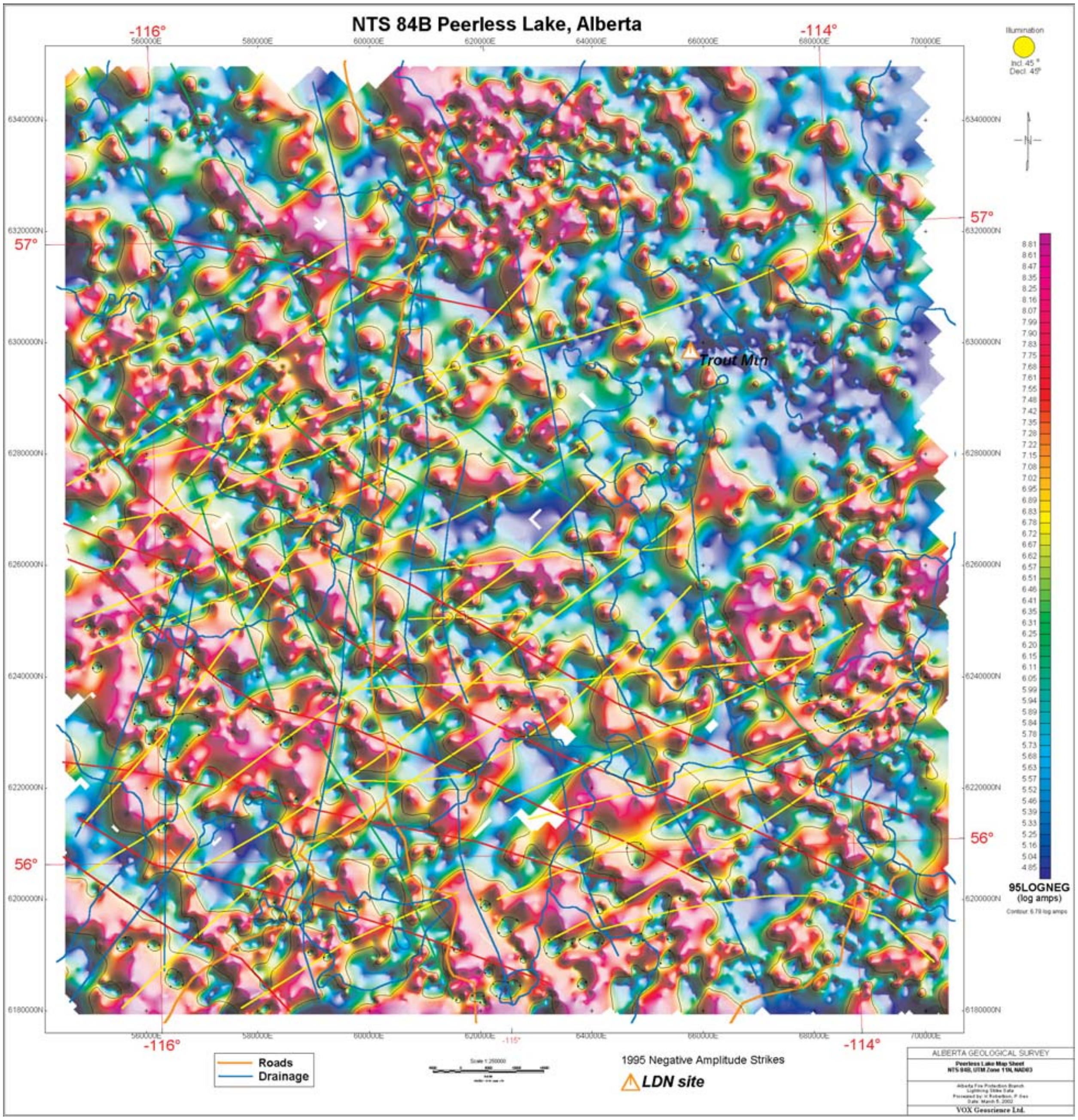

Figure 35. Peerless Lake area NTS 84B random gridded negative amplitude lightning strikes for the 1995 fire season with interpretation.

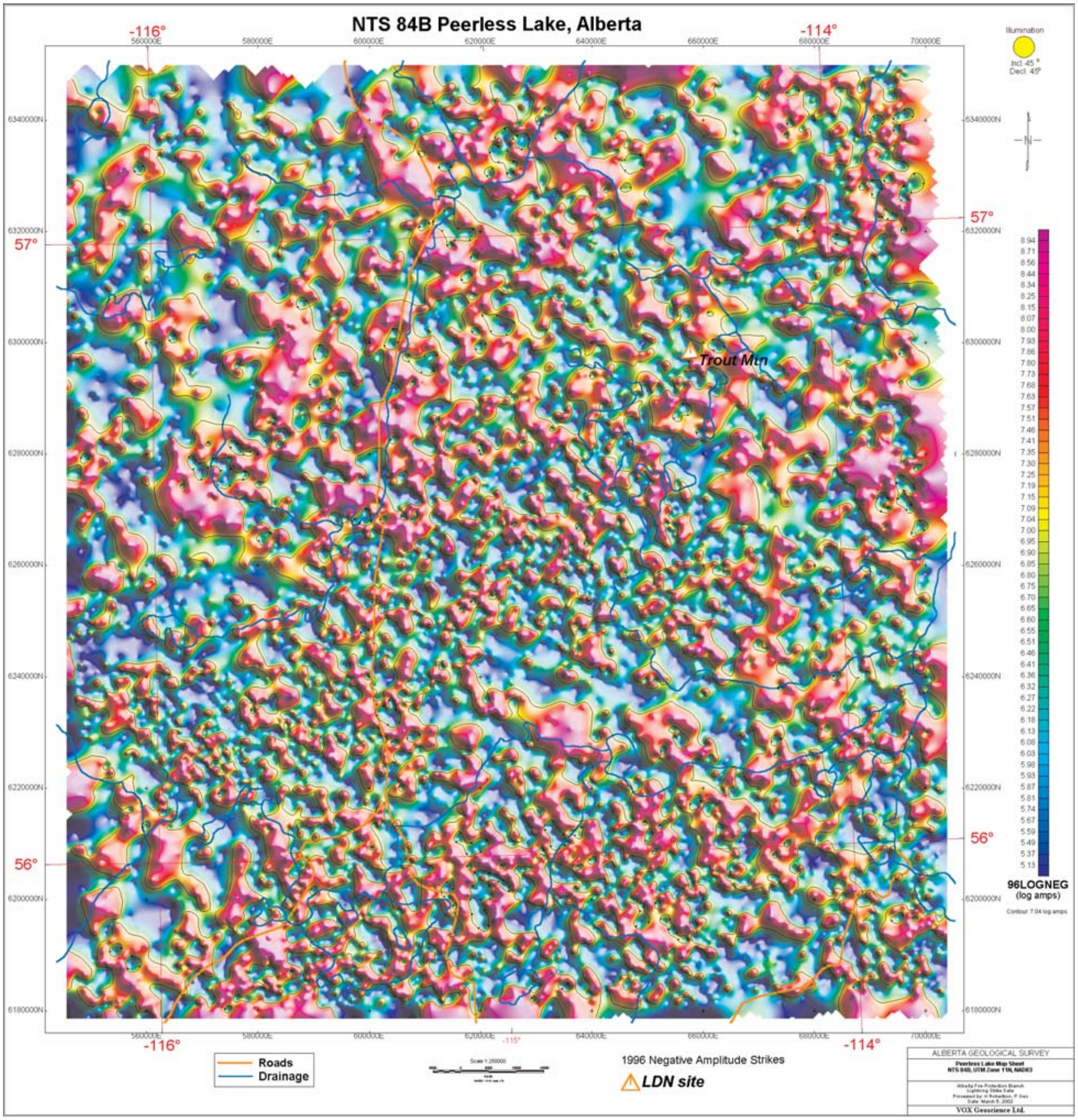

Figure 36. Peerless Lake area NTS 84B random gridded negative amplitude lightning strikes for the 1996 fire season.

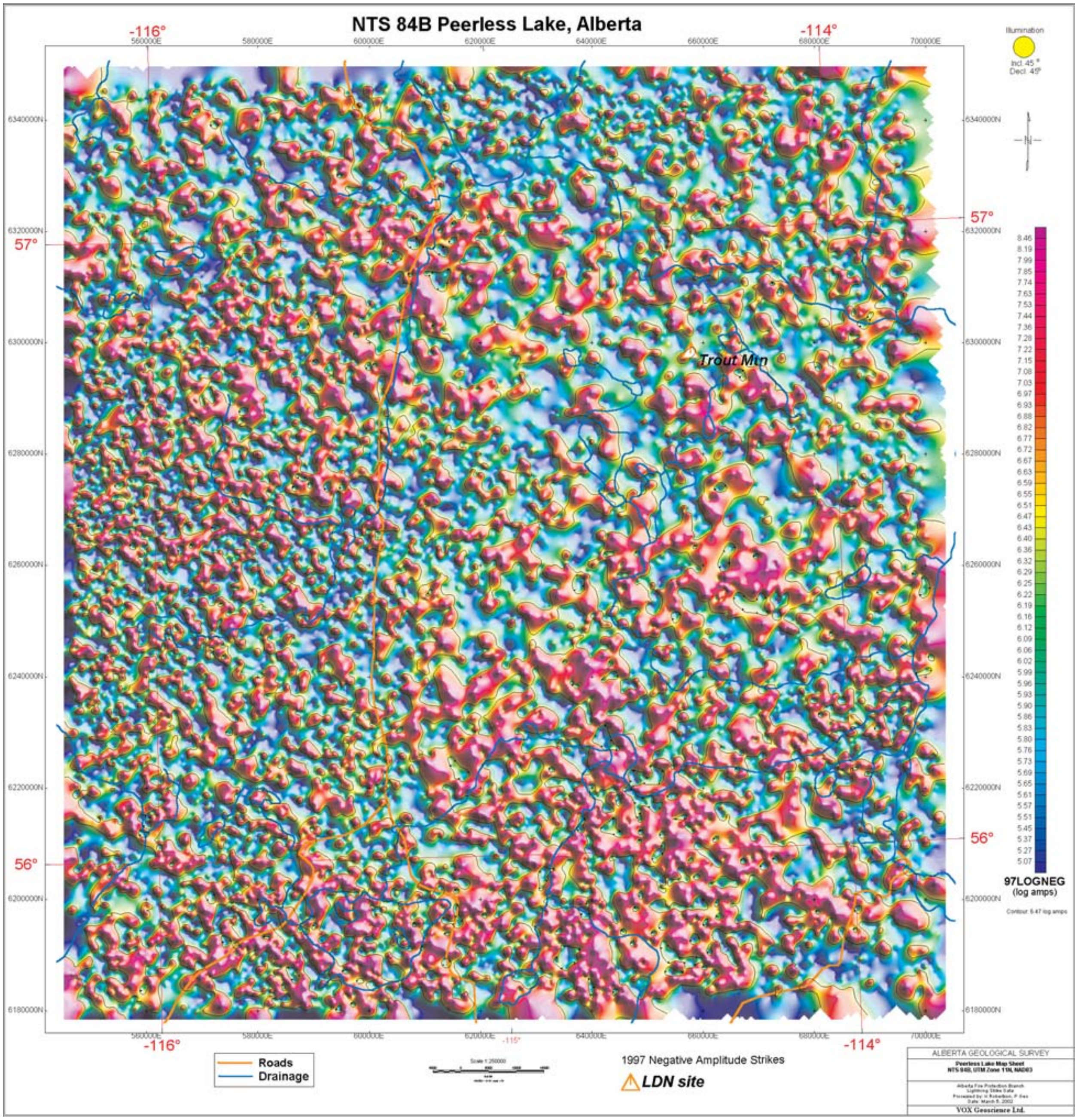

Figure 37. Peerless Lake area NTS 84B random gridded negative amplitude lightning strikes for the 1997 fire season.

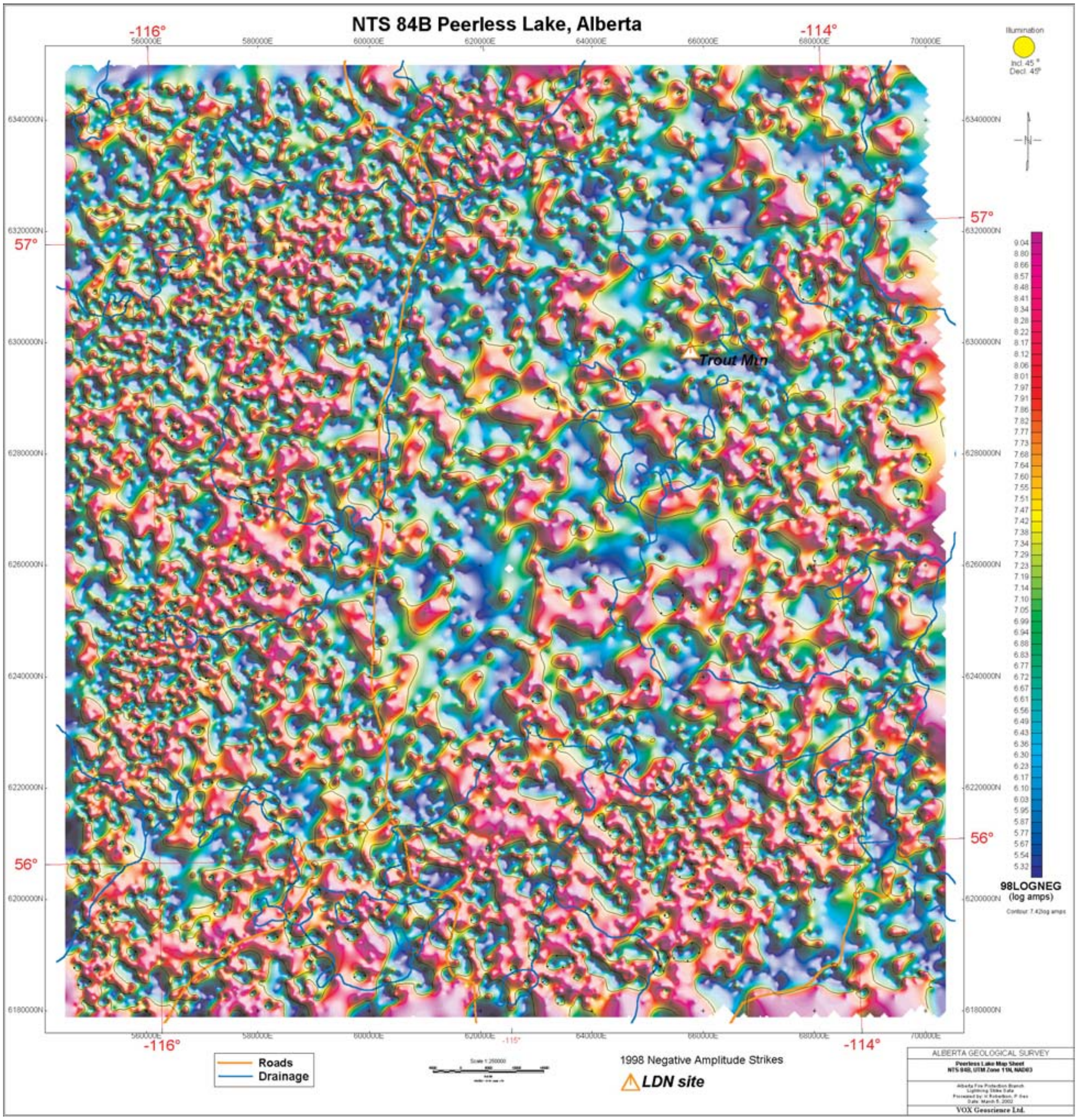

Figure 38. Peerless Lake area NTS 84B random gridded negative amplitude lightning strikes for the 1998 fire season.

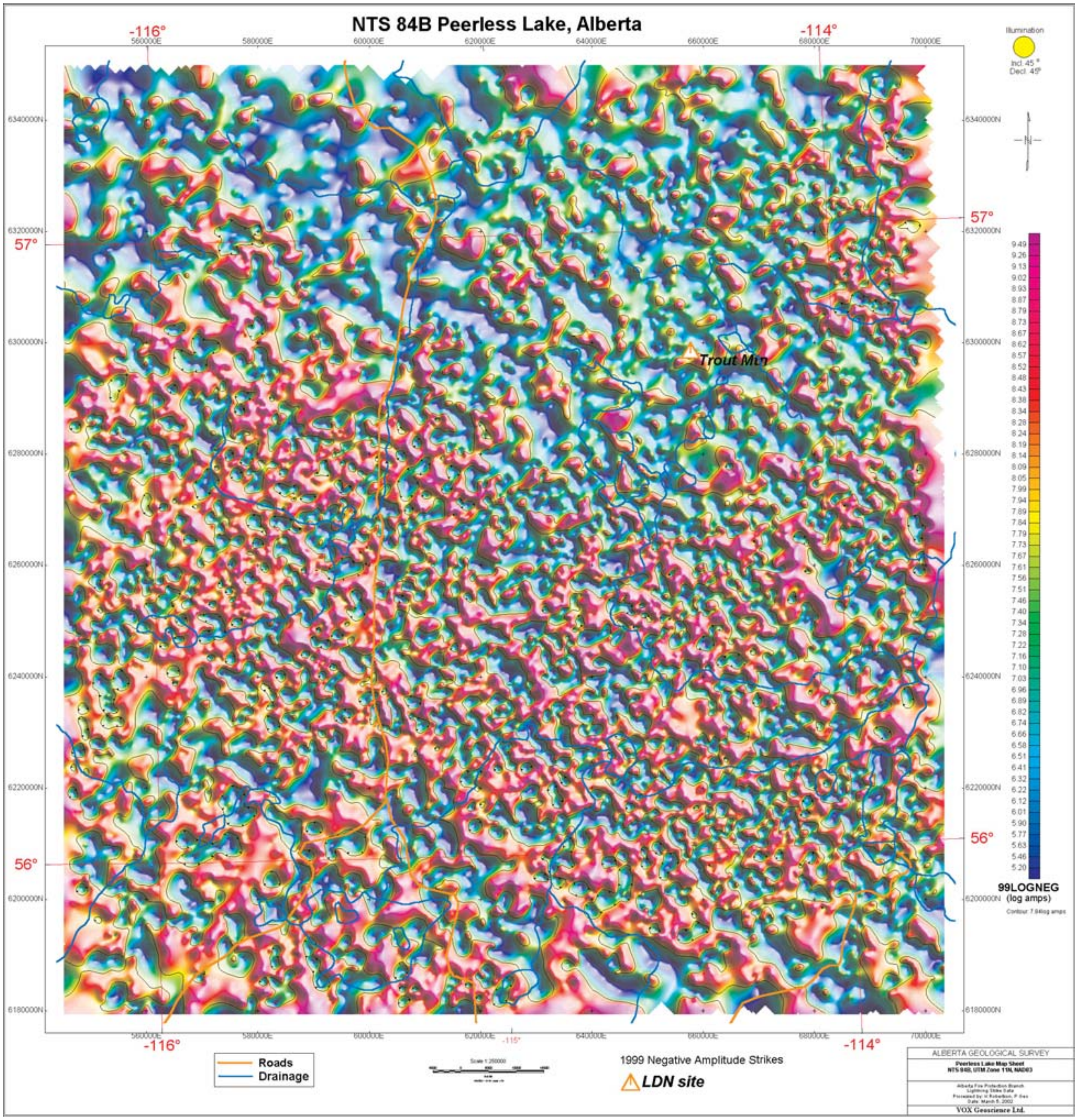

Figure 39. Peerless Lake area NTS 84B random gridded negative amplitude lightning strikes for the 1999 fire season.

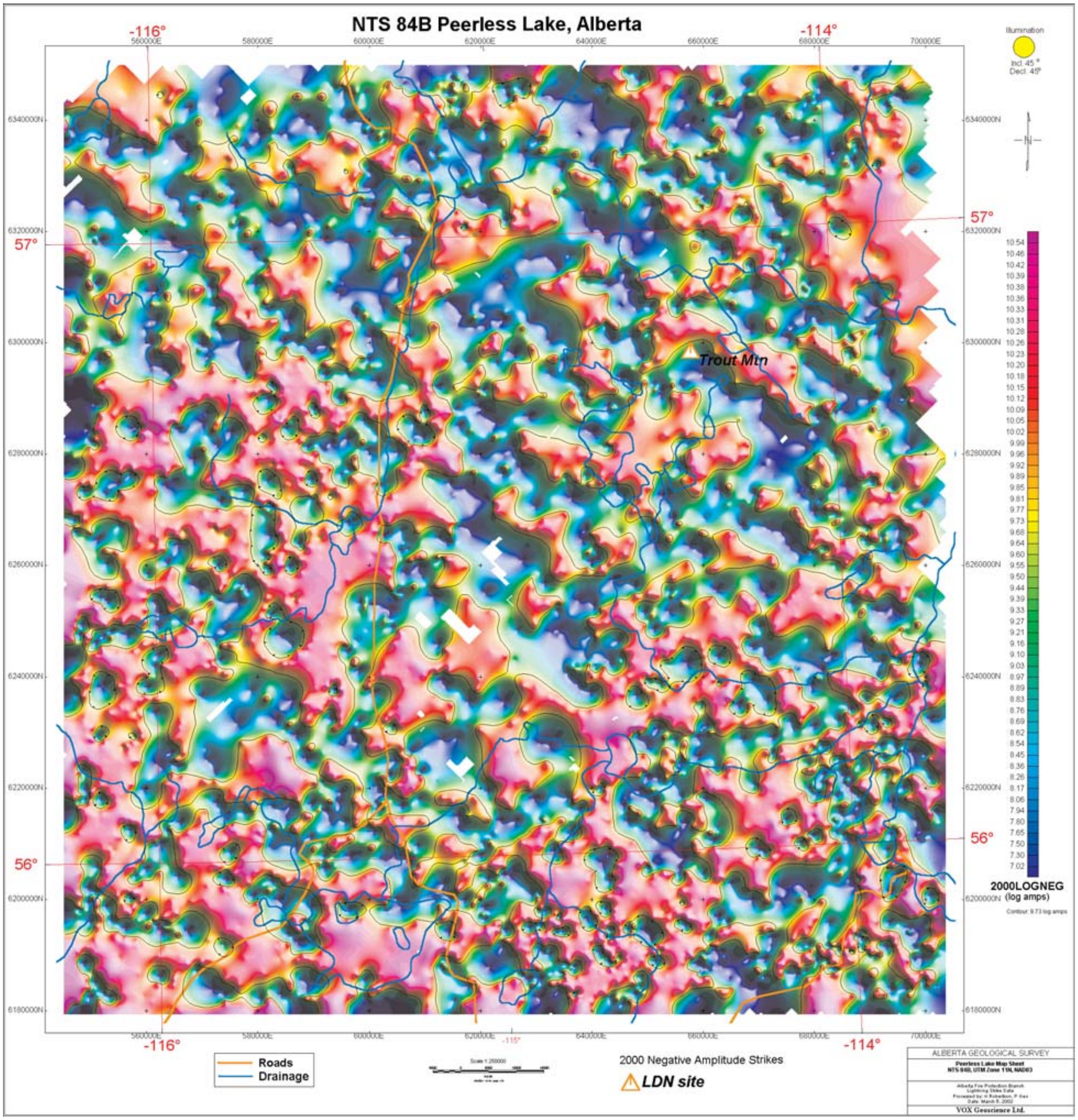

Figure 40. Peerless Lake area NTS 84B random gridded negative amplitude lightning strikes for the 2000 fire season.

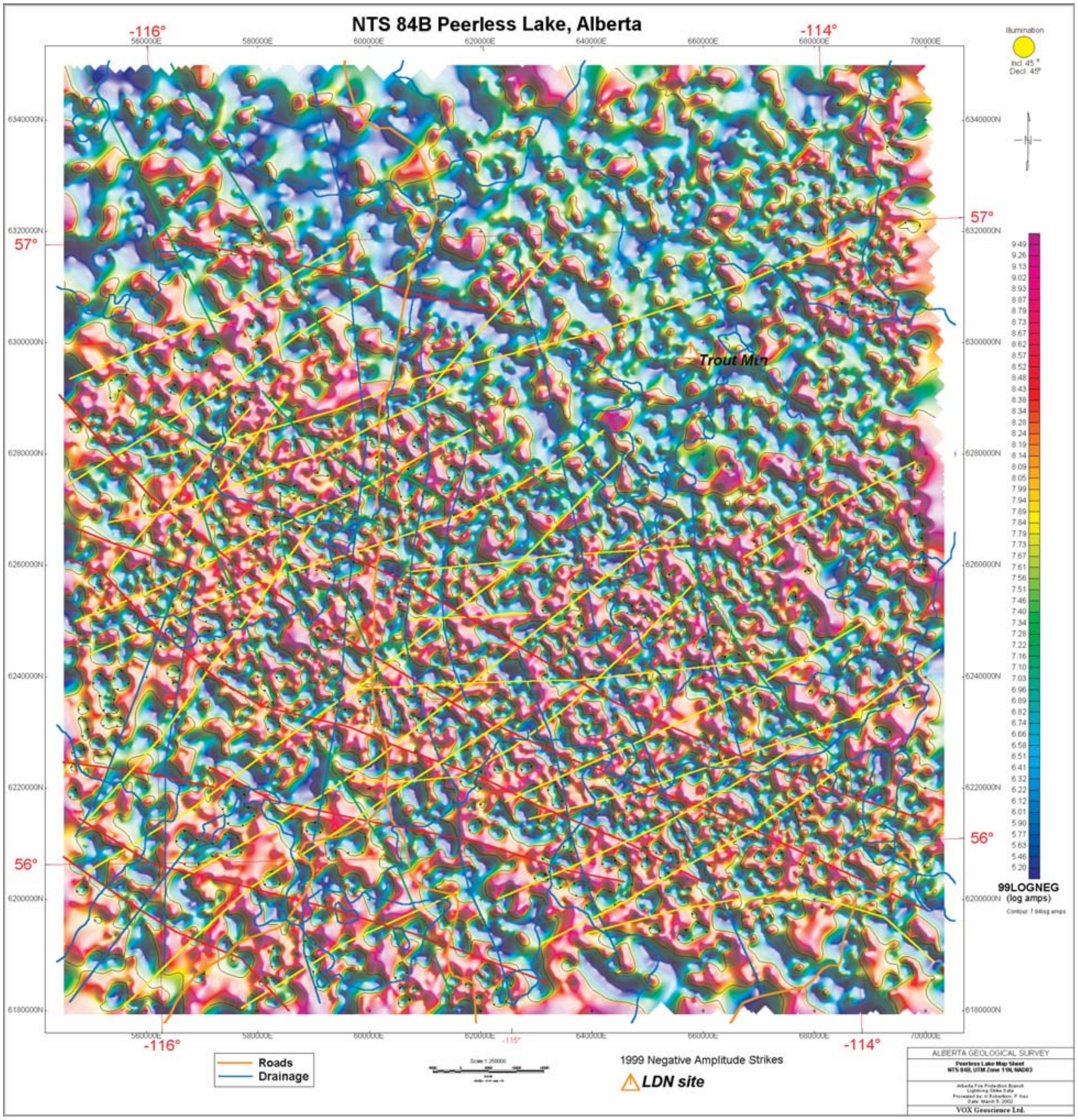

Figure 41. Peerless Lake area NTS 84B random gridded negative amplitude lightning strikes for the 1999 fires season with interpretation.

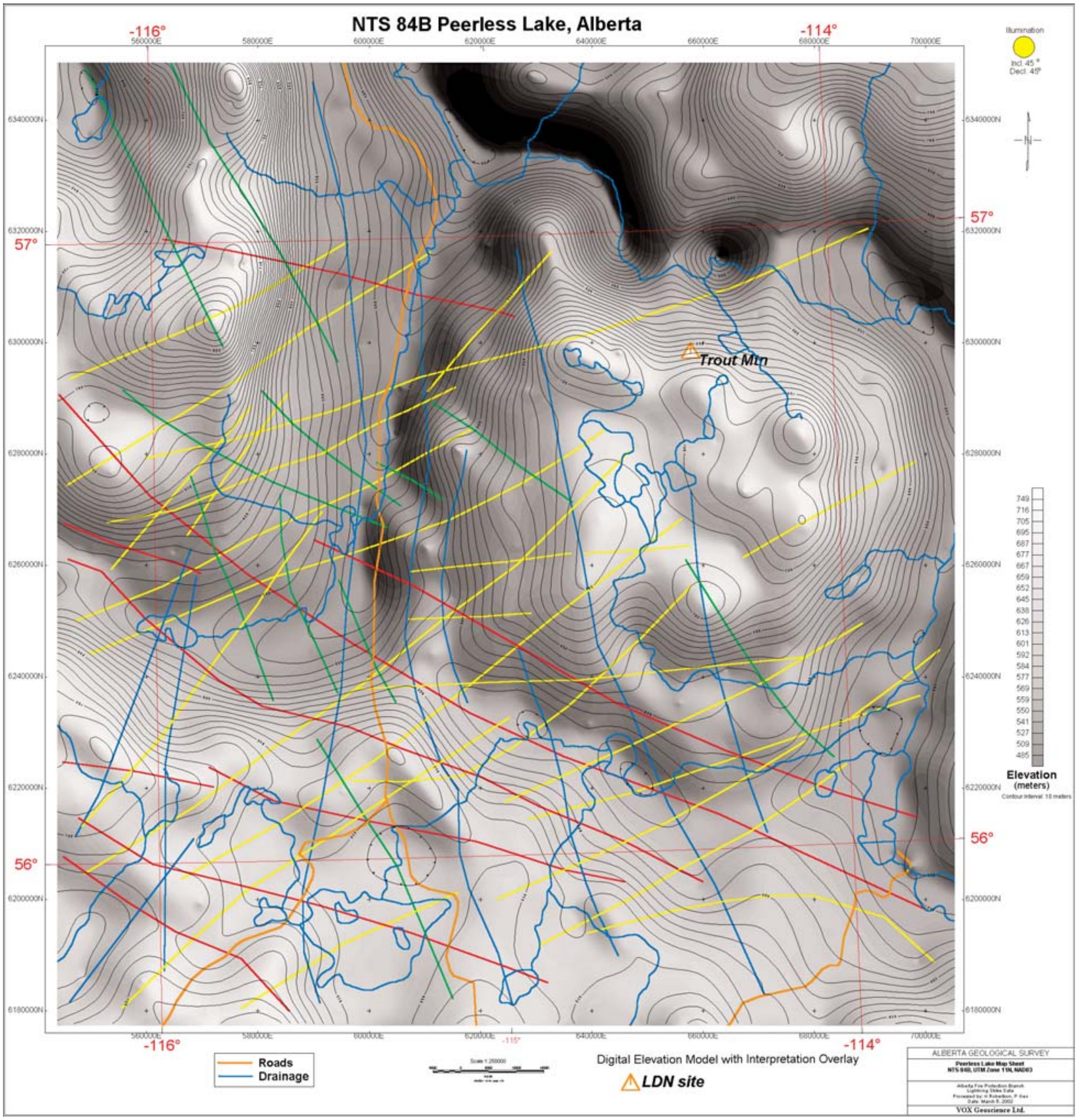

Figure 42. Peerless Lake area NTS 84B shaded relief topography with an overlay of the interpretation from Figure 41.

area. Lakes and rivers are drawn in cyan and roads in orange. Superimposed on the topography are the interpreted lineaments from the previous map. The lineaments have been roughly subdivided into four orientations: NW-SE (red), SW-NE (yellow), NNW-SSE (green) and N-S (blue).

Making a huge leap in confidence and assuming the lineaments reflect real structural features, locations where three or more intersect were marked by open red targets (approximately three km in diameter) on grey-shaded elevation (Figure 43). Picking 'triple-junctions' is common practice for some geoscientists when interpreting aeromagnetic surveys. One theory suggests these sites may represent areas of weakness that would open paths for hydrothermal fluids, diatremes, etc. Twenty-four targets were selected initially, using only the interpreted lineaments. Three were located at or near topographic highs and eight lay in valleys and appeared to be related to drainage features. These 11 initial targets were deleted, leaving a final pick of 13.

The Peerless Lake area was windowed from the Geological Map of Alberta and used as a background for the final two maps. Topographic contours were superimposed on the geology and a slight, not serious, registration shift from the digitized drainage pattern is evident (Figure 44). The final map (Figure 45) shows the interpreted lineaments in black and the final targets as open red circles overlain on the regional geology map. There has been no attempt to test these targets against recent geological mapping or exploration activities.

16 Conclusions

Earlier studies of lightning strike detection systems indicated several potentially informative diagnostic techniques in addition to the ones addressed in this study. They are

- plotting on geochemical bases;
- plotting on Landsat and/or RADARSAT bases;
- plotting on airborne electromagnetic survey results;
- apply GIS weights of evidence to see if there is an affinity for increased strikes in greenstone belts or along major structures;
- cross-reference lightning strikes to AFMAG (Audio Frequency MAGnetotelluric) studies; and
- cross-reference lightning strikes to spontaneous polarization (SP or self potential) studies.

The scientists with the Alberta Fire Protection Division estimate the Lightning Detection Network carries a positioning error of up to + six or seven kilometres, dependent on distance from the direction finder. If a target mineral deposit has a strike length of 1000 metres and width of 50 metres, a unique signature will not be developed. Similarly, only very large regional faults and structures might be expected to develop recognizable and repeatable patterns. The Great Slave Lake Shear Zone is a huge tectonic structure, but I observed nothing in the lightning strike data that would indicate its presence.

It is possible to generate biases in the randomly gridded data if the wrong parameters have been selected. Although the gridding parameters were carefully selected and tailored to the characteristics of the lightning strike data, the uneven distribution of records could lead to some aliasing. Therefore, although an interpretation of the randomly gridded 1999 Negative Amplitude Strikes (Figures 41 to 45) is included in this report, I do not have the same level of confidence in the lightning interpretation that I would have for potential field (magnetic and gravity) interpretations for the same area. The lineaments and targets must be supported by conventional geological knowledge before they can be substantiated. This study has created a number of maps and processing techniques based on the Province of Alberta

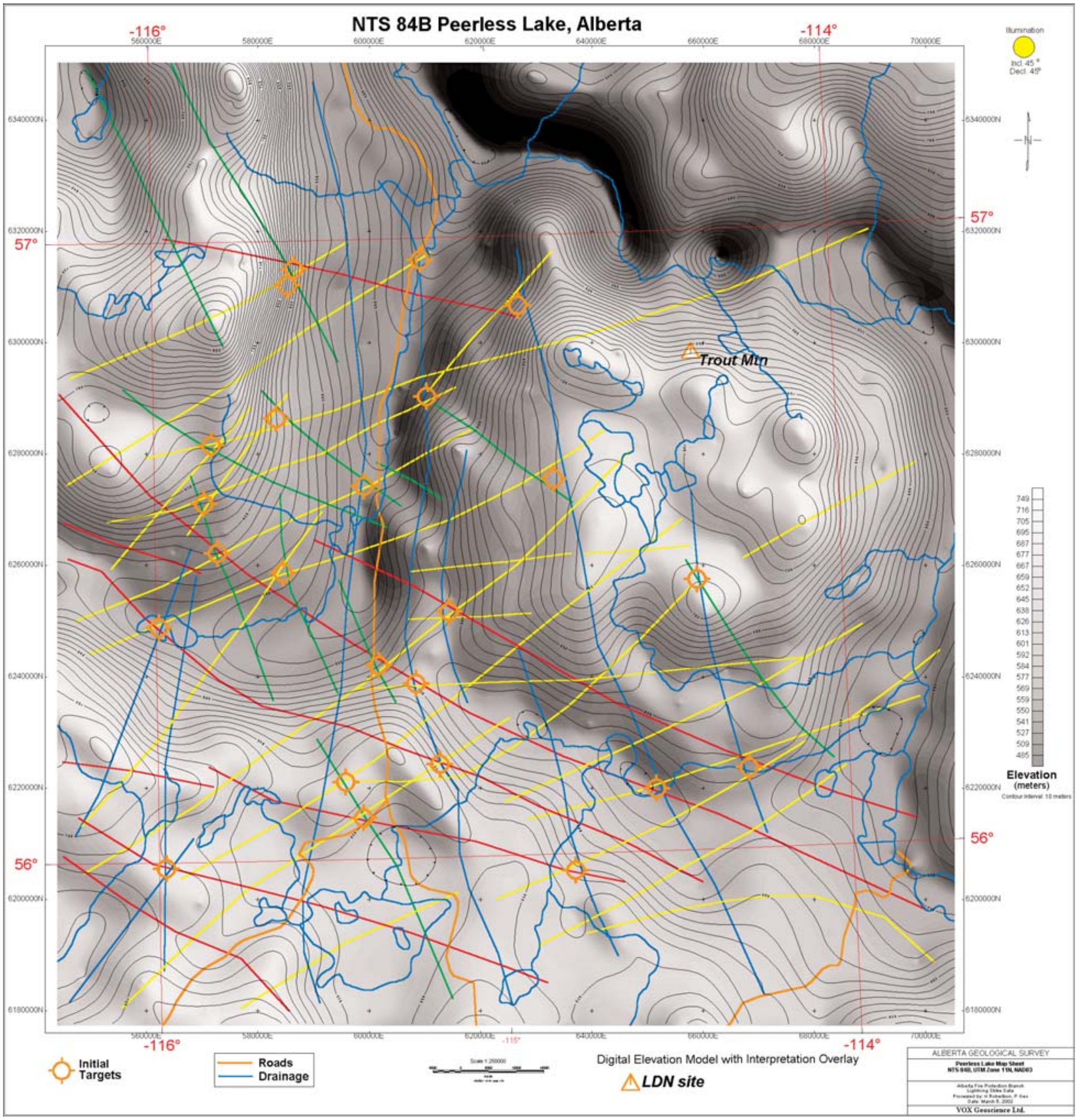

Figure 43. Peerless Lake area NTS 84B shaded relief topography with an overlay of the interpretation from Figure 41 and selected targets.

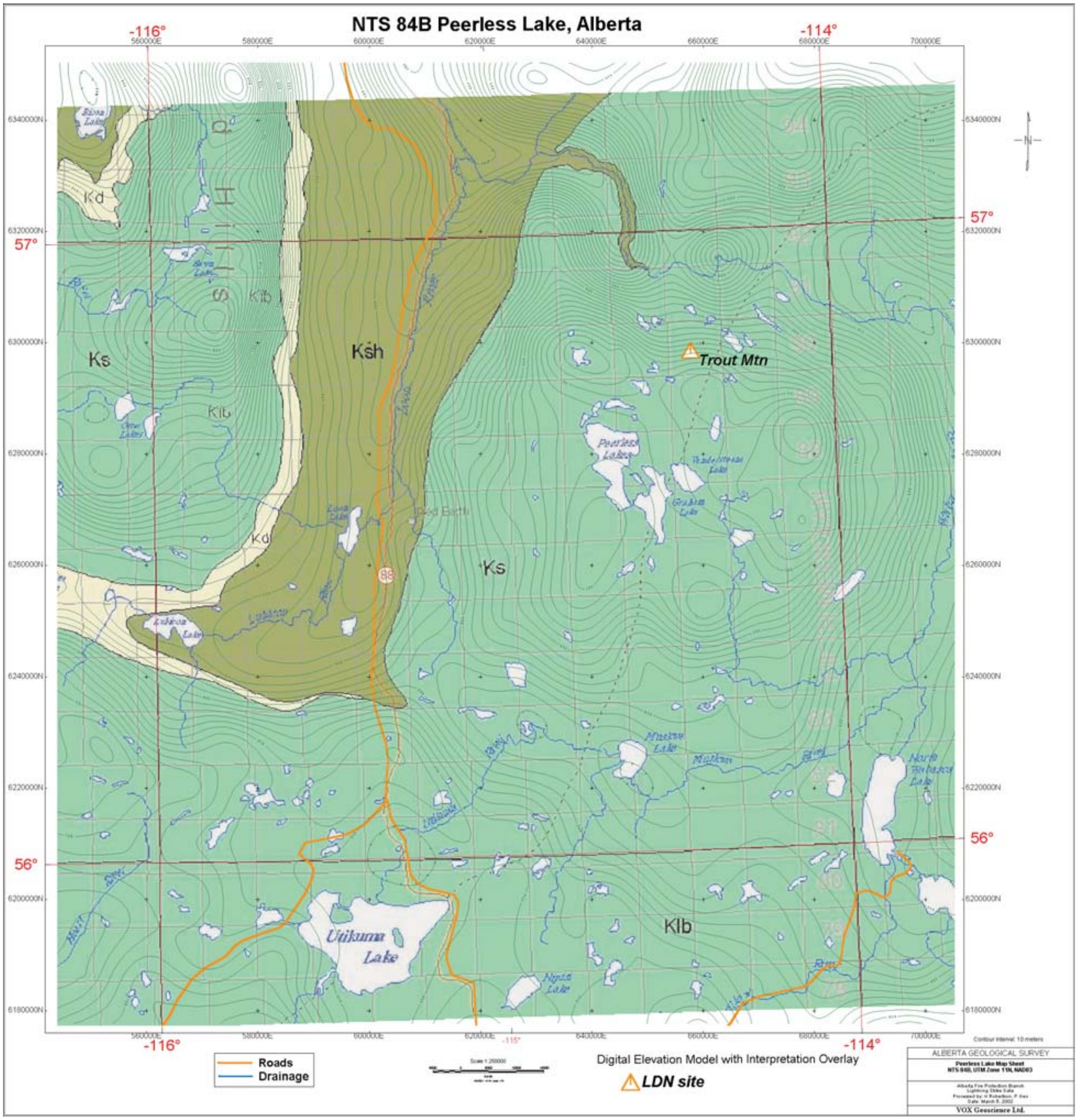

Figure 44. Peerless Lake area NTS 84B regional geology window from the Alberta provincial geology map with an overlay of topographic contours.

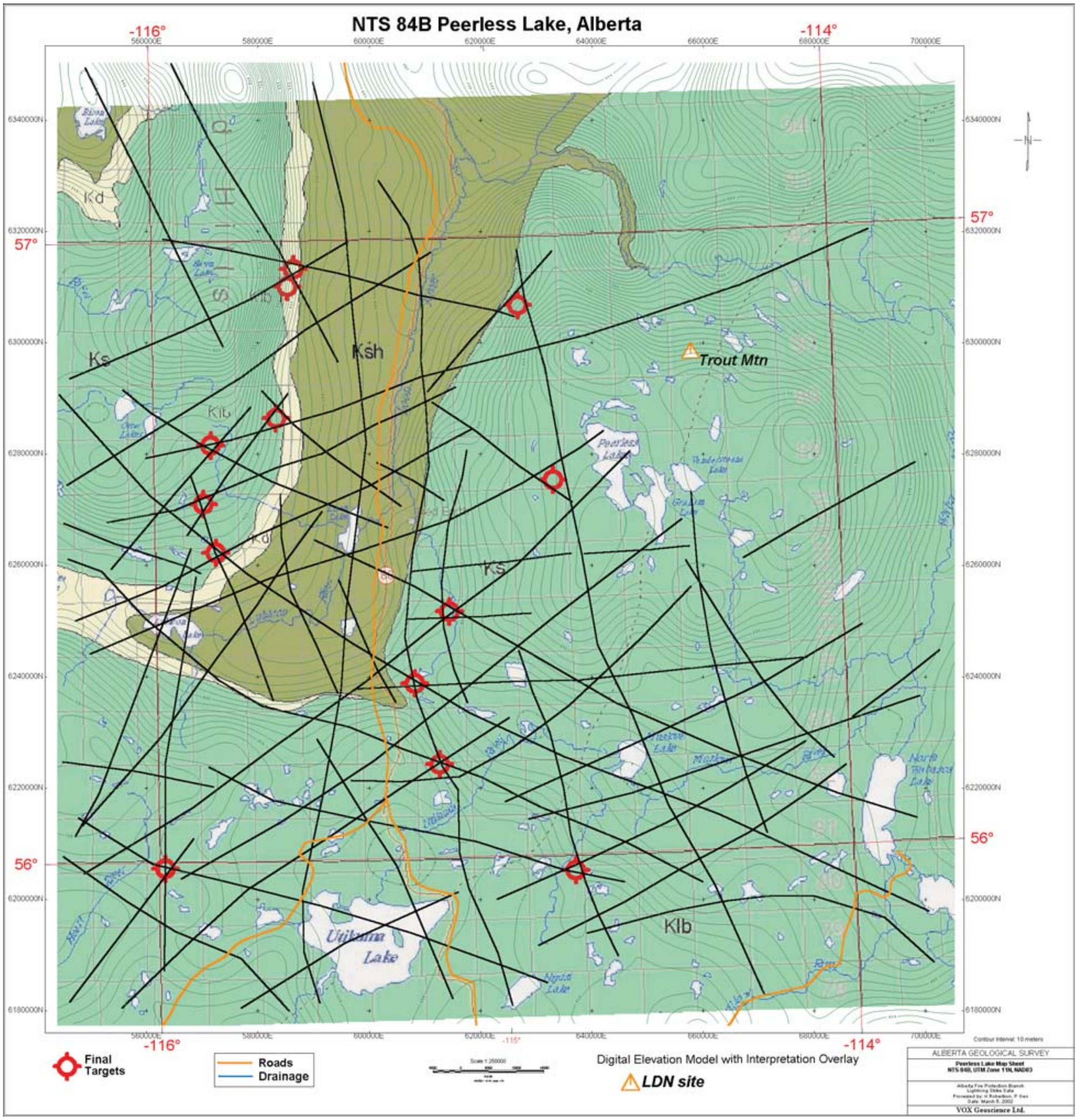

Figure 45. Peerless Lake area NTS 84B regional geology window from the Alberta provincial geology map with an overlay of topographic contours, the interpretation from Figure 41 and the final target selection.

Lightning Detection Network archival dataset. To the best of my knowledge, lightning strike records have not been previously used for geophysical or geological exploration or mapping. Although the initial results are inconclusive and remain to be corroborated by the geoscientists of the Alberta Geological Survey, enough evidence is observed to suggest there may be some merit to the concept.

With the continued evolution of lightning detection sensors, on the ground and in space, and improved accuracy of position analyzers problems associated with baseline biases, repeatability, decreases of measured intensity over distance and precision may be overcome. The six or seven kilometre margin of error in the current generation of lightning strike records may obscure critical observations.

17 Recommendations

Global Atmospherics, Inc. lightning detection equipment specifications imply a + 500 metre accuracy. The archival records from the U.S. and Canadian Lightning Detection Networks are routinely used by insurance companies to check claims of lightning damage. If the precision of the North American Lightning Detection Network were higher than the Alberta network, then those records would be worth processing.

In conversation with scientists working with the Canadian Lightning Detection Network, they claim the positioning of and the greater number of their detectors makes the system less prone to baseline biases. If so, this would remove a second source of uncertainty from the lightning strike records.

If more precise and uncluttered data become available, more thorough numerical analysis and statistical tools should be applied. The processed results should be imported into a robust GIS system and weights of evidence and other screening techniques used to augment the visual and qualitative approaches.

The results of this study, for the Peerless Lake NTS map area 84B, require scrutiny against the detailed geology and geophysics of the Buffalo Hills areas.

Existing well log data, mapped geology, structure, geophysical survey results, et cetera should be referenced by the Alberta Geological Survey staff, and possibly industry geoscientists active in the Buffalo Hills area, and applied to the interpretations in this study to provide third party, unbiased, scientific opinions.

Finally, preliminary studies of lightning strike data, by the author, have indicated interesting and unexpected observations that may relate to geological features. This field of research is not addressed in any of the geology or geophysical texts or publications that I have accessed and reviewed. If any papers or articles can be brought to my attention I would be grateful for the knowledge. Volumes of information about atmospheric electricity can be referenced but there seems to be a dearth of knowledge about atmospheric electricity as it may relate to whole earth geophysics. Many characteristics of atmospheric electricity remain a mystery after two centuries of study. Meteorologists and atmospheric physicists have advanced theories but they are difficult to test and verify using existing technology.

Respectfully submitted,
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VOX Geoscience Ltd.

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Appendix I – Example of Data Listing Format

Latitude	Longitude	Date	Multiplicity	Strength
54.027	-116.189	"01-JUL-98"	1	-17.2
54.185	-115.743	"01-JUL-98"	2	-19.7
54.076	-116.722	"01-JUL-98"	3	-506.3
54.054	-111.661	"01-JUL-98"	1	-11.2
54.130	-116.503	"01-JUL-98"	1	-110.6
54.057	-116.261	"01-JUL-98"	1	-245.7
54.498	-118.700	"01-JUL-98"	1	-47.6
54.190	-116.251	"01-JUL-98"	1	-48.2
54.259	-116.467	"01-JUL-98"	1	-496.9
54.197	-116.486	"01-JUL-98"	1	-309.3
54.487	-118.708	"01-JUL-98"	3	-15.3
54.343	-118.968	"01-JUL-98"	1	-47.1
54.057	-116.517	"01-JUL-98"	2	-27.0
54.184	-116.373	"01-JUL-98"	3	-354.1
54.102	-116.841	"01-JUL-98"	1	-25.9
54.107	-116.060	"01-JUL-98"	3	-114.7
54.560	-118.886	"01-JUL-98"	1	-885.8
54.166	-116.359	"01-JUL-98"	3	-653.6
54.013	-116.640	"01-JUL-98"	1	-21.1
54.389	-118.654	"01-JUL-98"	3	-376.4
54.175	-116.405	"01-JUL-98"	1	-223.2
54.255	-116.442	"01-JUL-98"	2	-417.4
54.477	-116.585	"01-JUL-98"	1	-746.9
54.208	-116.409	"01-JUL-98"	2	-284.7
54.210	-116.345	"01-JUL-98"	6	-280.3
54.229	-116.305	"01-JUL-98"	3	-366.7
54.249	-116.371	"01-JUL-98"	3	-194.3
54.250	-116.385	"01-JUL-98"	2	-346.2
54.199	-116.422	"01-JUL-98"	2	-1201.9
54.457	-116.703	"01-JUL-98"	6	-89.4
54.268	-116.352	"01-JUL-98"	3	-46.7
54.067	-116.623	"01-JUL-98"	1	-344.5
54.032	-116.038	"01-JUL-98"	1	-183.7
54.133	-116.318	"01-JUL-98"	2	-191.9
54.012	-116.199	"01-JUL-98"	1	299.1
54.038	-116.012	"01-JUL-98"	2	-119.0
54.191	-116.323	"01-JUL-98"	1	-223.7
54.257	-116.323	"01-JUL-98"	1	-160.4
54.000	-116.072	"01-JUL-98"	2	-218.8
54.060	-116.076	"01-JUL-98"	3	-706.2
54.242	-116.003	"01-JUL-98"	1	-11.0
54.012	-115.408	"01-JUL-98"	4	-39.5
54.021	-116.045	"01-JUL-98"	2	-128.4
54.080	-116.236	"01-JUL-98"	8	-1269.7
54.247	-115.540	"01-JUL-98"	2	-21.2
54.038	-114.908	"01-JUL-98"	1	-18.8

Latitude	Longitude	Date	Multiplicity	Strength
54.264	-116.312	“01-JUL-98”	1	-10.1
54.249	-116.699	“01-JUL-98”	2	-35.8
54.047	-114.933	“01-JUL-98”	2	-17.0
54.430	-116.389	“01-JUL-98”	1	-47.6
54.021	-116.129	“01-JUL-98”	4	-738.8
54.284	-116.392	“01-JUL-98”	2	-1015.5
55.106	-116.910	“01-JUL-98”	1	-28.7
54.742	-116.270	“01-JUL-98”	2	-93.3
54.022	-116.019	“01-JUL-98”	3	-104.1

Appendix II –Frequently Asked Questions (FAQ) about Lightning

By Kerry Anderson, Canadian Forest Service, Edmonton, Alberta (file posted on the Alberta Forest Protection web site)

1.0 INTRODUCTION

Lightning is one of the most spectacular meteorological phenomenon and the most common severe weather to affect mankind directly. This FAQ is intended to provide the reader with a basic knowledge about lightning and answer some commonly asked questions about lightning.

2.0 THE EARTH'S ELECTRICAL STRUCTURE

2.1 *What is the Earth's charge?*

The Earth is electrically charged and acts as a spherical capacitor. The Earth has a net negative charge of about a million couloumbs, while an equal and positively charge resides in the atmosphere.

The electrical resistivity of the atmosphere decreases with height to an altidude of about 30 miles, where the resistivity becomes more or less constant. This region is known as the electrosphere. There is about a 300,000 volt potential difference between the Earth's surface and the electrosphere, which gives an average electric field strength of about 6 volts/m throughout the atmosphere. Near the surface, the fine-weather electric field strength is about 100 V/m.

2.2 *If there is a fair weather electric field strength of 100 volts/m, why can't I set up two plates 10 centimetres apart, which could act like a battery and power my Walkman?*

You can't do this because batteries don't work that way. The resistivity of air is 3 gigaohms/m for a 1 cm cross section near the surface, thus the internal resistance of this hypotheical battery would be too great to be feasible.

2.3 *What charges the Earth?*

Because the atmosphere is not a perfect insulator, there is a small current between the electrosphere and the Earth. Negative charge leaks from the Earth and rises to the electrosphere. This is called the fair weather electric and it is about 2000 amps at any given moment. At this rate, the Earth's charge would dissipate in less than an hour, but, as it turns out, lightning recharges the Earth's by delivering negative charge back to the surface.

2.4 *How many lightning flashes happen each day?*

There are roughly 2000 thunderstorms in progress around the world at any one time producing about 30 to 100 cloud to ground flashes each second or about five million flashes a day.

3.0 THUNDERSTORM STRUCTURE

3.1 *What is a thundercloud?*

Lightning is associated with convective activity. Thunder (and thus lightning) is used by the professional weather observer to classify the severity of convective activity. Cumulonimbus clouds are the largest form of convective cloud and typically produce lightning. Cumulonimbus clouds with lightning activity are generally referred to as thunderclouds.

3.2 *How are thunderclouds charged?*

The classical thundercloud model can be described as a positive electric dipole with a positively charged region above a negatively charged region. A weaker, positively charged region at the base of the cloud gives it more of a double-dipole structure, but because of the weak strength of the lower charge region, both the positive dipole and the double-dipole can be used to describe the general structure of a thundercloud.

The three centres of accumulated charge are commonly labelled p, N, and P. The upper positive centre, P, occupies the top half of the cloud. The negative charge region, N, is located in the middle of the cloud. The lowest centre, p, is a weak, positively charged centre at the cloud base. The N and the P regions have approximately the same charge, creating the positive dipole. Malan (1963) documented charges and altitudes above ground level for the p, N and P regions of a typical South African thundercloud (1.8 km ASL) as +10 C (coulombs) at 2 km, -40 C at 5 km, and +40 C at 10 km. These are representative of values that can vary considerably with geography and from cloud to cloud.

3.3 *Is there an association between lightning activity and RADAR echoes?*

There is a general association between radar reflectivity and negatively charged lightning flashes. Lightning discharge sources are located near, but not necessarily within, the area of highest reflectivity (MacGorman et al. 1983). This is supported by Mazur (1983) and Mazur and Rust (1985). In two studies of thunderstorms developing off Wallops Island, Virginia, Mazur found that the region of maximum flash density was close to the leading edge of the precipitation core, defined by 50 dBZ weather radar reflectivity. Though Mazur did not state the polarity of these flashes, it is inferred that they come from the negative charge centre. Lopez, Otto, Ortiz, and Holle (1990) also observed that, in a Colorado thunderstorm, the peak lightning activity occurred in the gradient areas of high reflectivity.

4.0 CHARGE GENERATION IN THUNDERCLOUDS

4.1 *How do clouds get charged?*

It is not fully known how thunderclouds get charged. There are two general theories to explain the charge buildup required to electrify a thundercloud. They are the convective theory and the gravitational theory.

The convective theory proposes that free ions in the atmosphere are captured by cloud droplets and then are moved by the convective currents in the cloud to produce the charged regions.

The gravitational theory assumes that negatively charged particles are heavier and are separated from lighter positively charged particles by gravitional settling.

For the gravitational theory to work, there must be some charge exchange process between particles of different sizes. Charge can be exchanged between particles in various states by inductive and non-inductive processes. The most promising is the non-inductive exchange between ice crystals and hailstones, referred to as the ice-ice process. The effectiveness of the ice-ice process lies in the thermo-electric properties of ice. The mobility of the (OH3)+ defect in ice is greater than the (OH)- defect and the number of defects increase with temperature. When warm and cold ice particle come in contact, the positive defect flows faster from the warmer to the colder particle than the converse giving the colder particle a net positive charge. Therefore in the typical scenario, a warm hailstone or snow pellet will acquire a net negative charge as it falls through a region of cold ice crystals.

Theories of thundercloud charge generation is still very speculative. The favourability of one process over another has fluctuated over time due to the inadequate number of laboratory experiments and scarcity of useful field observations. One clear conclusion is that there is no unique mechanism to generate the required charge under all conditions. For example, the ice-ice process, presently the most favoured, does not explain warm cloud lightning, albeit a not too frequent event. As research develops, the most likely explanation will lie in a combination.

5.0 THE LIGHTNING FLASH

5.1 *Why does lightning happen?*

The charge buildups in thunderclouds are unstable. When electric fields generated by the charge buildups becomes too strong - typically 3-4 kV/cm at the altitude of the negative charge region of the cloud - electrical breakdown of the air occurs and charge is exchanged within the cloud or to the ground. Charge is exchanged by a lightning flash.

5.2 *In what ways can lightning occur?*

Lightning can occur in four ways. Lightning can travel between points within a cloud, from a cloud to clear air, from a cloud to an adjacent cloud, and from a cloud to ground. These flashes are referred to as intracloud, cloud-to-air, cloud-to-cloud, and cloud-to-ground, respectively.

Intracloud (IC) flashes, redistributing the charge within the cloud, account for over half the lightning flashes in northern latitudes (Uman and Krider 1989). Cloud-to-cloud and cloud-to-air flashes are less common. Besides aviation, these three types of flashes have little impact on man.

Cloud-to-ground (CG) flashes are very common and have been well documented. They exchange charge between the cloud and ground. These flashes affect man greatly, causing injury and death, disrupting power and communications, and igniting forest fires. Because of these impacts, the cloud-to-ground flash has been the topic of much research.

The cloud-to-ground lightning flash can lower positive (+CG) or negative (-CG) charge, depending on the source of the flash. This can be determined by the polarity of the stroke's current. Characteristics of negative and positive cloud-to-ground flash are summarized below.

Table 1. Some characteristics of positive and negative cloud-to-ground flashes.

Characteristic	Negative	Positive
% occurrence	90	10
Average peak current (kA)	30	35
Average current half life (microsec)	30	230
Average number of strokes	3-4	1
% containing long continuing current	20	80

Ground-to-cloud flashes (those that originate from the ground) occur as well, as observed from large buildings such as the Empire State Building, but are not normally distinguished from CG flashes in studies.

5.3 _Does lightning go up or down?_

The answer is both! A cloud-to-ground lightning flash, by definition, originates from the cloud but flashes often originate from the ground, as suggested by the lightning branch structures observed in photographs.

But to properly answer whether lightning goes up or down, one must understand the question, and to understand the question, one must look at the processes involved in a lightning flash.

The negative cloud-to-ground lightning flash can be broken down into three stages. The stepped leader, the return stroke, and the dart leader.

The stepped leader is a small packet of negative charge that descends from the cloud to the ground along the path of least resistance. In its path, the leader leaves a trail of ionized gas. It moves in steps, each typically tens of metres in length and microseconds in duration. After a step, the leader pauses for about 50 microseconds, then takes its next step. The leader charge packet sometimes breaks up to follow different paths, giving lightning its forked appearance.

As the stepped leader approaches the ground, electrons on the surface retreat from the leader creating a region of positive charge. Corona discharges (dielectric breakdowns in the air, also known as St. Elmo's Fire) are released from tall objects on the surface and reach out to the approaching leader. When the downward moving leader connects with a surface corona discharge, a continuous path between the cloud and the ground is established and a powerful return stroke is triggered. The return stroke rapidly moves as a wave upwards into the cloud following the ionized trail of the stepped leader, stripping the electrons from its path.

After the return stroke, the lightning flash may end or, if enough charge in the cloud is collected, a dart leader may come down from the cloud following a direct path to the surface. In turn, the dart leader triggers a second return stroke.

A single lightning flash can be comprised of several return strokes. The average number of return strokes in a lightning flash is 3 or 4, each stroke typically separated by 40 to 80 milliseconds.

5.4 *Positive flashes? Negative flashes? Huh?*

The positive cloud-to-ground flash is less common than the negative. Coming from higher altitudes in the cloud, positive flashes make up about 10% of all lightning flashes. They are usually composed of a single stroke, and have longer, continuing currents (see Table 1). From the forestry perspective, positive flashes are of more concern as the longer currents are more likely to start fires.

Several studies have concentrated on the characteristics of the positive flash but results are inconclusive due to the number of observations. The percentage of positive flash appears to increase with latitude and with the height of local terrain. Also, positive flashes are more common in winter storms. The apparent cause for this is that the lower freezing level places the positive charge centre closer to the ground thus increasing the likelihood of a flash.

Positive flashes are more common in stratiform clouds while negative flashes tend to occur in areas of strong convection. Also, thunderstorms that predominantly consist of negative flashes in their early stages, often end with positive discharges as the storm matures and the anvil spreads out.

A popular theory is that horizontal wind shears force a tilting of the dipole axis providing a route for the positive flash but this has yet to be shown conclusively.

6.0 LIGHTNING DETECTION

6.1 *How is lightning detected? How are lightning maps made?*

Most forest and weather services now use the wide band magnetic gate design lightning detector manufactured by Lightning Location and Protection Inc. (LLP) of Tucson, Az. The LLP lightning detection system determines the time and location of a lightning flash by triangulating information from direction finder stations situated in the network These data are stored on magnetic tape. Maps can be processed to show the location and polarity of lightning flashes that occur over a period of time.

The LLP lightning detection system has three components: the direction finder, the position analyzer and the remote display processor.

The direction finder (DF) senses the electromagnetic field radiated by a lightning flash using two erect, orthogonal wire loop antennas and a horizontal flat plate antenna. The antenna's bandwidths are from 1 kHz to 1 MHz. The radiated field of a lightning flash induces a current in the loops. The voltage signal measured in the loops is related to the flash's generated magnetic field strength by the cosine of the angle between the loop antenna and the direction to the flash. By comparing the voltage signals from the two loops, a direction to the flash can be determined. The flat plate antenna is used to resolve the 180 degree ambiguity associated with the calculations.

The direction finder can discriminate cloud-to-ground flash from other forms of lightning or noise by the electromagnetic signature. When the stepped leader reaches the ground, the return stroke is triggered producing a sharp voltage rise. This telling factor distinguishes a cloud-to-ground flash from other electromagnetic noise.

The direction finder sends the data of each registered lightning flash to the position analyzer (PA). The position analyzer triangulates data from direction finders to locate the position of a lightning flash. If the flash is in line with or directly between two direction finders (called the baseline), the position analyzer uses the ratio of the signal strengths as well.

From the position analyzer, users can view a map of the lightning data on a remote display processor (RDP). The display can focus on desired time and location windows covered by the detection network, and can show up to 30,000 flashes.

6.2 *<u>Is lightning detectable with RADAR</u>*

The basic reason is that the lightning discharge ionizes the air, creating a "plasma" field through the lightning path. This plasma responds to the radar's EM wave based upon the "plasma frequency" F(p), where:

F(p)= w(p)/(2*pi) = 1/(2*pi) * sqrt (n*e^2/E(0)*m) with

n=electron density (depends on T)
e=dielectric charge
m=electronic mass
E(0)= /epsilon naught/ permittivity of free space

If the incident frequency (F(radar)) is less than F(plasma), then the plasma is sufficiently dense to have a sheath surround the main channel of the plasma flow. This sheath around the plasma acts as a very good conductor, and thus provides a strong return signal back to the radar. If F(r) > F(p), then the plasma acts more as a dielectric than a conductor and becomes a poor reflector of the EM wave.

Typically, the temperatures reached (5,0000 to 10,000 K) are high enough to achieve overdense lightning channels at the wavelengths used by meteorological radars. However, masking of the signal by precipitation can be significant.

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7.0 SUGGESTED READING

For this list, I have included general texts and magazine articles that provide a good background to the topic of lightning and tatmospheric electricity. Most should be available at a college or university library.

Most of the texts are showing their age but clearly the most up-to-date and comprensive books are by Dr. Uman. His book, All About Lightning, is a wonderful book written at perhaps the junior high shool level. It answers specific questions at a layman's (lay-person's?) level, is full of pretty pictures, and is cheap.

Uman's other book, The Lightning Discharge, is the definitive, academic publication on the subject. It covers all aspects of lightning and provides extensive references throughout.

Chalmer, J.A. 1967. Atmospheric electricity. Pergamon press, New York, NY. 515 pp.
Golde, R.H. 1977. Lightning: volume 1, physics of lightning. Academic Press, London. 496 pp.
Malan, D.J. 1963. Physics of lightning. The English Universities Press Ltd., London. 176 pp.
Mason, B.J. 1971. The physics of clouds. Clarendon Press, Oxford. 671 pp.
Uman, M.A. 1969. Lightning. Mcgraw Hill, New York, NY. 264 pp.
Uman, M.A. 1986. All About Lightning. Dover Publications, Inc., New York, NY. 167 pp.
Uman, M.A. 1987. The Lightning Discharge. Academic Press, Orlando, FL. 377 pp.
Viemeister, P.E. 1972. The Lightning Book. MIT Press, Cambridge, MA. 316 pp.
Williams, E.R. 1988. The electrification of thunderstorms. Scientific American, November 1988: 88-99.

Appendix III - Geographic Locations of Alberta Lightning Detection Network Direction Finders

LDN Receiver (Direction Finder)	Latitude.		Longitude
Gooseberry	52° 07’	16” N	110° 45’ 00 W
Sparwood	49° 50’	00” N	114° 53’ 00 W
McBride	53° 18’	00” N	120° 06’ 00 W
Dawson Creek	55° 43’	43” N	120° 15’ 30 W
Debolt	55° 09’	43” N	117° 47’ 00 W
Footner	58° 35’	59” N	117° 17’ 13 W
Anzac	56° 31’	16” N	111° 16’ 48 W
Jasper	52° 59’	34” N	118° 03’ 26 W
Kinusco	55° 16’	53” N	115 ° 24’ 14 W
Lacory	54° 26’	59” N	110° 45’ 56 W
Park Lake	49° 48’	20” N	112° 55’ 06 W
Peery	53° 46’	29” N	116° 02’ 20 W
Peace River	56° 09’	23” N	117° 11’ 13 W
Rocky Mtn	52° 23’	42” N	114° 56’ 57 W
Trout Mtn	56° 48’	07” N	114° 25’ 16 W
Turner Valley	50° 39’	07” N	114° 19’ 13 W
Hay River	60° 47’	00” N	115° 49’ 25 W
Birch	57° 41’	32” N	111° 49’ 24 W
Brisco	50° 49’	47” N	116° 17’ 35 W
Fort Nelson	58° 50’	43” N	122° 49’ 36 W

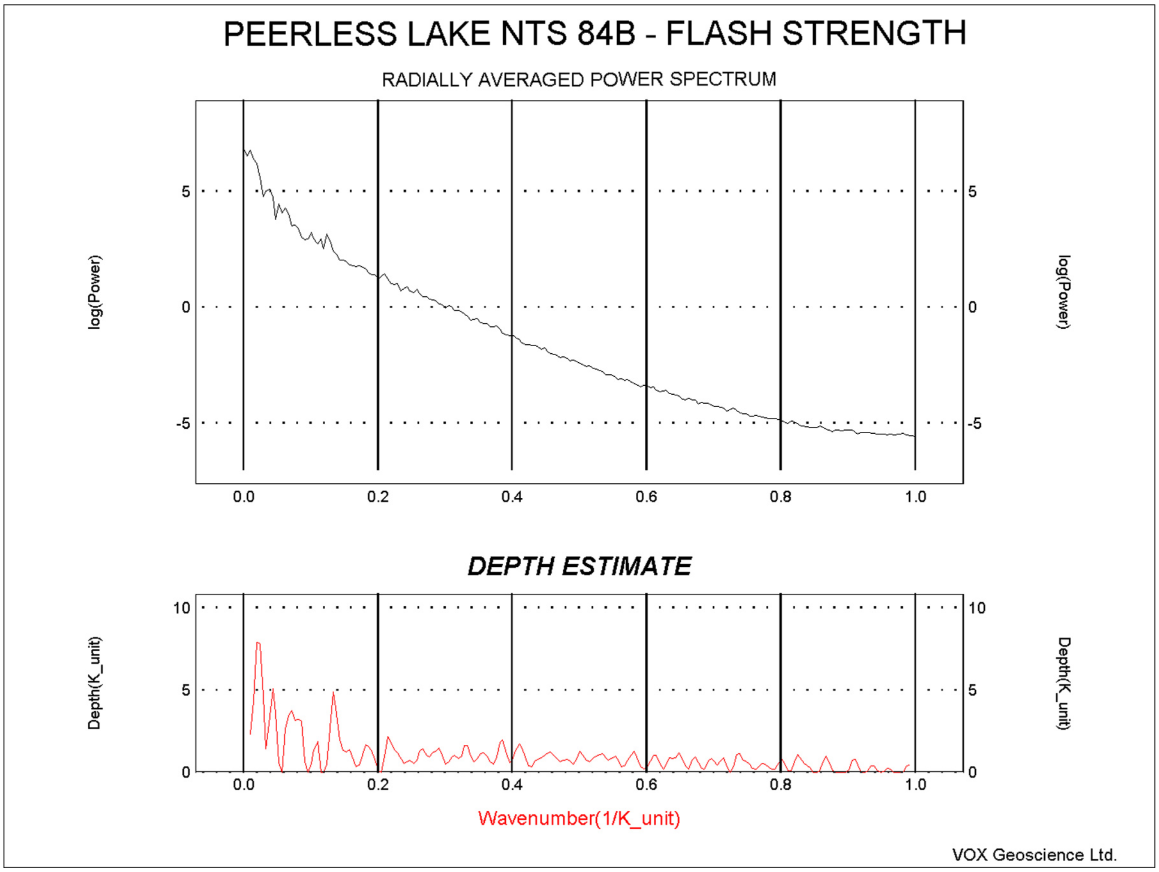
Appendix IV - 2-D Radially Averaged Power Spectrum for Peerless Lake NTS 84B, 1999 Flash Strength, Average Spectrum Density Ln(E)=2.42632e+001

/ CYC/K_unit	#_SAMP	LOG_P	3_DEPTH	5_DEPTH
0.00000e+000	1.00000e+000	6.85669e+000	5.29697e+000	*
4.76190e-003	6.34315e+000	6.53972e+000	5.79185e-001	*
9.52381e-003	1.24546e+001	6.78738e+000	1.38207e+000	2.30159e+000
1.42857e-002	1.90596e+001	6.37432e+000	4.94350e+000	4.32812e+000
1.90476e-002	2.44101e+001	6.19574e+000	6.65879e+000	7.86694e+000
2.38095e-002	3.25840e+001	5.57739e+000	1.19985e+001	7.79003e+000
2.85714e-002	3.69993e+001	4.75976e+000	4.71277e+000	4.65606e+000
3.33333e-002	4.39585e+001	5.01337e+000	0.00000e+000	1.43688e+000
3.80952e-002	5.05589e+001	5.08805e+000	2.34095e+000	3.43564e+000
4.28571e-002	5.59206e+001	4.73321e+000	1.07091e+001	5.10370e+000
4.76190e-002	6.41033e+001	3.80639e+000	2.26109e+000	3.61272e+000
5.23810e-002	6.77438e+001	4.46260e+000	0.00000e+000	5.87486e-001
5.71429e-002	7.58087e+001	4.06155e+000	1.63336e+000	0.00000e+000
6.19048e-002	8.23335e+001	4.26712e+000	2.25126e-001	2.70735e+000
6.66667e-002	8.71092e+001	4.03461e+000	6.26357e+000	3.48961e+000
7.14286e-002	9.53559e+001	3.51750e+000	3.98013e+000	3.73032e+000
7.61905e-002	9.86037e+001	3.55827e+000	9.47265e-001	3.18381e+000
8.09524e-002	1.08592e+002	3.40413e+000	4.62403e+000	3.20940e+000
8.57143e-002	1.12719e+002	3.00486e+000	4.05692e+000	3.09078e+000
9.04762e-002	1.18910e+002	2.91860e+000	5.91410e-001	6.53742e-001
9.52381e-002	1.26340e+002	2.93409e+000	0.00000e+000	0.00000e+000
1.00000e-001	1.30684e+002	3.24019e+000	1.04545e-001	5.67886e-001
1.04762e-001	1.40039e+002	2.92157e+000	4.28621e+000	1.39023e+000
1.09524e-001	1.43261e+002	2.72722e+000	0.00000e+000	1.86946e+000
1.14286e-001	1.50605e+002	2.94791e+000	1.54221e+000	0.00000e+000
1.19048e-001	1.57852e+002	2.54264e+000	0.00000e+000	0.00000e+000
1.23810e-001	1.62830e+002	3.15743e+000	0.00000e+000	4.64985e-001
1.28571e-001	1.70911e+002	2.89070e+000	6.05381e+000	2.78525e+000
1.33333e-001	1.74013e+002	2.43291e+000	5.21014e+000	4.91794e+000
1.38095e-001	1.83041e+002	2.26715e+000	3.48986e+000	3.57665e+000
1.42857e-001	1.88930e+002	2.01524e+000	2.02994e+000	1.95387e+000
1.47619e-001	1.94133e+002	2.02421e+000	3.41798e-001	1.34209e+000
1.52381e-001	2.02008e+002	1.97434e+000	1.65453e+000	1.23837e+000
1.57143e-001	2.05359e+002	1.82619e+000	1.71878e+000	1.36857e+000
1.61905e-001	2.15885e+002	1.76863e+000	7.32397e-001	8.29429e-001
1.66667e-001	2.19201e+002	1.73854e+000	3.71091e-002	3.45514e-001
1.71429e-001	2.25716e+002	1.76419e+000	2.67036e-001	4.58832e-001
1.76190e-001	2.32784e+002	1.70658e+000	1.07235e+000	1.09699e+000
1.80952e-001	2.37884e+002	1.63585e+000	1.95158e+000	1.66924e+000
1.85714e-001	2.47047e+002	1.47302e+000	1.98379e+000	1.53326e+000
1.90476e-001	2.49610e+002	1.39843e+000	6.64411e-001	1.32694e+000
1.95238e-001	2.58260e+002	1.39350e+000	1.33261e+000	8.07580e-001
2.00000e-001	2.63524e+002	1.23895e+000	4.25723e-001	1.10339e-001
2.04762e-001	2.70344e+002	1.34255e+000	0.00000e+000	0.00000e+000
2.09524e-001	2.77648e+002	1.40977e+000	9.14319e-001	9.72338e-001
2.14286e-001	2.80528e+002	1.23312e+000	3.43001e+000	2.20089e+000
2.19048e-001	2.90488e+002	9.99266e-001	2.25835e+000	1.85630e+000
2.23810e-001	2.95011e+002	9.62845e-001	0.00000e+000	1.39368e+000
2.28571e-001	3.01684e+002	1.01356e+000	2.04214e+000	1.17265e+000

2.33333e-001	3.07806e+002	7.18443e-001	1.59528e+000	8.45178e-001
2.38095e-001	3.12576e+002	8.22640e-001	0.00000e+000	5.41126e-001
2.42857e-001	3.23493e+002	8.50316e-001	1.12998e+000	6.20997e-001
2.47619e-001	3.24914e+002	6.87404e-001	1.83489e+000	7.67409e-001
2.52381e-001	3.34039e+002	6.30716e-001	0.00000e+000	5.22570e-001
2.57143e-001	3.37902e+002	7.66710e-001	3.95465e-001	7.51843e-001
2.61905e-001	3.45370e+002	5.83387e-001	2.52271e+000	1.30559e+000
2.66667e-001	3.54090e+002	4.64793e-001	9.98599e-001	1.45149e+000
2.71429e-001	3.55618e+002	4.63875e-001	8.33162e-001	1.02871e+000
2.76190e-001	3.66537e+002	3.65080e-001	1.25437e+000	9.44374e-001
2.80952e-001	3.69108e+002	3.13753e-001	7.45596e-001	1.17597e+000
2.85714e-001	3.77602e+002	2.75847e-001	1.52795e+000	1.30050e+000
2.90476e-001	3.84373e+002	1.30888e-001	1.62795e+000	1.49108e+000
2.95238e-001	3.86706e+002	8.10149e-002	1.31735e+000	1.07555e+000
3.00000e-001	3.98621e+002	-2.67721e-002	2.81354e-001	5.17473e-001
3.04762e-001	4.00612e+002	4.73426e-002	0.00000e+000	6.54725e-001
3.09524e-001	4.09779e+002	-2.12321e-002	1.72911e+000	9.55828e-001
3.14286e-001	4.14297e+002	-1.59597e-001	1.18466e+000	1.06379e+000
3.19048e-001	4.17979e+002	-1.63012e-001	2.77584e-001	8.47738e-001
3.23810e-001	4.31900e+002	-1.92818e-001	1.08097e+000	9.91842e-001
3.28571e-001	4.30482e+002	-2.92382e-001	1.61697e+000	1.61893e+000
3.33333e-001	4.41763e+002	-3.86337e-001	2.15885e+000	1.64922e+000
3.38095e-001	4.44570e+002	-5.50753e-001	1.17185e+000	1.01419e+000
3.42857e-001	4.51706e+002	-5.26584e-001	0.00000e+000	6.32604e-001
3.47619e-001	4.61693e+002	-5.16268e-001	1.01410e+000	8.21692e-001
3.52381e-001	4.61645e+002	-6.47951e-001	1.73911e+000	1.12297e+000
3.57143e-001	4.73686e+002	-7.24405e-001	6.15693e-001	1.16681e+000
3.61905e-001	4.76434e+002	-7.21637e-001	1.14561e+000	9.70297e-001
3.66667e-001	4.83984e+002	-8.61511e-001	1.14959e+000	6.23796e-001
3.71429e-001	4.91448e+002	-8.59219e-001	0.00000e+000	4.84855e-001
3.76190e-001	4.92752e+002	-8.10790e-001	7.28789e-001	9.53488e-001
3.80952e-001	5.05263e+002	-9.46441e-001	2.55549e+000	1.85094e+000
3.85714e-001	5.08314e+002	-1.11663e+000	2.26855e+000	1.95338e+000
3.90476e-001	5.16324e+002	-1.21794e+000	1.03612e+000	1.11144e+000
3.95238e-001	5.21371e+002	-1.24063e+000	2.96423e-002	5.85450e-001
4.00000e-001	5.25039e+002	-1.22149e+000	6.90590e-001	7.30593e-001
4.04762e-001	5.37508e+002	-1.32328e+000	1.47155e+000	1.34882e+000
4.09524e-001	5.38044e+002	-1.39760e+000	1.88433e+000	1.74539e+000
4.14286e-001	5.48671e+002	-1.54880e+000	1.88031e+000	1.48032e+000
4.19048e-001	5.50942e+002	-1.62264e+000	6.76336e-001	9.47146e-001
4.23810e-001	5.59882e+002	-1.62974e+000	2.84792e-001	4.07554e-001
4.28571e-001	5.66953e+002	-1.65672e+000	2.61533e-001	3.59864e-001
4.33333e-001	5.69163e+002	-1.66104e+000	5.33267e-001	7.20990e-001
4.38095e-001	5.79845e+002	-1.72054e+000	1.36817e+000	8.11428e-001
4.42857e-001	5.82993e+002	-1.82478e+000	5.32844e-001	9.10268e-001
4.47619e-001	5.92656e+002	-1.78431e+000	8.29786e-001	1.07216e+000
4.52381e-001	5.96495e+002	-1.92409e+000	1.85384e+000	1.18610e+000
4.57143e-001	6.00659e+002	-2.00618e+000	8.74681e-001	1.22199e+000
4.61905e-001	6.11747e+002	-2.02877e+000	9.37452e-001	1.02524e+000
4.66667e-001	6.13863e+002	-2.11837e+000	1.26359e+000	7.95477e-001
4.71429e-001	6.25192e+002	-2.18000e+000	1.85388e-001	6.12888e-001
4.76190e-001	6.26501e+002	-2.14056e+000	3.89685e-001	7.46005e-001
4.80952e-001	6.33415e+002	-2.22664e+000	1.66294e+000	8.11418e-001
4.85714e-001	6.44018e+002	-2.33958e+000	3.81629e-001	6.80302e-001

4.90476e-001	6.43458e+002	-2.27231e+000	0.00000e+000	5.08347e-001
4.95238e-001	6.56561e+002	-2.33914e+000	1.14707e+000	7.90476e-001
5.00000e-001	6.56780e+002	-2.40959e+000	1.22802e+000	1.29639e+000
5.04762e-001	6.68200e+002	-2.48611e+000	1.51408e+000	1.06389e+000
5.09524e-001	6.73638e+002	-2.59080e+000	4.49565e-001	7.65453e-001
5.14286e-001	6.74904e+002	-2.53991e+000	3.32717e-001	6.49407e-001
5.19048e-001	6.87606e+002	-2.63062e+000	1.16594e+000	8.48139e-001
5.23810e-001	6.88104e+002	-2.67945e+000	1.04576e+000	9.66038e-001
5.28571e-001	7.00958e+002	-2.75577e+000	6.86413e-001	1.04593e+000
5.33333e-001	7.03368e+002	-2.76160e+000	1.40562e+000	1.12755e+000
5.38095e-001	7.06965e+002	-2.92400e+000	1.29064e+000	9.37423e-001
5.42857e-001	7.19597e+002	-2.91607e+000	1.16018e-001	7.44591e-001
5.47619e-001	7.19946e+002	-2.93788e+000	8.27121e-001	8.66462e-001
5.52381e-001	7.31773e+002	-3.01506e+000	1.65625e+000	1.01301e+000
5.57143e-001	7.32952e+002	-3.13610e+000	5.55651e-001	8.13309e-001
5.61905e-001	7.40571e+002	-3.08156e+000	2.28030e-001	3.64208e-001
5.66667e-001	7.51268e+002	-3.16339e+000	3.08943e-001	3.79353e-001
5.71429e-001	7.50430e+002	-3.11853e+000	6.01086e-001	7.75365e-001
5.76190e-001	7.62692e+002	-3.23533e+000	1.41607e+000	1.06199e+000
5.80952e-001	7.63288e+002	-3.28800e+000	1.16881e+000	1.25460e+000
5.85714e-001	7.75654e+002	-3.37521e+000	1.17892e+000	8.03140e-001
5.90476e-001	7.80085e+002	-3.42910e+000	6.16847e-002	3.63842e-001
5.95238e-001	7.82920e+002	-3.38259e+000	0.00000e+000	2.13827e-001
6.00000e-001	7.93237e+002	-3.41126e+000	7.28879e-001	3.41868e-001
6.04762e-001	7.95557e+002	-3.46983e+000	4.45809e-001	7.27394e-001
6.09524e-001	8.07295e+002	-3.46461e+000	1.00749e+000	1.06147e+000
6.14286e-001	8.09281e+002	-3.59040e+000	1.73111e+000	1.02762e+000
6.19048e-001	8.15563e+002	-3.67179e+000	3.44266e-001	5.05823e-001
6.23810e-001	8.24987e+002	-3.63160e+000	0.00000e+000	1.75084e-001
6.28571e-001	8.27956e+002	-3.60502e+000	7.38889e-001	4.77258e-001
6.33333e-001	8.38529e+002	-3.72003e+000	1.25079e+000	8.80700e-001
6.38095e-001	8.38600e+002	-3.75471e+000	6.52419e-001	8.18931e-001
6.42857e-001	8.48206e+002	-3.79812e+000	5.53581e-001	8.80848e-001
6.47619e-001	8.57386e+002	-3.82097e+000	1.43654e+000	1.17722e+000
6.52381e-001	8.58276e+002	-3.97004e+000	1.54153e+000	8.68400e-001
6.57143e-001	8.69568e+002	-4.00546e+000	0.00000e+000	4.12514e-001
6.61905e-001	8.69092e+002	-3.92542e+000	6.88855e-002	1.77026e-001
6.66667e-001	8.83637e+002	-4.01370e+000	8.35065e-001	7.61312e-001
6.71429e-001	8.84980e+002	-4.02536e+000	1.37999e+000	9.53751e-001
6.76190e-001	8.91031e+002	-4.17886e+000	6.46203e-001	6.14590e-001
6.80952e-001	8.99995e+002	-4.10269e+000	0.00000e+000	2.41219e-001
6.85714e-001	9.02225e+002	-4.15702e+000	2.59874e-001	2.03952e-001
6.90476e-001	9.15206e+002	-4.13380e+000	5.34401e-001	7.07524e-001
6.95238e-001	9.14493e+002	-4.22098e+000	1.32830e+000	8.16703e-001
7.00000e-001	9.23047e+002	-4.29277e+000	5.87408e-001	7.05843e-001
7.04762e-001	9.31922e+002	-4.29128e+000	2.01824e-001	4.35498e-001
7.09524e-001	9.34595e+002	-4.31692e+000	5.17262e-001	7.02825e-001
7.14286e-001	9.45547e+002	-4.35319e+000	1.38939e+000	8.77572e-001
7.19048e-001	9.44489e+002	-4.48320e+000	7.26065e-001	3.20564e-001
7.23810e-001	9.56892e+002	-4.44008e+000	0.00000e+000	0.00000e+000
7.28571e-001	9.62064e+002	-4.34512e+000	2.42703e-001	3.24808e-001
7.33333e-001	9.66087e+002	-4.46913e+000	1.88548e+000	1.09268e+000
7.38095e-001	9.76491e+002	-4.57077e+000	1.14986e+000	1.11573e+000
7.42857e-001	9.75085e+002	-4.60674e+000	3.11840e-001	7.48060e-001

7.47619e-001	9.92742e+002	-4.60809e+000	7.82476e-001	6.49676e-001
7.52381e-001	9.89912e+002	-4.70039e+000	8.54712e-001	5.02682e-001
7.57143e-001	9.98133e+002	-4.71039e+000	0.00000e+000	2.69959e-001
7.61905e-001	1.00607e+003	-4.68494e+000	8.43088e-002	2.23651e-001
7.66667e-001	1.00945e+003	-4.72048e+000	7.15787e-001	4.16936e-001
7.71429e-001	1.02351e+003	-4.77060e+000	4.50713e-001	5.53700e-001
7.76190e-001	1.01948e+003	-4.77442e+000	4.94600e-001	4.71311e-001
7.80952e-001	1.03139e+003	-4.82979e+000	4.68620e-001	3.10286e-001
7.85714e-001	1.03753e+003	-4.83050e+000	0.00000e+000	1.86591e-001
7.90476e-001	1.04118e+003	-4.82592e+000	1.23516e-001	2.14098e-001
7.95238e-001	1.05346e+003	-4.84528e+000	5.51140e-001	5.11797e-001
8.00000e-001	1.04978e+003	-4.89188e+000	8.60736e-001	8.17996e-001
8.04762e-001	1.06545e+003	-4.94830e+000	1.04211e+000	5.37230e-001
8.09524e-001	1.06855e+003	-5.01660e+000	0.00000e+000	9.42668e-002
8.14286e-001	1.07206e+003	-4.91345e+000	0.00000e+000	8.97492e-002
8.19048e-001	1.08358e+003	-4.96057e+000	1.02856e+000	6.39977e-001
8.23810e-001	1.08202e+003	-5.03655e+000	1.35953e+000	1.08187e+000
8.28571e-001	1.09966e+003	-5.12328e+000	8.57524e-001	8.25344e-001
8.33333e-001	1.09721e+003	-5.13918e+000	2.58982e-001	5.71994e-001
8.38095e-001	1.10429e+003	-5.15428e+000	5.99477e-001	4.41385e-001
8.42857e-001	1.11311e+003	-5.21092e+000	4.65697e-001	3.17240e-001
8.47619e-001	1.11573e+003	-5.21001e+000	0.00000e+000	0.00000e+000
8.52381e-001	1.13027e+003	-5.19734e+000	0.00000e+000	0.00000e+000
8.57143e-001	1.12730e+003	-5.13736e+000	0.00000e+000	1.36053e-001
8.61905e-001	1.13715e+003	-5.19121e+000	1.06642e+000	6.65498e-001
8.66667e-001	1.14525e+003	-5.26499e+000	9.81332e-001	9.75030e-001
8.71429e-001	1.14820e+003	-5.30865e+000	8.77335e-001	5.90497e-001
8.76190e-001	1.15846e+003	-5.36999e+000	0.00000e+000	1.31703e-001
8.80952e-001	1.15828e+003	-5.29822e+000	0.00000e+000	0.00000e+000
8.85714e-001	1.17192e+003	-5.32271e+000	3.64744e-001	0.00000e+000
8.90476e-001	1.17547e+003	-5.34187e+000	0.00000e+000	0.00000e+000
8.95238e-001	1.17982e+003	-5.30114e+000	0.00000e+000	0.00000e+000
9.00000e-001	1.18828e+003	-5.29310e+000	3.95892e-002	1.52254e-001
9.04762e-001	1.19000e+003	-5.30588e+000	8.24722e-001	7.39787e-001
9.09524e-001	1.20558e+003	-5.39180e+000	1.35505e+000	8.04387e-001
9.14286e-001	1.20374e+003	-5.46805e+000	2.33388e-001	4.06622e-001
9.19048e-001	1.21351e+003	-5.41973e+000	0.00000e+000	0.00000e+000
9.23810e-001	1.21734e+003	-5.42394e+000	0.00000e+000	0.00000e+000
9.28571e-001	1.22556e+003	-5.39898e+000	9.02647e-003	1.42722e-001
9.33333e-001	1.23457e+003	-5.42502e+000	5.92553e-001	4.02987e-001
9.38095e-001	1.23342e+003	-5.46990e+000	6.07381e-001	4.33202e-001
9.42857e-001	1.24718e+003	-5.49771e+000	9.96719e-002	1.34502e-001
9.47619e-001	1.24882e+003	-5.48182e+000	0.00000e+000	0.00000e+000
9.52381e-001	1.25759e+003	-5.46138e+000	1.71676e-001	5.45933e-002
9.57143e-001	1.26432e+003	-5.50237e+000	2.95650e-001	2.53097e-001
9.61905e-001	1.26329e+003	-5.49677e+000	2.91966e-001	2.26000e-001
9.66667e-001	1.28111e+003	-5.53731e+000	9.03834e-002	6.53465e-003
9.71429e-001	1.27979e+003	-5.50758e+000	0.00000e+000	0.00000e+000
9.76190e-001	1.28983e+003	-5.49390e+000	0.00000e+000	0.00000e+000
9.80952e-001	1.29392e+003	-5.45194e+000	6.35079e-002	6.32961e-002
9.85714e-001	1.29607e+003	-5.50150e+000	5.91348e-001	3.41086e-001
9.90476e-001	1.31387e+003	-5.52271e+000	3.68402e-001	4.82278e-001
9.95238e-001	1.30739e+003	-5.54559e+000	4.87085e-001	*
1.00000e+000	1.29574e+003	-5.58100e+000	5.91793e-001	*



Radial average power spectrum for 1999 lightning strike strengths.