Energy, Mines and Resources Canada
Énergie, Mines et Ressources Canada

CANMET
Canada Centre for Mineral and Energy Technology
Centre canadien de la technologie des minéraux et de l'énergie

ROCKBURSTS IN ONTARIO MINES DURING 1984

COUPS DE TOIT DANS LES MINES DE L'ONTARIO EN 1984

MINERALS RESEARCH PROGRAM

PROGRAMME DE RECHERCHE SUR LES MINÉRAUX

MINING RESEARCH LABORATORIES

LABORATOIRES DE RECHERCHE MINIÈRE

SP85-5

Canada

ROCKBURSTS IN ONTARIO MINES DURING 1984

COUPS DE TOIT DANS LES MINES DE L'ONTARIO EN 1984

D.G.F. HEDLEY AND R.J. WETMILLER

ELLIOT LAKE LABORATORY

July 1985

D.G.F. HEDLEY ET R.J. WETMILLER

LABORATOIRE D'ELLIOT LAKE

Juillet 1985

MINERALS RESEARCH PROGRAM

MINING RESEARCH LABORATORIES

SP85-5

PROGRAMME DE RECHERCHE SUR LES MINÉRAUX

LABORATOIRES DE RECHERCHE MINIÈRE

SP85-5

Available in Canada through

Authorized Bookstore Agents
and other bookstores

or by mail from

Canadian Government Publishing Centre
Supply and Services Canada
Ottawa, Canada K1A 0S9

Catalogue No. M38-15/85-5
ISBN 0-660-53279-4

Canada: $3.60
Other countries: $4.30

Price subject to change without notice.

En vente au Canada par l'entremise de nos

agents libraires agréés
et autres librairies

ou par la poste auprès du:

Centre d'édition du gouvernement du Canada
Approvisionnements et Services Canada
Ottawa (Canada) K1A 0S9

N° de catalogue M38-15/85-5
ISBN 0-660-53279-4

au Canada: 3,60 $
à l'étranger: 4,30 $

Prix sujet à changement sans préavis.

ROCKBURSTS IN ONTARIO MINES DURING 1984

D.G.F. Hedley* and R.J. Wetmiller**

ABSTRACT

During 1984, more than 100 rockbursts occurred in seven mines in Ontario; a significant increase over previous years. An unusual feature was the multiple rockburst sequence that occurred in four mines over periods ranging from a few hours to months.

These rockbursts were recorded on the regional seismograph networks, and, in most cases, on the microseismic systems installed in the mines. It was possible to match magnitude values from the regional network to accurate source location from the mine networks, which greatly assisted in evaluating mechanisms, causes, and spread of rockburst activity.

Most rockburst activity occurred in pillars in thin tabular orebodies, either gently dipping as at Elliot Lake, or steeply dipping as at Red Lake and Kirkland Lake. Some rockbursts in the Sudbury mines have been attributed to a fault-slip mechanism.

*Research Scientist, Elliot Lake Laboratory, CANMET, Energy, Mines and Resources Canada, Elliot Lake, Ontario.
**Seismology and Geomagnetism Division, Earth Physics Branch, Energy, Mines and Resources Canada, Ottawa, Ontario.

COUPS DE TOIT DANS LES MINES DE L'ONTARIO EN 1984

D.G.F. Hedley* et R.J. Wetmiller**

RÉSUMÉ

En 1984, plus de 100 coups de toit se sont produits dans sept mines de l'Ontario; importante augmentation par rapport aux années précédentes. La série de plusieurs coups de toit dans quatre mines dans l'espace de quelques heures à quelques mois a été un événement inhabituel.

Ces coups de toit ont été enregistrés par le réseau de télémétrie de l'est du Canada et, dans la plupart des cas, par les systèmes microsismiques installés dans les mines. Il a été possible d'établir une correspondance entre les magnitudes enregistrées par le réseau régional et leurs sources exactes telles que localisées par les réseaux miniers. Ce rapprochement a beaucoup aidé à évaluer les mécanismes, les causes et l'étendue des coups de toit.

La plupart des coups de toit se sont produits dans des piliers de corps minéralisés tabulaires minces, faiblement inclinés comme à Elliot Lake ou fortement inclinés comme à Red Lake et à Kirkland Lake. Certains coups de toit dans les mines de Sudbury ont été attribués à des décrochements de failles.

* Scientifique, Laboratoire d'Elliot Lake, CANMET, Énergie, Mines et Ressources Canada, Elliot Lake (Ontario).

** Division de la séismologie et du géomagnétisme, Direction de la physique du globe, Énergie, Mines et Ressources (Ontario).

ACKNOWLEDGEMENTS

Campbell Red Lake Mines Ltd., Denison Mines Ltd., Dickenson Mines Ltd., Falconbridge Ltd., INCO Ltd., Lac Minerals Ltd., and Rio Algom Ltd. are gratefully acknowledged for providing the rockburst and microseismic data. Mrs. M. Cajka of the Seismology Division of Energy, Mines and Resources Canada calculated most of the rockburst magnitude values. Seismic records were also received from the Sandia National Laboratories, New Mexico.

REMERCIEMENTS

Nous tenons à exprimer notre reconnaissance à la Campbell Red Lake Mines Ltd., à la Denison Mines Ltd., à la Dickenson Mines Ltd., à la Falconbridge Ltd., à l'INCO Ltd., à la Lac Minerals Ltd. et à la Rio Algom Ltd., pour nous avoir fourni les données microsismiques et les données sur les coups de toit. Madame M. Cajka de la Division sismologique de l'Énergie, des Mines et des Ressources du Canada a calculé la plupart des magnitudes des coups de toit. Nous avons en outre reçu des enregistrements sismiques de la Sandia National Laboratories (Nouveau-Mexique).

CONTENTS

ABSTRACT i
RÉSUMÉ ii
ACKNOWLEDGEMENTS iii
REMERCIEMENTS iii
INTRODUCTION 1
INTRODUCTION 5
SEISMOLOGY 7
ROCKBURST STATISTICS 15
ROCKBURSTS AT ELLIOT LAKE MINES 17
ROCKBURSTS AT RED LAKE MINES 21
ROCKBURSTS AT SUDBURY MINES 25
ROCKBURSTS AT KIRKLAND LAKE MINES 31
DISCUSSION 33
REFERENCES 35

TABLES

1. Recorded rockbursts in Ontario mines in 1984 - Elliot Lake area (Coups de toit enregistrés dans les mines de l'Ontario en 1984 - secteur d'Elliot Lake) 12

2. Recorded rockbursts in Ontario mines in 1983/84 - Red Lake area (Coups de toit enregistrés dans les mines de l'Ontario en 1983-1984 - secteur de Red Lake) 13

3. Recorded rockbursts in Ontario mines in 1984 - Sudbury basin (Coups de toit enregistrés dans les mines de l'Ontario en 1984 - bassin de Sudbury) 14

4. Recorded rockbursts in Ontario mines in 1984 - Kirkland Lake area (Coups de toit enregistrés dans les mines de l'Ontario en 1984 - secteur de Kirkland Lake) 14

FIGURES

1. Rockbursts in Ontario mines, 1935-1984 (Coups de toit dans les mines de l'Ontario, 1935-1984) 3

2. Seismograph stations in Ontario in 1984 (Stations sismographiques de l'Ontario en 1984) 10

3. KAO seismogram showing the Falconbridge rockbursts of June 20, 1984 (Séismogramme KAO montrant les coups de toit du 20 juin 1984 à la Falconbridge) 11

4. Frequency-magnitude relationships for rockbursts in 1984 (Relations fréquence-magnitude des coups de toit en 1984) 16

5. Partial plan of Quirke and Denison Mines showing rockburst locations (Plan partiel des mines de Quirke et de Denison montrant les emplacements des coups de toit) 19

6. Longitudinal section of F Zone; Campbell Mine showing rockburst locations (Coupe longitudinale de la zone F, de la mine Campbell, montrant les emplacements des coups de toit) 23

7. Longitudinal section of Falconbridge Mine showing rockburst locations (Coupe longitudinale de la mine de Falconbridge montrant les emplacements des coups de toit) 28

8. Plan of 4025 level, Falconbridge Mine showing faulting and rockburst locations (Plan du niveau 4025, de la mine de Falconbridge, montrant les emplacements des failles et des coups de toit) 29

9. Creighton Mine, transverse section through No. 6 shaft showing damaged areas (projected) (Mine de Creighton, coupe transversale passant par le puits n° 6 et montrant les zones endommagées) .. 30

10. Longitudinal section of Macassa Mine showing rockburst locations (Coupe longitudinale de la mine de Macassa, montrant les emplacements des coups de toit) 32

11. Relationship between areal extent and time span of major rockburst activity (Relation entre l'étendue et la durée des principaux coups de toit) 34

INTRODUCTION

Rockbursts first occurred in northern Ontario in the Sudbury and Kirkland Lake mines during the early 1930's. They have continued to vary in number and magnitude and at different mining districts (Fig. 1). There was a rapid increase in rockburst activity in the late 1930's, almost exclusively in Sudbury and Kirkland Lake. During the 1940's and 1950's, activity declined from previous levels, but rockbursts were reported occasionally in the Red Lake and Timmins districts. After the flurry of rockbursts during the early 1960's, activity declined, especially with the closure of many gold mines at Kirkland Lake.

In many respects, reporting of these rockburst incidents is arbitrary. Criteria for reporting includes more than five tons of rock displaced, injury to workers, or damage to equipment. In many cases, rockbursts occur in abandoned areas of a mine or in the hanging wall or footwall where there is no access and, thus, go unreported. As shown in Fig. 1, 28 rockbursts were reported in 1984; historically, a low number. However, 1984 is remembered by the mining industry in Ontario and by the general public as being a year of significant rockburst activity. As shown later in this report, about 90 rockbursts were recorded in northern Ontario during 1984 by the Eastern Canada Seismic Network.

The first comprehensive investigation into rockbursts in Ontario was done in 1940 when the Ontario Mining Association retained R.G.K. Morrison to study the problem. In many respects, his report in (Morrison, 1942) is still relevant to mining practice in northern Ontario mines. He explained the stress distributions, rock properties, and structural weakness planes that are prone to rockbursts. Stope-and-pillar geometry, mining methods, sequence of extraction, and support systems were evaluated as a means of controlling rockbursts.

In this review, the main classification criterion of rockburst activity in Ontario mines is magnitude, which was also recommended by Morrison 43 years ago. The magnitude values are obtained from the regional seismic stations, as explained in the next section. In addition, rockbursts are classified by location and type. Location means hanging wall, orebody, or footwall and is determined from mine microseismic systems, or visual inspection, or both. Rockburst type attempts to define the mechanism involved and the major source of the liberated energy. Pillar bursts result in a change of potential energy as the hanging wall and footwall suddenly converge. Strain bursts result from the energy stored in the surrounding rock mass, and are usually associated with development openings. Fault-slippage bursts are divided into two subgroups; where movement takes place along an existing fault and where shear movement takes place through intact rock. Rock type, depth below surface for each rockburst, and mining method are also recorded.

During 1984, four microseismic monitoring systems were in operation in Ontario mines. All of these systems use geophone sensors. A 16-channel system installed at Creighton mine in 1980 was subsequently expanded to 48, then to 64 channels; an 8-channel system was installed at Falconbridge Mine in 1981; a 32-channel system installed in 1982 is shared between Quirke and the adjacent Denison Mine; and a 48-channel system was installed in 1983 at the Campbell Mine. These systems are the only reliable means of accurately locating rockbursts in the mines. During early 1985, another four microseismic systems were installed.

Rockbursts that started in the Campbell Red Lake Mine on December 30th, 1983 (included in 1984 records for sake of completeness), lasted for 28 hours, and resulted in one day's lost production. Falconbridge Mine subsequently experienced rockbursts on June 20, 1984. Activity was mainly confined to the first 12 hours and, unfortunately, four miners were killed. The mine was closed as a result of these rockbursts. On July 6, 1984, rockbursts occurred at INCO's Creighton Mine; fortunately during the summer shutdown when no one was underground. Most of the activity occurred during the first 150 minutes. As a result of these rockbursts, a section of the mine was closed down.

Following a lapse of about 30 months, significant rockburst activity again occurred in an old worked-out area of Rio Algom's Quirke Mine on September 6, 1984. About 120 rockbursts have been recorded at Quirke Mine up to April 1985. In addition to these major occurrences, isolated rockbursts have occurred at Dickenson Mine in Red Lake, Denison Mine in Elliot Lake, Stobie Mine in Sudbury, and Macassa Mine in Kirkland Lake. Descriptions of these mines and the sequence of events at each location are included in the following sections.

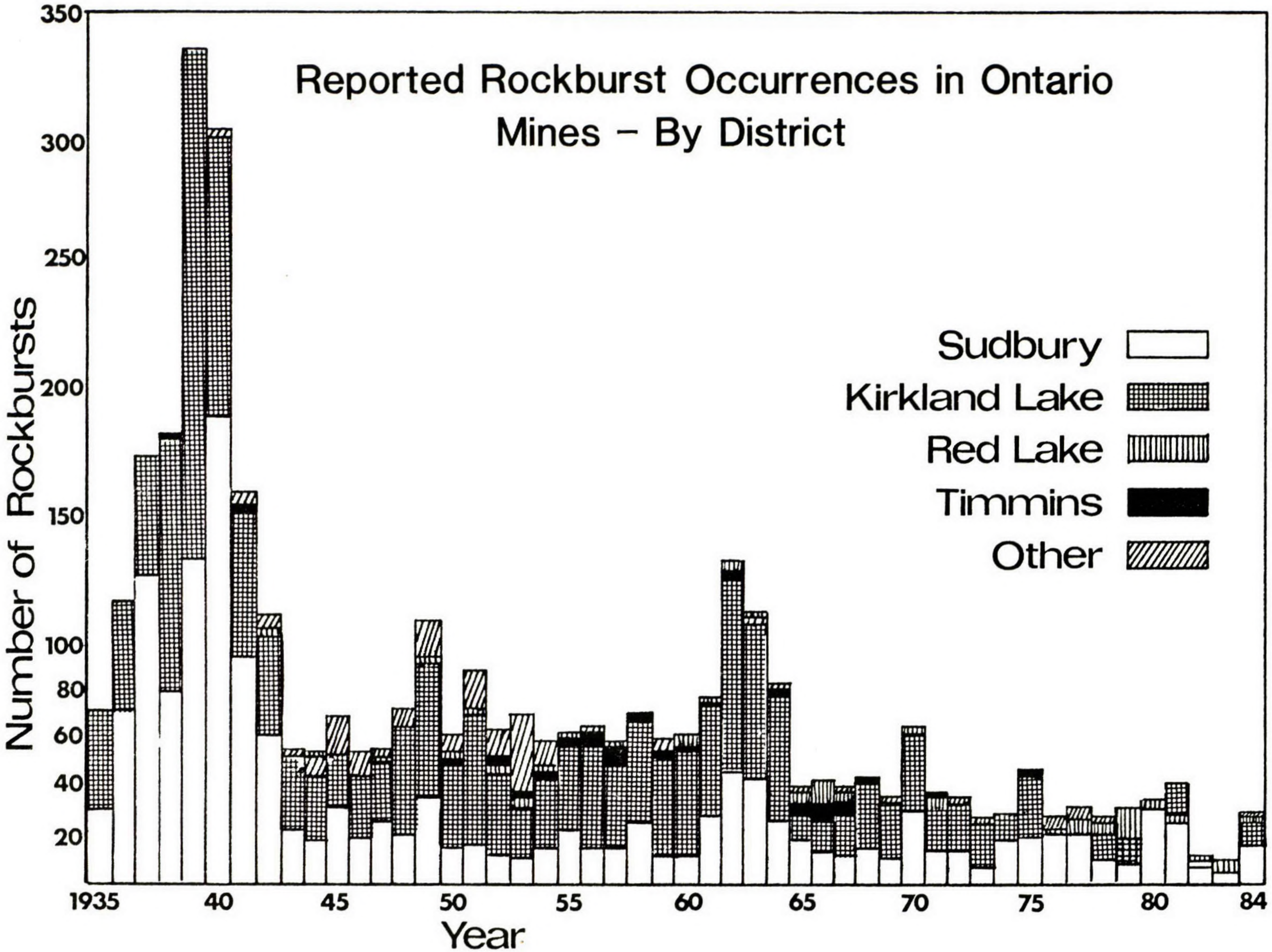

Fig. 1 -- Rockbursts in Ontario mines, 1935-1984

Coups de toit dans les mines de l'Ontario, 1935-1984

INTRODUCTION

Les premiers coups de toit se sont produits dans le nord de l'Ontario, dans les mines de Sudbury et de Kirkland Lake, au début des années 30. D'autres depuis, variant en nombre et en magnitude, se sont produits dans différents districts miniers comme le montre la figure 1. Le nombre des coups de toit a augmenté rapidement vers la fin des années 30; ils se sont produits presque exclusivement à Sudbury et à Kirkland Lake. Pendant les années 40 et 50, leur nombre a diminué, mais certains ont été signalés dans les districts de Red Lake et de Timmins. Nombreux au début des années 60, les coups de toit ont diminué, particulièrement après la fermeture d'un grand nombre de mines d'or à Kirkland Lake.

À bien des égards, rapporter des coups de toit est arbitraire. Les critères utilisés dans les rapports comprennent: déplacement de plus de 5 tonnes de roche, blessures corporelles ou dommages matériels. Dans un grand nombre de cas, des coups de toit se produisent dans des secteurs abandonnés d'une mine ou dans le toit ou un mur inaccessible et ne sont pas alors rapportés. Comme l'indique la figure 1, 28 coups de toit ont été rapportés en 1984; historiquement, c'est un nombre peu élevé. Cependant, l'industrie minière de l'Ontario et le public se rappellent de 1984 comme une année de forte activité. Comme on le mentionne plus loin dans le présent rapport, environ 90 coups de toit ont été enregistrés dans le nord de l'Ontario par le réseau de télémétrie de l'est du Canada.

La première étude sérieuse sur les coups de toit en Ontario a été effectuée en 1940, lorsque l'Ontario Mining Association a chargé R.G.K. Morrison d'étudier le problème. À bien des égards, son rapport de 1942 est encore pertinent en ce qui a trait aux méthodes actuelles d'exploitation des mines du nord de l'Ontario. M. Morrison traite des répartitions des tensions, des propriétés des roches et des plans de faiblesse structurale qui sont sujets aux coups de toit. La forme des chambres et piliers, les méthodes d'exploitation, la séquence d'extraction et les systèmes de support sont évalués comme moyens de contrôler les coups de toit.

Dans la présente étude sur les coups de toit dans les mines de l'Ontario, le principal critère de classification est la magnitude, le même critère recommandé par Morrison il y a 43 ans. On explique dans le chapitre suivant la façon dont on obtient les valeurs de magnitude des stations sismiques régionales. De plus, les coups de toit sont classés par emplacement et par type. L'emplacement peut être le toit, le corps minéralisé ou le mur, et il est déterminé par le système microsismique de la mine ou par une inspection visuelle. Par le type de coup de toit, on tente de définir le mécanisme en jeu et la source principale de l'énergie libérée. L'effondrement des piliers se traduit par une variation d'énergie potentielle lorsque le toit et le mur convergent soudainement. Les coups de pression ont pour origine l'énergie emmagasinée dans la masse rocheuse avoisinante et se produisent généralement autour des ouvertures de mise en valeur. Les coups dus au décrochement sont divisés en deux sous-groupes: coups associés à un mouvement le long d'une faille existante et coups associés à un mouvement de cisaillement dans une roche intacte. On note aussi le type de roche, la profondeur de chaque coup de toit et la méthode d'exploitation.

En 1984, quatre systèmes de contrôle microsismiques étaient opérationnels dans des mines de l'Ontario. Tous ces systèmes utilisent des géophones. Un système à 16 canaux dans la mine Creighton en 1980, a été porté plus tard à 48, puis à 64 canaux; un système à 8 canaux a été installé dans la mine Falconbridge en 1981; un système à 32 canaux, installé en 1982, dessert la mine de Quirke et la mine voisine Denison; et un système à 48 canaux a été installé en 1983 dans la mine Campbell. Ces systèmes sont les seuls moyens sûrs de localiser d'une façon précise les coups de toit dans les mines. Au début de 1985, 4 autres systèmes microsismiques ont été installés.

Les coups de toit qui ont commencé dans la mine Campbell à Red Lake le 30 décembre 1983 (consignés dans les enregistrements de 1984), ont duré 28 heures et ont entraîné la perte d'une journée de production. Ensuite, la mine Falconbridge a subi des coups de toit le 20 juin 1984. L'activité a été intense pendant les 12 premières heures, et malheureusement quatre mineurs ont trouvé la mort. La mine a été fermée à la suite de ces coups de toit. Le 6 juillet 1984, des coups de toit se sont produits dans la mine Creighton de l'INCO; heureusement, la mine était fermée pour l'été et personne ne s'y trouvait. L'activité a été intense pendant les 150 premières minutes. À la suite de ces coups de toit, une section de la mine a été fermée. Environ 30 mois plus tard, un grand nombre de coups de toit se sont produits de nouveau dans un secteur désaffecté de la mine Quirke de Rio Algom le 6 septembre 1984. On a enregistré environ 120 coups de toit dans cette mine jusqu'en avril 1985. En plus de ces principaux événements, des coups de toit isolés se sont produits dans la mine Dickenson à Red Lake, dans la mine Denison à Elliot Lake, dans la mine Stobie à Sudbury et dans la mine Macassa à Kirkland Lake. Ces mines et la séquence des événements qui s'y sont produits sont décrites dans les chapitres qui suivent.

SEISMOLOGY

Large mining-related rockbursts are detected to great distances by conventional seismograph stations. Data from such stations can be used to determine location, magnitude, and source properties (including focal mechanism) of the events in the same fashion as has been developed for the study of earthquakes. Such studies are considered important by seismologists because first-hand confirmation of the results can often be made by inspection in mines, thus providing an opportunity for calibration and improvement of seismological techniques. Rockbursts have been studied at the Earth Physics Branch (formerly the Dominion Observatory) in Ottawa since at least 1938. Much pioneering work on rockbursts was carried out by E.A. Hodgson of the Dominion Observatory at the Lake Shore Mine in Kirkland Lake, Ontario, in the 1940's (Hodgson, 1935) in conjunction with the high level of rockburst activity (see Fig. 1.) As well, a set of the larger Kirkland Lake rockbursts was used by Hodgson (1935) as a convenient source of information for an extensive refraction profile in Ontario and Quebec that determined one of the first crustal velocity models of the Canadian Shield.

More recently, a number of rockburst studies have appeared in the seismological literature, Smith et al. (1974) for Utah; McGarr et al. (1981) for South Africa; Gibbowicz and Chichowicz (1977) for Poland; Westbrook et al. (1980) for the United Kingdom; and Hinzen (1982) for Germany. These studies have generally pointed out the similarity of rockburst mechanisms to those of earthquakes, suggesting that, at least to a first-order approximation, some form of shear dislocation is fundamental to both types of events. The studies do not generally distinguish between different classes of rockbursts, such as pillar bursts, strain bursts, and fault bursts, that may be evident from inspection in the mines themselves, but they do indicate that some regional differences do exist between rockbursts at different mines. Finally, no conclusive way of discriminating between rockbursts and earthquakes on purely seismological grounds has yet been demonstrated.

It is important to note that many of the studies mentioned have been rather limited in extent and are site-specific. Spottiswoode and McGarr (1975), for instance, used only one seismograph station located on the surface above the mine in their study. Hence, the conclusions are representative of only the largest seismic events in the mine. Many kinds of small discrete microseismic events occur in mines, which do not record on surface stations, and could have mechanisms significantly different from the larger events. It is unfortunate that the microseismic monitoring equipment now installed in many mines to record the microseismic activity still does not preserve enough information about the seismic waveforms to be useful for detailed seismological studies. A set of comprehensive waveforms could provide much valuable information about the origin and cause of the seismic events.

The Earth Physics Branch (EPB) of Energy, Mines and Resources operates special networks of seismograph stations across Canada for the purpose of locating earthquakes. The Ontario stations OTT, LHC, EFF, SXO, GTO, KAO, and SUD

(Fig. 2) produce conventional, continuous, 60 mm/min, short-period, vertical seismograms that must be collected in Ottawa for analysis. LHC and OTT also have horizontal and long-period components. The stations WEO, CKO, OTT, WBO, EEO, and SUD are connected directly to the EPB via telephone links and produce a triggered, 60-sample/sec, short-period, vertical, digital data file as well as an optional conventional seismogram like the others. The operation of the stations SXO, GTO, KAO, and EEO is supported by Atomic Energy of Canada Ltd. through the Nuclear Fuel Waste Management Program specifically to improve the detection capability of small earthquakes in northern Ontario. The pass band for Canadian short-period seismograph stations is usually set from 1 to 16 Hz, with individual stations modified to meet particular site conditions. Calibration details for EPB stations are given by Shannon et al. (1984).

LND, ELF, and DLA form a local telemetry network operated by the Department of Geophysics, University of Western Ontario. Data from all stations are recorded on magnetic tape in London.

KGN, GNQ, LNX, and HBK form a local telemetry network operated by the Department of Geological Sciences at Queen's University in Kingston.

RSON is part of the Regional Seismic Telemetry Network operated by the U.S. Department of Energy. Data from RSON are sent via satellite link to the Sandia National Laboratory in New Mexico, whence a triggered, 40-sample/sec, three-component, digital, short-period data file can be obtained on request.

The location accuracy by regional seismograph networks is typically not much better than 5% of the distance to the third closest station. For the network in Ontario, this means that errors of about 5-10 km should be considered typical. Thus, although the existing seismograph network can identify the source region for events over 2.5 M, it often cannot identify the specific mine responsible for rockbursts in any one particular region. Focal depth cannot be reliably estimated unless the distance to at least one station is less than the depth of the event.

Figure 3 shows the KAO seismogram for a 24-hour period on June 19/20, 1984, the day of the dramatic rockburst activity at the Falconbridge Mine in Sudbury (see Table 3). This station is about 343 km north of the mine, but the three largest events in the sequence are clearly visible on the record. At this distance, the ground motion arrives in four phases, representing different propagation paths for the energy, where the last arriving phase, *Lg* in seismological notation, is the dominant one. The peak amplitude of the *Lg* is used for the calculations of specific magnitude, but the slight difference in magnitude between the three events (3.4, 3.5, and 3.3) can be seen in the relative strengths of all the phases. Four other smaller events in the mine were detected on closer seismograph stations, but are not visible on the KAO record. In all, about 250 microseismic events were picked up by the monitoring system in the Falconbridge Mine during this sequence.

EPB documents any earthquakes recorded on its stations and maintains an up-to-date data file of the epicentres and magnitudes of all located events. In the past, EPB has not routinely documented all the rockburst activity, but many of the larger rockbursts in Ontario mines were analyzed to confirm the mining source, and were included in the data base. An example of this is the large rockburst at the Wright-Hargreaves mine in Kirkland Lake on August 15, 1964 (Smith and Milne, 1969). Since the beginning of 1984, in co-operation with CANMET and mining industry officials, a special effort has been made to identify and assign magnitudes to all large rockbursts in Ontario mines recorded on the Ontario seismograph stations. The results are given in Tables 1-4, which present a comprehensive and relatively unbiased summary of the significant seismic activity in Ontario mines during 1984.

The magnitudes calculated by EPB for earthquakes and rockbursts in Ontario are based on the regional magnitude scales developed by Nuttli (1973). These scales are applicable to central and eastern North America, and are comparable to the original magnitude scale developed by Richter (1958) for California. Specifically, EPB magnitudes (M) are now calculated by the formula:

$$M = -0.1 + 1.66 \log(D) + \log(A/T)$$

where: D = epicentral distance in km,
A = maximum vertical zero-peak ground amplitude in micrometres,
T = period of the ground motion at the peak value in seconds.

Only readings for distances 50 km or greater are used. Magnitude values calculated by this or other similar formulae typically show a scatter of 0.3 to 0.5 units resulting from the radiation pattern of earthquakes so that they are not precise measures of the event's size, particularly when comparing events in different areas. Generally speaking, earthquakes with $M < 2$ are not felt on the surface, those with M 3-4 are felt on surface, whereas only those with $M > 5$ are likely to cause property damage to surface structures. For rockbursts, however, experience has shown that significant damage to underground mine workings can occur for events with magnitudes as small as 2 or less depending on the proximity of the event to the workings and the nature and state of the workings at the time of the event.

Prior to 1979, magnitudes for Ontario rockbursts (and earthquakes) were calculated by a different formula that could result in an overestimate of the magnitude by as much as one magnitude unit if data from beyond 500 km were used. Thus, some of the published values for the older events are too high by present standards, and should be used with caution. Revised estimates can be obtained from the EPB.

The seismograph stations operated by EPB (see Fig. 2) can independently detect and locate rockburst activity with magnitudes of about 2.5 or greater in all main Ontario mining areas. Specifically, in the mining areas where rockburst activity has been most prominent in 1984, the estimated detection levels for which the seismograph network can provide reliable information are:

Mining Area	Magnitude
Red Lake	2.6
Kirkland Lake	2.4
Elliot Lake	2.2
Sudbury	2.2

where the variation is related to proximity to one or more of the EPB stations shown in Fig. 2. In practice, smaller events that can be identified as rockbursts by their correlation with a *felt* report at one of the mines, are often recorded on one or two stations, but the statistics compiled for these events below the nominal detection thresholds are not necessarily complete or accurate.

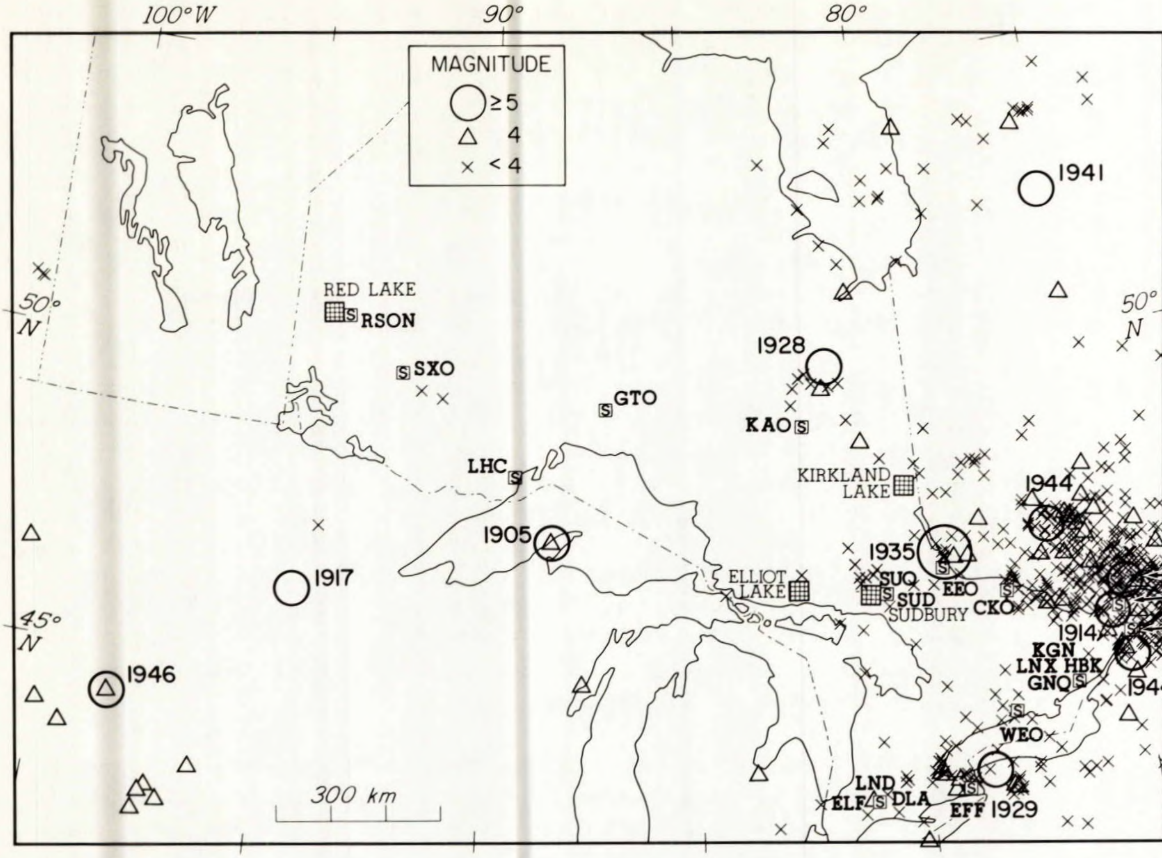

Fig. 2 *-- Seismograph stations in Ontario in 1984*

Stations sismographiques de l'Ontario en 1984

Note: *Stations SXO, LHC, GTO, KAO, SUD, SUO, EEO, CKO, EFF, WEO, OTT, and WBO are operated by the Earth Physics Branch; DEMR, LND, DLA, and ELF are operated by the University of Western Ontario; KGN, LNX, GNQ, and HBK are operated by Queen's University; and RSON is operated by the Sandia National Laboratory of the U.S. Department of Energy. The four mining areas with rockburst activity in 1984 discussed in the text are indicated. The background shows the seismic activity known in Ontario and surrounding areas to 1980 taken from Basham and Cajka (1984). Active seismic zones that affect Ontario are found in eastern Ontario (West Quebec Seismic Zone), and in the Niagara Peninsula-Western Lake Ontario region (Attica Seismic Zone). The remaining parts of Ontario are subject to lower levels of earthquake activity with no distinct clustering, but northern Ontario east of 850°W has historically been more active than the region to the west. The strongest earthquake experienced in Ontario was the M 6 1/4 event in the Temiskaming region in 1935. The 1944 M 5 3/4 event at Cornwall caused the most property damage, amounting to $2 000 000.*

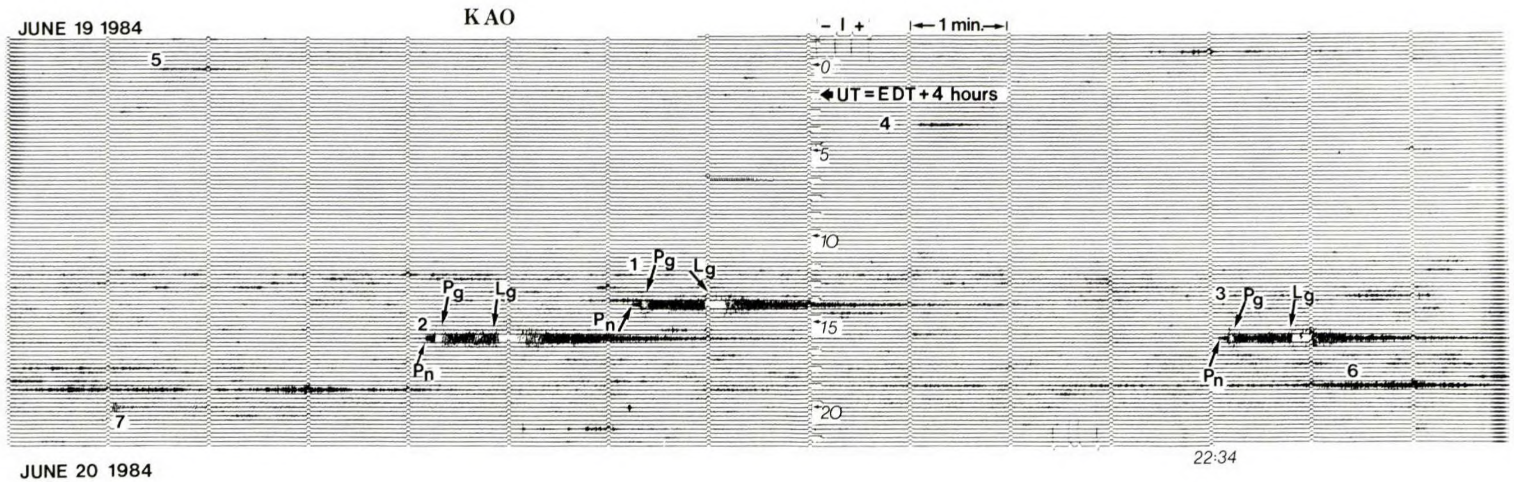

Fig. *3 -- KAO seismogram showing the Falconbridge rockbursts of June 20, 1984*

Séismogramme KAO montrant les coups de toit du 20 juin 1984 à la Falconbridge

Note: The station is located 343 km north of the mine. Events 1-3 are the three largest rockbursts in the sequence of hundreds of events that occurred in that mine. The magnitudes of the events are (1) 3.4; (2) 3.5; and (3) 3.2. The phases of the seismic record are indicated on each event; Pn is energy refracted along the base of the crust; Pg is energy coming directly through the crust, and Lg is a local earthquake surface wave propagated in the continental crust. The fourth local earthquake phase, Sn, is not present on these records. Event (4) is a blast at one of the mines in the Timmins area; (5) is a M 2.9 earthquake in Quebec; (6) is a record of a train passing close to the seismograph station; and (7) is the teleseismic P phase of a M 5.5 earthquake in Argentina.

Table 1 -- Recorded rockbursts in Ontario mines in 1984 -- Elliot Lake area

Tableau 1 -- Coups de toit enregistrés dans les mines de l'Ontario en 1984 -- secteur d'Elliot Lake

No.	Date	Time*	Magnitude+	Mine	Type	Place	Rock	Depth, m	Mining Method
1	May 9	15:57	2.6	Quirke	Pillar	Orebody	Qtz. Conglomerate	420	Stope-and-Pillar
2	May 28	01:08	2.3	"	"	"	" "	410	" " "
3	Sept. 1	01:50	2.5	"	"	"	" "	465	" " "
4	Sept. 6	20:46	2.4	"	"	"	" "	440	" " "
5	"	20:54	2.2	"	"	"	" "	425	" " "
6	"	20:55	2.4	"	"	"	" "	425	" " "
7	"	20:55	2.2	"	"	"	" "	420	" " "
8	Sept. 7	02:59	3.0	"	"	"	" "	395	" " "
9	Sept. 9	04:13	2.9	"	"	"	" "	490	" " "
10	"	05:23	2.3	"	"	"	" "	420	" " "
11	"	09:27	2.7	"	"	"	" "	425	" " "
12	"	09:54	2.3	"	"	"	" "	420	" " "
13	Sept. 12	02:30	3.0	"	"	"	" "	395	" " "
14	"	04:04	2.5	"	"	"	" "	395	" " "
15	Sept. 13	02:03	2.4	"	"	"	" "	420	" " "
16	Sept. 14	05:30	2.5	"	"	"	" "	475	" " "
17	Sept. 15	01:05	2.2	"	"	"	" "	475	" " "
18	Sept. 16	11:10	2.9	"	"	"	" "	490	" " "
19	Sept. 17	09:17	2.3	Denison	"	"	" "	460	Room - and -Pillar
20	"	23:05	2.8	Quirke	"	"	" "	?	Stope-and-Pillar
21	Sept. 18	04:19	2.6	"	"	"	" "	430	" " "
22	"	09:30	2.3	"	"	"	" "	440	" " "
23	"	09:59	2.6	"	"	"	" "	440	" " "
24	Sept. 22	06:25	2.0	"	"	"	" "	555	" " "
25	Sept. 23	19:33	2.5	"	"	"	" "	520	" " "
26	Sept. 24	03:58	2.5	"	"	"	" "	470	" " "
27	Nov. 9	22:33	2.0	"	"	"	" "	490	" " "
28	Nov. 14	07:14	2.2	"	"	"	" "	380	" " "
29	Nov. 15	07:26	1.9	"	"	"	" "	380	" " "
30	Nov. 18	18:51	1.6	"	"	"	" "	455	" " "
31	Nov. 20	23:16	1.6	"	"	"	" "	425	" " "
32	Dec. 15	07:55	2.2	"	"	"	" "	425	" " "
33	"	20:25	2.3	"	"	"	" "	410	" " "
34	Dec. 17	04:36	3.4	"	"	"	" "	410	" " "
35	"	04:40	2.5	"	"	"	" "	410	" " "
36	"	04:42	2.1	"	"	"	" "	410	" " "
37	"	08:27	2.0	"	"	"	" "	425	" " "
38	"	23:23	1.6	"	"	"	" "	535	" " "
39	Dec. 18	11:34	2.4	"	"	"	" "	535	" " "
40	Dec. 19	02:55	1.7	"	"	"	" "	550	" " "
41	"	03:26	1.7	"	"	"	" "	380	" " "
42	"	08:57	1.6	"	"	"	" "	380	" " "
43	"	13:49	1.6	"	"	"	" "	565	" " "
44	"	15:30	2.1	"	"	"	" "	425	" " "
45	"	18:53	2.0	"	"	"	" "	455	" " "
46	Dec. 21	00:18	1.6	"	"	"	" "	535	" " "
47	"	22:33	2.5	"	"	"	" "	395	" " "
48	Dec. 22	17:48	2.1	"	Fault Slip?	Hanging Wall?	Quartzite	490	" " "
49	Dec. 24	15:57	1.9	"	Pillar	Orebody	Qtz. Conglomerate	455	" " "
50	"	18:42	2.0	"	"	"	" "	455	" " "
51	Dec. 26	07:29	2.3	"	"	"	" "	425	" " "
52	"	14:23	3.0	"	"	"	" "	520	" " "
53	"	16:25	1.9	"	"	"	" "	455	" " "
54	Dec. 27	02:36	2.2	"	"	"	" "	535	" " "
55	"	16:54	2.8	"	"	"	" "	440	" " "
56	Dec. 28	06:29	1.9	"	"	"	" "	440	" " "
57	"	22:18	2.5	"	"	"	" "	535	" " "
58	Dec. 29	00:13	1.9	"	"	"	" "	520	" " "
59	"	15:49	2.0	"	"	"	" "	410	" " "

* Eastern Standard and Daylight time; + Magnitude M_N (Nuttli, 1973).

Table 2 -- Recorded rockbursts in Ontario mines in 1983/84 -- Red Lake area

Tableau 2 -- Coups de toit enregistrés dans les mines de l'Ontario en 1983-1984 -- secteur de Red Lake

No.	Date	Time*	Magnitude+	Mine	Type	Place	Rock Type	Depth, m	Mining Method
1	Dec.30/83	00:51	2.1	Campbell	Pillar	Orebody	Andesite	425	Shrinkage
2	"	00:59	2.7°	"	"	"	"	470	"
3	"	01:36	2.4	"	"	"	"	470	"
4	"	04:20	2.2	"	"	"	"	425	"
5	"	04:22	1.9	"	"	"	"	425	"
6	"	07:44	2.6°	"	"	"	"	380	"
7	"	08:09	1.8	"	"	"	"	380	"
8	"	08:18	2.2	"	"	"	"	380	"
9	"	11:31	1.6	"	"	"	"	?	"
10	"	11:33	2.9°	"	"	"	"	?	"
11	"	13:21	2.2	"	"	"	"	425	"
12	"	13:46	1.6	"	"	"	"	380	"
13	"	22:40	2.5	"	"	"	"	335	"
14	"	22:41	2.1	"	"	"	"	335	"
15	Dec. 31	01:17	2.0	"	"	"	"	290	"
16	"	02:30	3.3°	"	"	"	"	335	"
17	"	02:33	2.8	"	"	"	"	425	"
18	"	05:11	2.2	"	"	"	"	520	"
19	Jan. 9/84	12:53	2.3	"	"	"	"	425	"
20	Feb. 7	12:08	2.6	"	"	"	"	425	"
21	Feb. 22	13:06	1.7	"	"	"	"	380	"
22	May 10	14:30	1.6	Dickenson	"	"	"	700	Cut-and-Fill
23	July 8	20:48	2.1	"	"	"	"	740	"
24	July 26	09:13	2.0	"	"	"	"	480	Shrinkage
25	July 31	03:30	1.6	"	"	"	"	480	"
26	Nov. 14	15:11	1.5	Campbell	"	"	"	810	Cut-and-Fill

* Central Standard and Daylight Times; ° Magnitudes from Seismology Div., EMR - rest estimated from Sandia records.

Table 3 -- Recorded rockbursts in Ontario mines in 1984 -- Sudbury basin

Tableau 3 -- Coups de toit enregistrés dans les mines de l'Ontario en 1984 -- bassin de Sudbury

No.	Date	Time*	Magnitude+	Mine	Type	Place	Rock Type	Depth, m	Mining Method
1	April 5	05:07	2.7	Creighton	Strain	Orebody	Dis/Sulphides	1830	Cut-and-Fill
2	June 20	10:12	3.4	Falconbridge	Fault-Slip	Footwall	Norite	1220	
3	"	12:12	3.5	"	"	"	"	1240	
4	"	12:20	3.2	"	"	"	"	1280	Cut-and-Fill
5	"	12:38	2.0	"	"	"	"	1265	and
6	"	13:00	1.5	"	"	"	"	1305	Undercut-and-Fill
7	June 23	00:47	2.5	"	"	"	"	1115	
8	July 5	18:45	2.2	"	"	"	"	1065	
9	July 6	13:25	4.0	Creighton	Shear	Hanging Wall	"	1035	
10	"	13:52	2.1	"	Strain	Footwall	Granite		Cut-and-Fill
11	"	13:56	2.4	"	"	"	"	975	and
12	"	14:19	2.2	"	"	"	"	to	Undercut-and-Fill
13	"	14:52	2.5	"	"	"	"	1220	
14	July 7	19:18	2.2	"	"	"	"		
15	Aug. 10	09:30	2.4	"	"	Orebody	Dis/Sulphides	1980	Undercut-and-Fill
16	Oct. 26	08:25	2.4	Stobie	Pillar	"	"	680	Vertical Retreat

Table 4 -- Recorded rockbursts in Ontario mines in 1984 -- Kirkland Lake area

Tableau 4 -- Coups de toit enregistrés dans les mines de l'Ontario en 1984 -- secteur de Kirkland Lake

No.	Date	Time*	Magnitude+	Mine	Type	Place	Rock Type	Depth, m	Mining Method
1	Mar. 13	14:24	3.1	Macassa	Pillar	Orebody		1875	Cut-and-Fill
2	Apr. 26	12:32	2.4	"	Strain	"	Tuff	1835	Development
3	Sept. 17	00:05	2.6	"	Pillar	"	Porphyry	1950	Cut-and-Fill
4	Oct. 2	14:54	2.5	"	"	"	Basic	1615	Cut-and-Fill
5	Oct. 3	17:16	2.2	"	Strain	Footwall	Syenite	1410	Undercut-and-Fill

* Eastern Standard and Daylight Times. + Magnitude M_N (Nuttli, 1973).

ROCKBURST STATISTICS

The rockbursts that have been recorded during 1984 at Elliot Lake, Red Lake, Sudbury, and Kirkland Lake are listed in Tables 1, 2, 3, and 4, respectively. Most of these rockbursts were recorded by Energy, Mines and Resources, Canada, except for the smaller events in the Red Lake area for which the records from RSON were used. In these tables, information is given on time, name of mine, type (i.e., pillar, strain, fault), place (i.e., hanging wall, orebody, footwall), rock type, depth, and mining method.

In all, 106 rockbursts were recorded ranging in magnitude from 1.5 to 4.0 M_N, and 55% of them occurred in Quirke Mine at Elliot Lake. A pillar burst within the orebody, as occurred in Campbell, Dickenson, Quirke, Denison, and Macassa mines, is the most common rockburst mechanism, and accounts for over 80% of the events. In the Sudbury mines, the rockbursts at Falconbridge Mine were caused by a fault-slip mechanism along existing faults in the footwall. The first event at Creighton Mine, of magnitude 4.0 M_N is thought to be either slippage along a dyke contact or shearing through intact rock in the hanging wall followed by a series of strain bursts around development openings in the footwall.

Depth below surface of rockbursts ranges from 290 to 1950 m with a preponderance between 300 to 500 m reflecting the activity at Quirke and Campbell mines. Mining methods in use at, or near, locations where rockbursts are occurring are mainly incremental methods such as cut-and-fill in the Sudbury and Kirkland Lake mines, shrinkage at Red Lake mines, and stope-and-pillar at Elliot Lake mines, rather than the bulk mining methods such as blasthole and vertical-retreat methods that have been introduced recently.

A comparison of rockburst incidents and mining methods between various mining camps is not valid. More meaningful would be a comparison within a mining camp or individual mine on the occurrence or non-occurrence of rockbursts. Even here, other parameters may be more important including the areal extent of mining and the proportion and location of remaining pillars.

The frequency of rockbursts of varying magnitude and by mining camp are shown in Fig. 4(a) and as a log-log relationship in Fig. 4(b). It has been observed that both natural earthquakes and mining-induced rockbursts usually follow a consistent relationship between magnitude and frequency of occurrence (McGarr, 1982) expressed by:

$$\log N = a - b\, M_N$$

where: N = number of events per unit time of magnitude greater than or equal to M_N

a and b = constants.

For rockbursts and earthquakes 'b' is normally around 1.0. The results shown in Fig. 4(b) follow this relationship between M_N = 2.2 - 3.5 with b = 1.03. Below M_N = 2.2 there is an ever-increasing deficit in the number of rockbursts recorded as compared to expected. This difference is probably because the seismograph stations are usually located more than 100 km away from the mining camps.

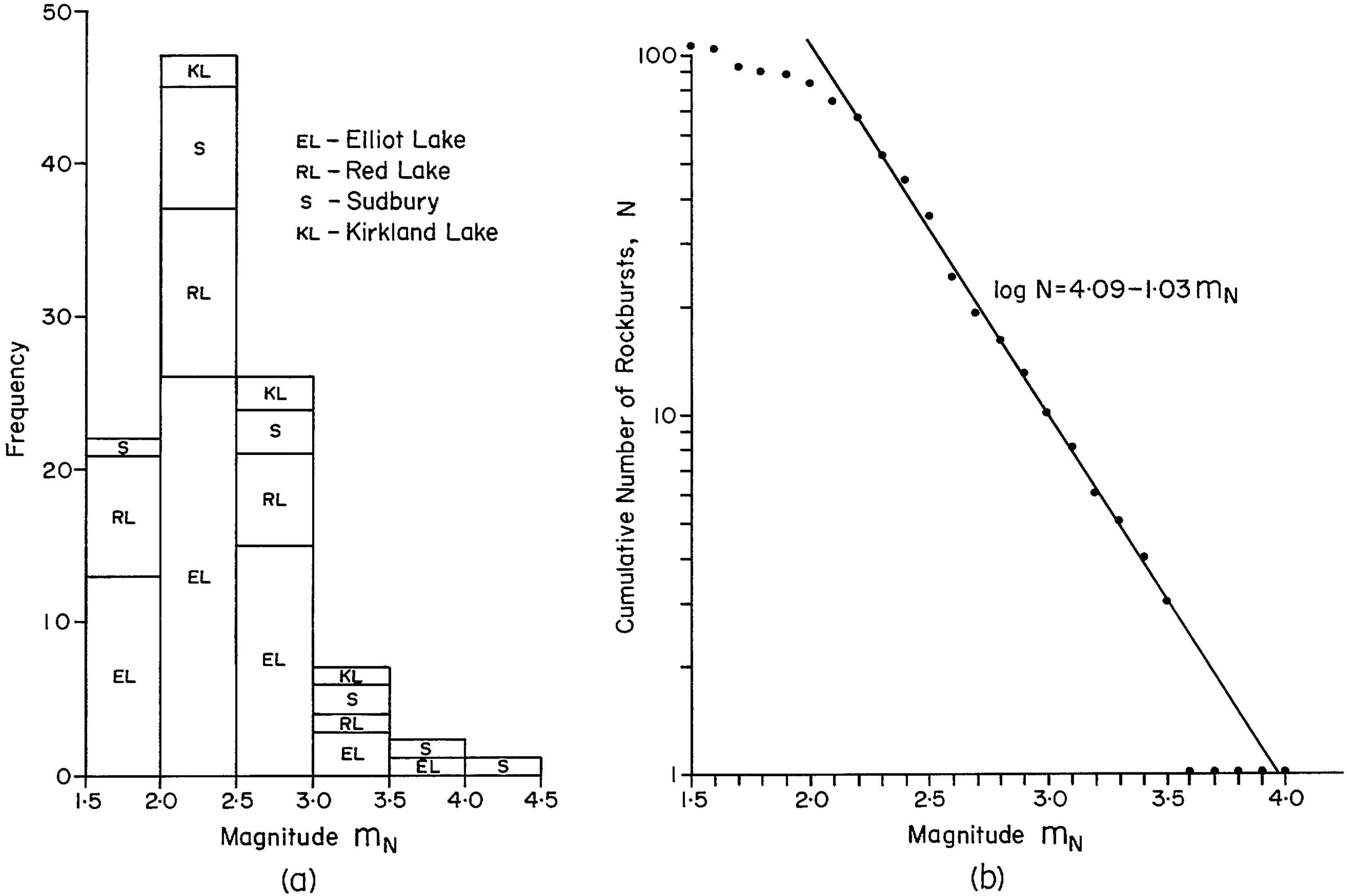

Fig. 4 *-- Frequency-magnitude relationships for rockbursts in 1984*

Relations fréquence-magnitude des coups de toit en 1984

ROCKBURSTS AT ELLIOT LAKE MINES

The uranium-bearing conglomerate reefs at Elliot Lake are deposited on the north and south limbs of a broad syncline. Producing mines are Denison Mine and Rio Algom's Quirke and Panel mines on the north limb, and Rio Algom's Stanleigh Mine on the south limb.

Figure 5 is a partial plan of Quirke Mine and the adjacent Denison Mine. The main reef, 3 - 7 m thick, dips to the south at about 20°. A second reef, 40 m above the main reef, overlays part of both mines. Quartzite beds both overlay and underlay the reefs. A stope(or room-) and-pillar layout is used at all mines at Elliot Lake using either jacklegs and slushers or trackless equipment. Extraction ranges from 60 to 85% depending mainly on depth below surface and ore thickness.

Rockbursts first occurred in an old mined-out area of Quirke Mine in March 1982. A case history of these events has been published (Hedley et al., 1984). Initiation was just up dip of a trial trackless area where the rib pillars were oriented on apparent dip rather than true dip (just left of centre in Fig. 5). The causes of rockbursting were identified as follows:

- The pillars were highly stressed because of the depth (about 440 m) below surface, and an extraction rate of 75 - 80%.

- Pillars were in different orientations, which resulted in some being weaker than others, or they were less effective in transmitting stress through them.

- A low-angled, mud-coated, thrust fault and a vertical, mud-coated fault pass through the trackless area, which could have affected the redistribution of stress.

Of these, high pillar stresses were a prerequisite. However, pillars in other areas of the mine were equally highly stressed, but did not initiate rockbursts. Consequently, the weakness of the rib pillars in the trackless area, or the mud-coated faults, or both, are seen as the triggering mechanism.

Over a five-day period in March 1982, eight major rockbursts up to a magnitude of 3.0 were recorded on the regional seismic network. Afterwards, seismic activity continued and spread outwards. In August 1982, a 16-channel microseismic network was installed around the affected area which was enlarged to 32 channels in 1983, with 9 channels being installed on the Denison side of the boundary pillar. At the end of 1983, the area of observed pillar deterioration extended 1200 m on strike by 550 m on dip. Within this area, there was a zone of complete pillar failure (see Fig. 5).

At the beginning of 1984, seismic activity averaged three events per day on the microseismic network. This activity increased progressively and, in May 1984, two isolated rockbursts were recorded on the regional network. By August

1984, seismic activity was averaging 11 events per day. As listed in Table 1, major rockbursts again started on September 6, 1984, and 24 were recorded during September by the regional seismic network, up to 3.0 M_N. The locations of these and subsequent rockbursts are shown in Fig. 5. The September rockbursts were located around the periphery of the zone of pillar failure, centred on the trial trackless area. Activity on the microseismic network averaged 104 events per day during September, and reached a maximum of 250 events per day. Also in September, an isolated rockburst occurred in the adjacent Denison Mine about 1300 m from the nearest rockburst in Quirke Mine.

In October 1984, microseismic activity subsided to 18 events per day and down to 16 events per day in November although in this latter month, five rockbursts of magnitudes 1.6 - 2.2 were recorded on the regional network. Major rockbursts again occurred in mid-December and especially on December 17, 1984. In all, 27 major rockbursts were recorded in this month with magnitudes up to 3.4, and microseismic activity averaged 64 events per day. This level of microseismic activity and major rockbursts continued into 1985.

As can be seen in Fig. 5, all of the major rockbursts in 1984 except one are located outside the estimated zone of pillar failure prior to 1984. It is considered that these rockbursts are located in the orebody and result from the violent failure of the pillars. The sudden change in potential energy as the hanging wall moves down is thought to be the major source of the liberated seismic energy. The rockburst on December 22, 1984, is located in the centre of the trial trackless area. From visual observations in July 1982, it is known that the pillars in this area are extensively crushed, and that their peak strength has been exceeded. Based on this observation, it is concluded that this rockburst probably occurred in the hanging wall. A mud-coated thrust fault is located 36 m above the orebody at this location, and slippage could have occurred along this fault. The geophones in the microseismic network are almost in a planar array which makes vertical resolution of rockbursts difficult.

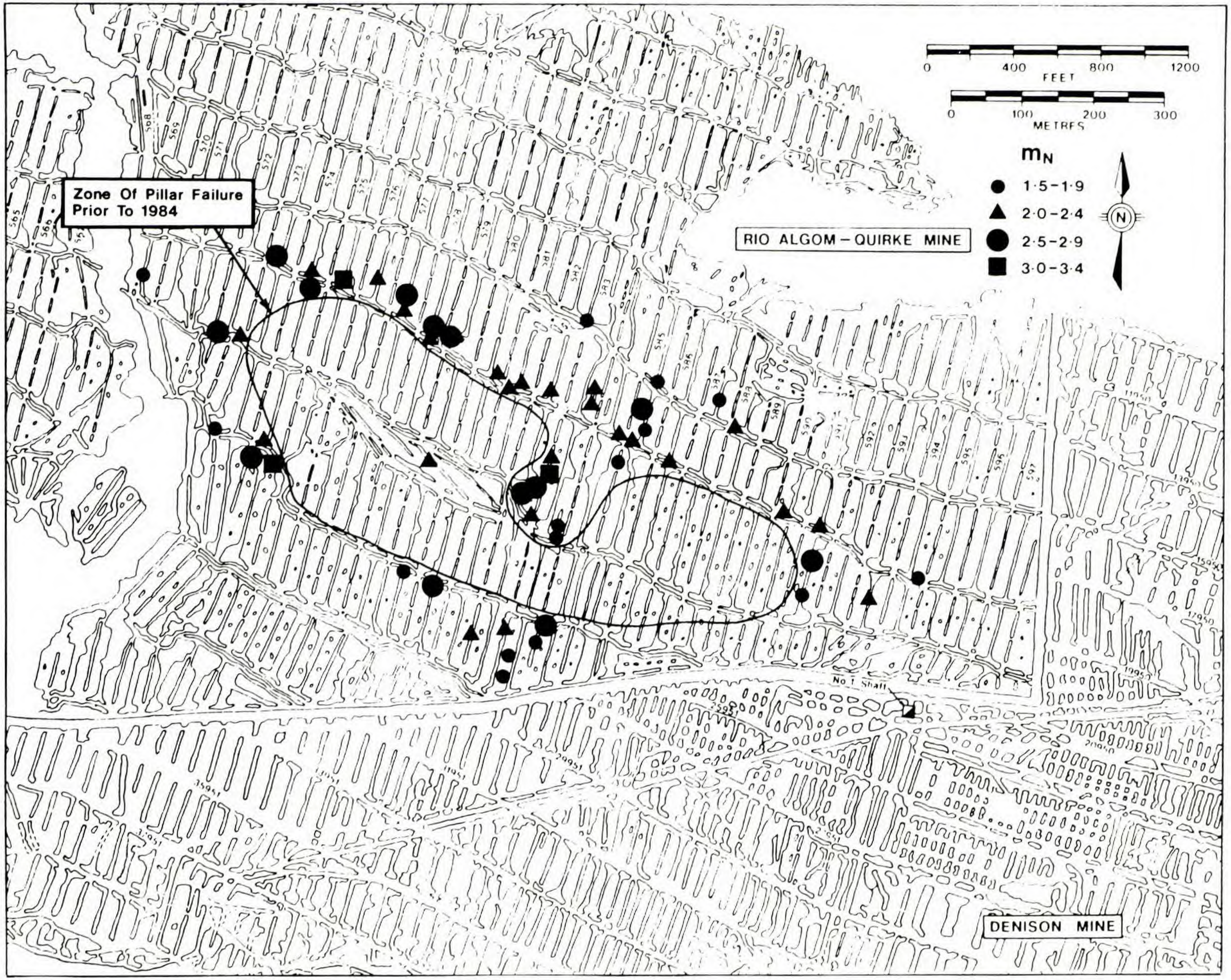

Fig. 5 *-- Partial plan of Quirke and Denison Mines showing rockburst locations*

Plan partiel des mines de Quirke et de Denison montrant les emplacements des coups de toit

ROCKBURSTS AT RED LAKE MINES

There are two adjoining operating mines in the Red Lake district; Campbell Red Lake and Dickenson. Gold-bearing ore zones are found in steeply dipping faulted Precambrian volcanic rocks. There are two main vein structures: replacement veins 0.6 - 9 m wide and quartz carbonate fracture-filled veins 0.2 - 1 m wide. Andesite is the host rock for all veins.

Initially, shrinkage-stoping techniques were used exclusively in both mines with small, boxhole pillars above a level and a 4.6-m wide sill pillar below the level. In the early 1960's, a change was made to cut-and-fill methods at depths below 600 m.

The first rockbursts in both mines occurred in 1960, and have continued sporadically since that time. At the Campbell Mine, most bursts occurred in boxhole and sill pillars as they were being removed by long-hole blasts. A significant series of rockbursts occurred in the F ore zone of Campbell Mine in late December 1983. These rockbursts are listed at the beginning of Table 2, and their location and sequence are shown on a longitudinal section in Fig. 6. A case history of these events has been published (Hedley et al., 1985).

The first minor burst in the F zone occurred in July 1981, on the west end of the 11th level. Mining was stopped in the 12th level stopes, but ore drawdown was accelerated in these stopes. This resulted in more boxhole pillar bursts directly above locations of greatest ore drawdown. All mining activity was stopped in the F zone in September 1982, after a destressing blast on the 14th level triggered a series of small boxhole pillar bursts on the 9th, 10th, and 11th levels.

In August 1983, a 32-channel geophone network was installed throughout the mine to monitor seismic activity. Afterwards, a renovation crew was moved into the 7th level, but left after eight days because of "working" ground. Subsequently, boxhole pillars burst on this level in October and November 1983. The renovation crew was moved to the 12th level, but left again on December 20 because of seismic activity and a visible change in the boxhole pillars. One more burst occurred on the 11th level on December 25 before the major sequence of bursts on December 30.

At 0051 on December 30, 1983, the first violent rockburst was felt on surface followed rapidly by other seismic events. The microseismic network at the mine recorded 860 events on that day and 360 events on the following day. Eighteen of these events, up to a magnitude of 3.3, were recorded on the Canadian seismic stations at ULM and SXO and at RSON. Rockbursts were initiated on the 10th level, and within minutes had spread to the 11th level, and within an hour to the 9th level (see Fig. 6). After eight hours, rockbursts had spread to the 8th level. During the rest of December 30, rockbursts were confined mainly to the 8th, 9th, and 10th levels, and after the flurry of rockbursts at 0230 on December 31, activity ceased on these levels. For the rest of December 31 and January 1, activity was mainly on the 7th, 12th, and 13th levels. The extent of the rockbursts (see Fig. 6) closely matches the visible evidence of damage underground (i.e., 7th to 12th levels completely closed off). The vast majority of major seismic events occurred where the sill pillars are 6 m wide (on dip); very few events occurred where the sills are 15 m wide. Another common feature is that the first rockburst on a level often was located where a raise comes through the sill pillar. After January 1, 1984, seismic activity decreased drastically, and there have been only sporadic events in the F zone since that time.

From visual observations, all the rockbursts occurred within the orebody and were the result of violent failure of some of the sill pillars (rather than boxhole pillars). The major driving force appears to be the change in potential energy as the hanging wall and footwall suddenly converge.

Other rockbursts in 1984 in the Red Lake district occurred in the Dickenson Mine during May and July. Although these events were recorded by Campbell's microseismic system, accurate locations could not be obtained from this system. From visual observations, it is thought that these rockbursts occurred in the sill pillars of cut-and-fill stopes, and often are associated with shear zones.

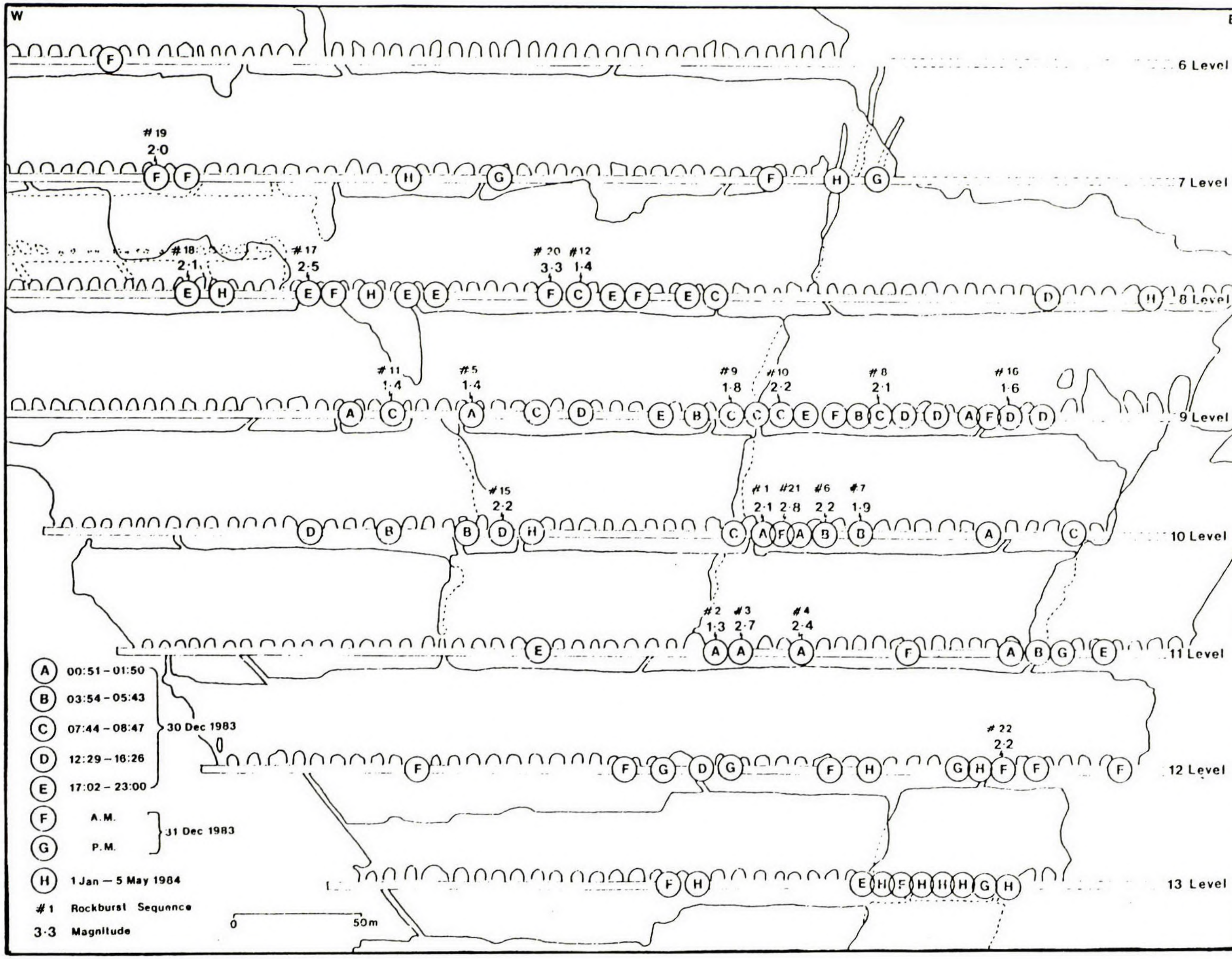

Fig. 6 -- *Longitudinal section of F Zone; Campbell Mine showing rockburst locations*

Coupe longitudinale de la zone F, de la mine Campbell, montrant les emplacements des coups de toit

ROCKBURSTS AT SUDBURY MINES

During 1984, Falconbridge Ltd. operated six mines (Strathcona, Fraser, North, Lockerby, Falconbridge, and East) and INCO Ltd. operated nine mines (Levack, McCreedy, Creighton, Copper Cliff South and North, Frood, Stobie, Little Stobie, and Garson) in the Sudbury basin.

The Falconbridge Mine is located on the southeast rim of the basin. The tabular orebody strikes eastwest and extends to a depth of 1800 m. It dips steeply north in the upper levels, then reverses and dips steeply south at depth. The orebody pinches and swells with an average width of 5 m. Footwall rock at depth is norite and the hanging wall is greenstone. Major fault structures intersect the orebody, which itself is on the main fault and the norite-greenstone contact. The No. 1 flat fault dips at about 45° to the northeast and extends across the whole mine and into the adjacent East Mine. Gouge on this fault varies from a few centimetres to half a metre in width. The No. 1 and 2 ore pass faults are steeply dipping, and intersect the orebody at an acute angle.

Levels are established at 53-m vertical intervals. The main mining method is longitudinal cut-and-fill using cemented tailings. Remnant and sill pillars are frequently recovered using undercut-and-fill techniques. By 1984, the major remaining ore reserves were in a pillar around the hoistroom on the 3850 level.

Since 1955, the Falconbridge Mine has had a history of sporadic rockbursts. In 1981, an eight-geophone, microseismic system was installed around the hoistroom pillar in preparation for its recovery. This system indicated that most seismic activity was occurring in the footwall norites near prominent faults. In September 1983, a large rockburst of magnitude 2.8 M_N occurred on the 3325 level, which caused damage to this level and to the one above.

At 1012 on June 20, 1984, the first of a series of major rockbursts occurred and, over a 24-h period, about 250 seismic events were picked up by the microseismic system. A case history of these rockbursts has been written (West, 1985). The seven rockbursts over a magnitude 1.5 M_N recorded on the regional seismic network are listed (see Table 3), and their locations are shown plotted on a longitudinal section in Fig. 7. Those rockbursts near the 4025 level are plotted on this level plan in Fig. 8 which also shows the location of the major faults.

The first rockburst of magnitude 3.4 M_N occurred, without apparent warning, on the No. 1 flat fault on the 4025 level. Unfortunately, this was about 20 m from where four miners were working in an undercut-and-fill stope. Shock waves from this rockburst caused the overlying mat to collapse entrapping the miners in backfill. Two hours later, the next major rockburst, 3.5 M_N, occurred on the No. 1 ore pass fault between the 4025 and 4200 levels followed eight minutes later by a 3.3 M_N event on the same fault and on the 4200 level. For the rest of June 20-21, seismic activity was mainly restricted between the 4025 and 4350 levels and over a distance of 200 m on strike; a relatively small area (see Fig. 7). Most of this activity appeared to be associated with the No. 1 flat fault, the No. 1 and 2 ore pass faults, and the Ropeway dyke. During June 23, seismic activity moved up dip and one rockburst, 2.5 M_N, occurred on the 3675 level again on the No. 1 ore pass fault. The last major rockburst, 2.2 M_N, occurred on July 5 on the 3500 level and on the No. 1 flat fault.

Visual inspection of the mine workings indicated damage between the 4025 to 4375 levels with about 1000 - 2000 tonnes of rock displaced. This is much less than that observed at Quirke Mine in Elliot Lake or Campbell Mine at Red Lake for pillar bursts of similar magnitude. Slight damage, such as extension of fresh cracks, was observed over a circular area of radius 150 m centred on the 3.5 M_N event.

The location of the rockbursts from the microseismic system plus the visual observations, point to a fault-slip failure mechanism. This was visually confirmed for the 2.2 M_N rockburst on July 5 where there was no observed damage, and from striation marks on the No. 1 flat fault on the 3500 and 3675 levels, the west block had moved laterally 1 - 2 cm towards the orebody.

After July 5, 1984, minor seismic activity continued sporadically. In the same month, it was decided to close down the mine as a direct result of the rockburst incidents.

INCO's Creighton Mine is located on the southern rim of the Sudbury Basin. Disseminated and massive sulphides are found in the lower sublayer of the hanging wall norites. Footwall rocks are mainly granite and gabbro. Quartz diorite and lamprophyre dykes are also encountered. The orebodies although interconnected, are irregular in shape and size, but generally dip at 65° to the northwest. They extend from surface to below 2200 m in depth. The main operating shafts are No. 5 down to the 4000 level (1220 m) and No. 9 down to the 7000 level (2135 m). Levels are usually developed at 60 m vertical intervals.

Over its 80 years of production, many mining methods have been used at Creighton Mine including open pit, shrinkage, blasthole, panel caving, square set, overhand and underhand cut-and-fill, and vertical-retreat blasthole methods. Both unconsolidated and cemented backfills have been used. Present mining methods are mainly vertical-retreat blasthole and cut-and-fill techniques with cemented tailings.

Creighton Mine has a history of rockbursts dating back to 1935. Experience has indicated that vertical shafts and raises encountered bursting below a depth of 800 m, whereas with lateral development, problems were experienced below a depth of 1200 m. In stoping operations, a common practice was to sequence primary mining in an inverted V formation. Rockbursts and severe damage were usually confined to the leading stopes.

A 16-channel microseismic system, subsequently expanded to 48 channels, was installed at Creighton in 1980. This system covered the area between the 5400 and 7000 levels (1645 - 2135 m depth) where most mining activity was taking place. Rockbursts nos. 1 and 15 (see Table 3) are typical of the rockbursts that occur at these deeper levels. In recent years, there have been an average of about three rockbursts per year.

At 1325 on July 6, 1984, a rockburst of magnitude 4.0 M_N occurred near the Creighton Mine which was felt throughout the Sudbury area and up to 50 km away. The mine, at that time, was one week into the summer shutdown with no one underground. Fourteen minutes later, a series of smaller rockbursts (1.5 - 2.5 M_N) occurred which lasted for about 90 minutes. The final rockburst in this sequence occurred on the following day. A case history of these rockbursts has been written (Oliver, 1985).

Visual inspection of the mine workings took place on July 7, and damage was found on the 3200, 3400, 3600, 3800, and 4000 levels (975 - 1220 m depth) with most damage on the middle three levels. A transverse section, through No. 6 shaft, is shown in Fig. 9 on which the areas of damage have been projected. An additional damaged area was found near No. 5 shaft on the 3400 level where a quartz diorite dyke intersects the development drift and some 250 m away from the other damaged areas. About 1000 tonnes of displaced rock was observed in the access drifts with little or no damage in either the cut-and-fill or undercut-and-fill stopes in this area. Quite a few damaged areas were adjacent to the quartz diorite and lamprophyre dykes. This level of damage is consistent with strain energy type of bursts of 1.5 - 2.5 M_N. No evidence could be found of the first 4.0 M_N event.

The microseismic system recorded the major rockbursts and other seismic activity. After the first rockburst, 76 recognizable seismic events were recorded on July 6. However, 36 of these could be attributed to normal seismic activity in other parts of the mine. By July 7, seismic activity had reduced to normal levels.

Although the microseismic system recorded the events, the nearest geophone was about 1000 m away from the damaged areas. Also, all the geophones lay within a narrow cone configuration relative to the damaged areas making accurate source location difficult. However, it was possible to obtain approximate locations by evaluating the sequence of geophone triggering. For the first rockburst, 4.0 M_N, the best location is a few hundred metres into the hanging wall and between the 3400 and 4000 levels. All subsequent rockbursts (1.5 - 2.5 M_N) were located in the footwall, presumably at the locations where damage was observed. The most likely mechanism of the first rockburst is sheer-slippage either along a dyke contact or on the western edge of a subsidence zone above the 4400 level stopes. This changed the stress regime in the area, which resulted in the subsequent strain energy bursts in the footwall.

Besides Creighton Mine, one isolated rockburst occurred on October/26, 1984 at INCO's Stobie Mine. From visual observations, it was located in a sill pillar above a vertical-retreat blasthole stope.

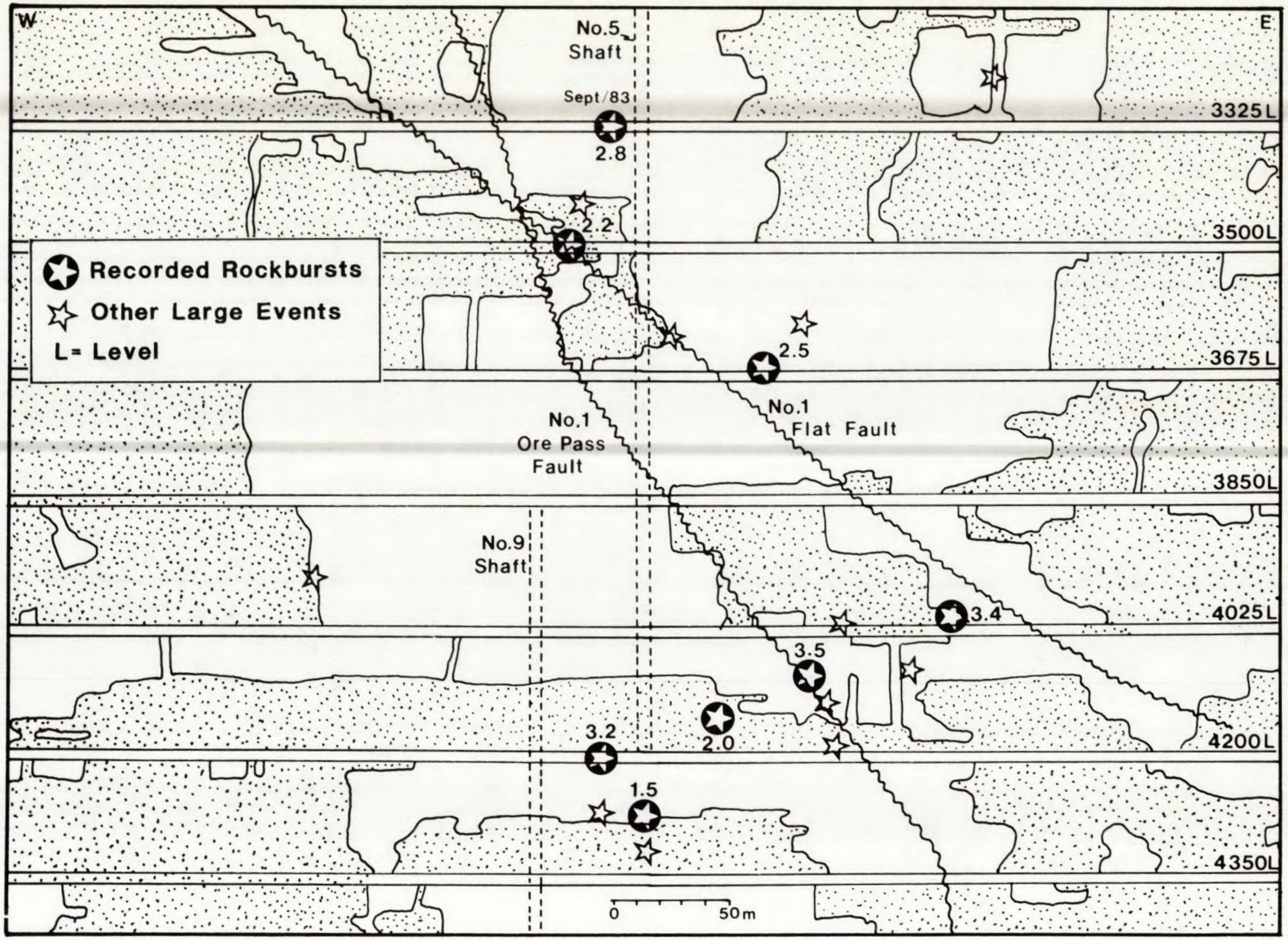

Fig. 7 -- Longitudinal section of Falconbridge Mine showing rockburst locations

Coupe longitudinale de la mine de Falconbridge montrant les emplacements des coups de toit

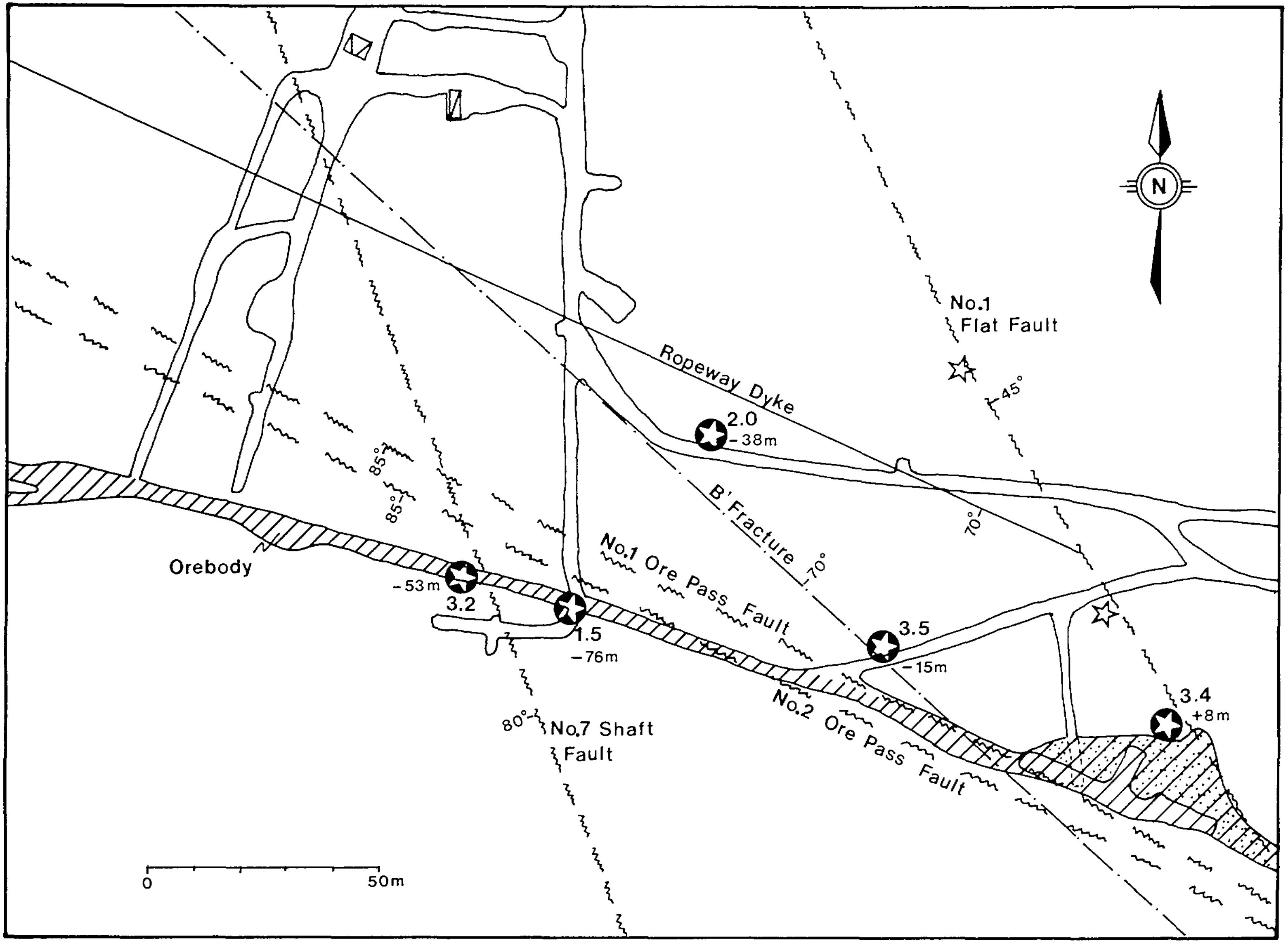

Fig. 8 *-- Plan of 4025 level, Falconbridge Mine, showing faulting and rockburst locations*

Plan du niveau 4025, de la mine de Falconbridge, montrant les emplacements des failles et des coups de toit

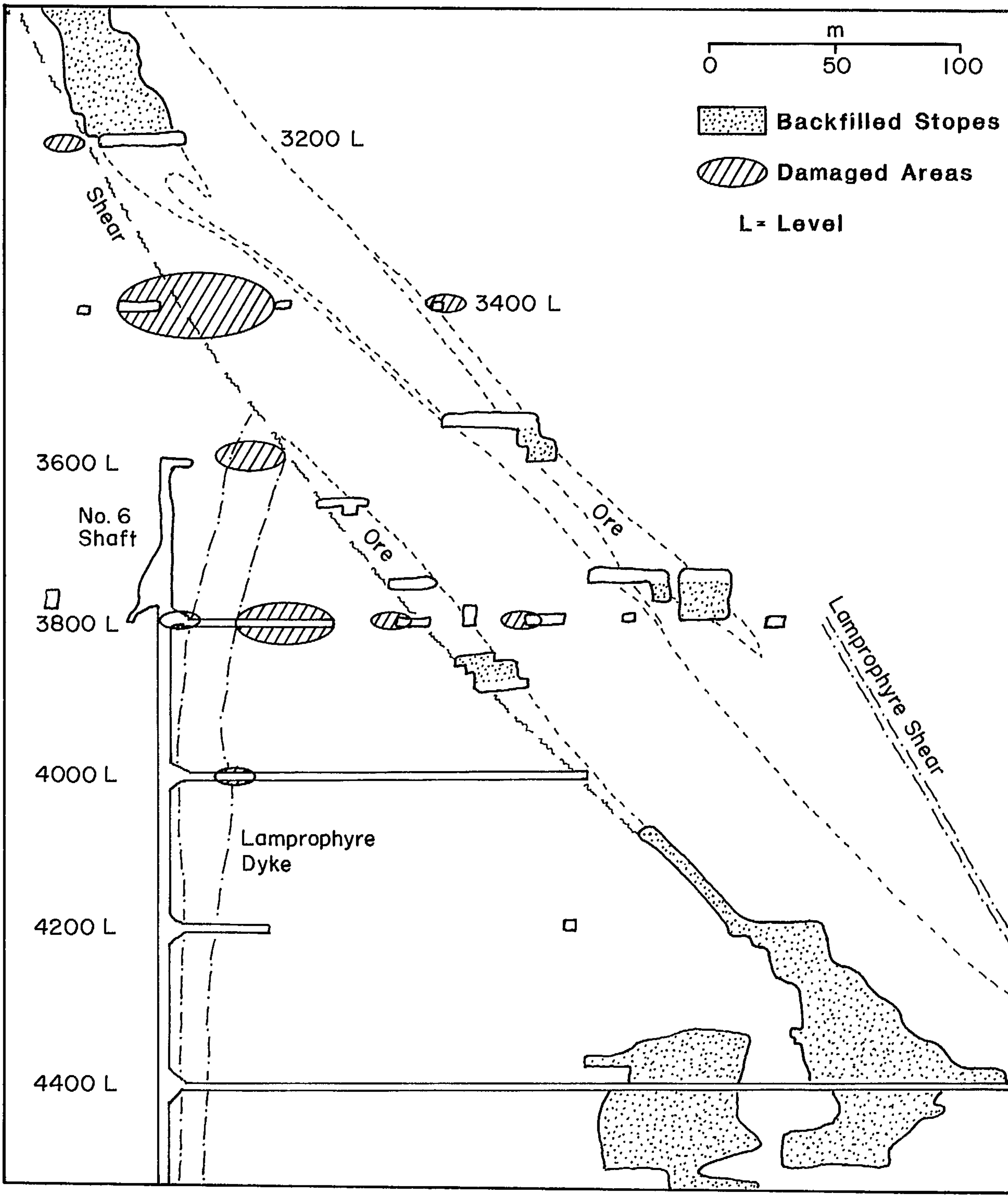

Fig. 9 -- Creighton Mine, transverse section through No. 6 shaft showing damaged areas (projected)

Mine de Creighton, coupe transversale passant par le puits n° 6 et montrant les zones endommagées

ROCKBURSTS AT KIRKLAND LAKE MINES

Originally, there were seven active mines in the Kirkland Lake camp, but, since 1965, only the Macassa Mine of Lac Minerals Ltd. has been operating. Gold-bearing quartz veins about 2 m wide are associated with several fault systems designated as the "Main Break" or Kirkland Lake Fault. The Macassa Mine is on the westerly extension of this fault system. The Main Break extends 6 km across the whole Kirkland Lake camp and dips steeply to the south. At depth, it splits into north and south branches. Major north-south, trending faults have displaced the Main Break over considerable distances. The host rocks are porphyry, tuff, and basic syenite. Although all these rocks are hard and brittle, rockbursts are most often associated with the tuff material.

The workings at Macassa Mine, at present, extend down to a depth of 1960 m. A new shaft is being sunk to a depth of 2217 m to exploit ore reserves at the west end of the property. Levels are developed at 46 m vertical intervals. Horizontal cut-and-fill methods are used to mine the first 24-m height of a stope using waste development rock as a backfill. The remaining 22-m sill pillar is recovered using the Avoca method again using waste development rock. In certain cases, undercut-and-fill methods are used to recover sill pillars using a poured concrete slab as the overlying mat.

Mines at Kirkland Lake have had a long history of rockbursts dating back to the early 1930's. The Lake Shore and Wright-Hargreaves mines were the most affected. The largest rockburst ever recorded in Canada, of estimated magnitude 4.5 - 5.0, occurred at the Wright-Hargreaves Mine on August 14, 1964, and resulted in the immediate closure of the mine and indirectly the closure of the adjacent Lake Shore Mine. Accounts of this rockburst suggest that the shaft pillar burst between 730 - 1220 m depth. Stoping areas at Macassa Mine have generally been more scattered than at Lake Shore and Wright-Hargreaves mines, and the rockburst problem has been less severe. Bursts that have occurred have generally been associated with sill pillars and more often than not occur shortly after blasting, a feature common to the Kirkland Lake mines.

Macassa Mine does not have a microseismic monitoring system, and rockbursts are reported by the work crews with visual inspection to determine source location. During 1984, five rockbursts were recorded on the national seismic network (see Table 4). Locations of the centres of most damage for four of these rockbursts are shown on a longitudinal section (Fig. 10). The three largest rockbursts of magnitudes 2.5, 2.6, and 3.1 M_N all appear to have occurred in the sill pillars and within the orebody. Most damage was observed in the levels and sub-levels and up to 130 m of the 6150 level was closed after the 3.1 M_N event. The 2.4 M_N event on the 6025 level appears to be a strain burst because it occurred in an isolated development drift. Similarly, the 2.2 M_N event on the 4600 level, in the central area of the mine, was also in an access drift with no noticeable damage to the adjacent stopes.

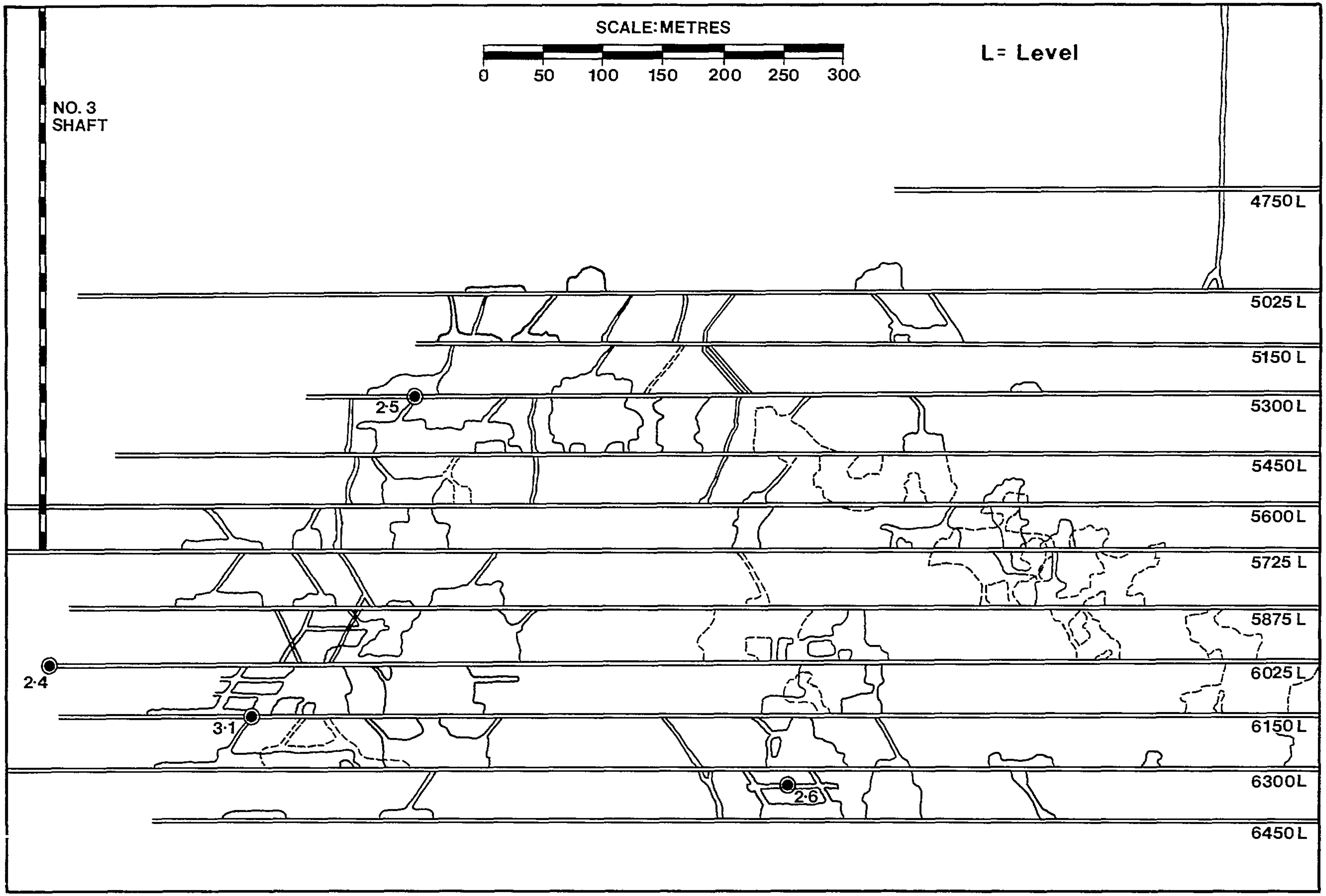

Fig. 10 -- Longitudinal section of Macassa Mine showing rockburst locations

Coupe longitudinale de la mine de Macassa, montrant les emplacements des coups de toit

DISCUSSION

Although rockbursts are known to have occurred in Ontario hardrock mines during the last 50 years, 1984 was a year of major activity. In most previous years, rockbursts occurred sporadically and were localized, whereas in 1984 at four mines, they occurred in rapid succession, and were regional in nature. As far as is known, the last major multiple rockburst sequence (other than the events at Quirke Mine in March 1982) was at the Wright-Hargreaves Mine at Kirkland Lake in August 1964.

Isolated rockbursts, such as those at depth in Dickenson, Stobie, Macassa, and Creighton mines at depth, more often than not all in active mining areas, and all triggered by recent mining activity. Multiple rockbursts at Quirke and Campbell mines began in areas that had been mined-out a number of years previously, and there was no active mining in the vicinity. At both Falconbridge and Creighton mines, hoistroom pillars were being extracted. Prior to the first major rockburst, no mining had taken place during the previous week at Creighton, and only minor mining activity was taking place at the edge of the hoistroom pillar at Falconbridge. It appears, at all these four mines, that regional instability and multiple rockbursts were caused by the cumulative mining effects over a number of years rather than by recent mining activity. That five series of multiple rockbursts should occur in one year at mines up to 1000 km apart seems to be coincidental.

The time span over which major rockbursts occur ranges from 90 min at Creighton Mine to 134 days (December 17, 1984, to April 30, 1985) at Quirke Mine. Although this time span can be affected by the type of rockbursts, mining methods, and support (i.e., backfill) there appears to be a reasonable correlation with the areal extent of rockburst activity (as shown in Fig. 11). Although the end of a major rockburst sequence is somewhat arbitrary because small seismic activity continues and a real rather than volume extent is used, a log-log relationship adequately fits the data from all four mines. This type of relationship requires further scrutiny of its implications on rates of energy released and rockburst propagation.

At both Quirke and Campbell mines a pillar bursting mechanism has been identified. In both cases, audible noises or increased activity, or both, on the microseismic systems preceded the major rockburst sequence. However, even in these cases, it was impossible to predict the exact time or place of rockburst initiation. At Falconbridge Mine and for the first rockburst at Creighton Mine, a fault or shear-slip mechanism has been identified. In both cases, the microseismic system gave no prior evidence of a build-up or warning of rockburst initiation.

Pillar bursts are preceded by a build-up in stress, and increased microseismic activity is anticipated. Fault-slip bursts could be caused by a decrease in the normal (or clamping) stress, in which case increased microseismic activity may be absent.

The installation of microseismic monitoring systems at the mines has greatly assisted in accurate source location and identification of rockburst mechanisms. The expansion to 12 operating systems in 1985-86 will mean better rockburst data in the future. Also waveform studies will greatly assist in determining mechanisms.

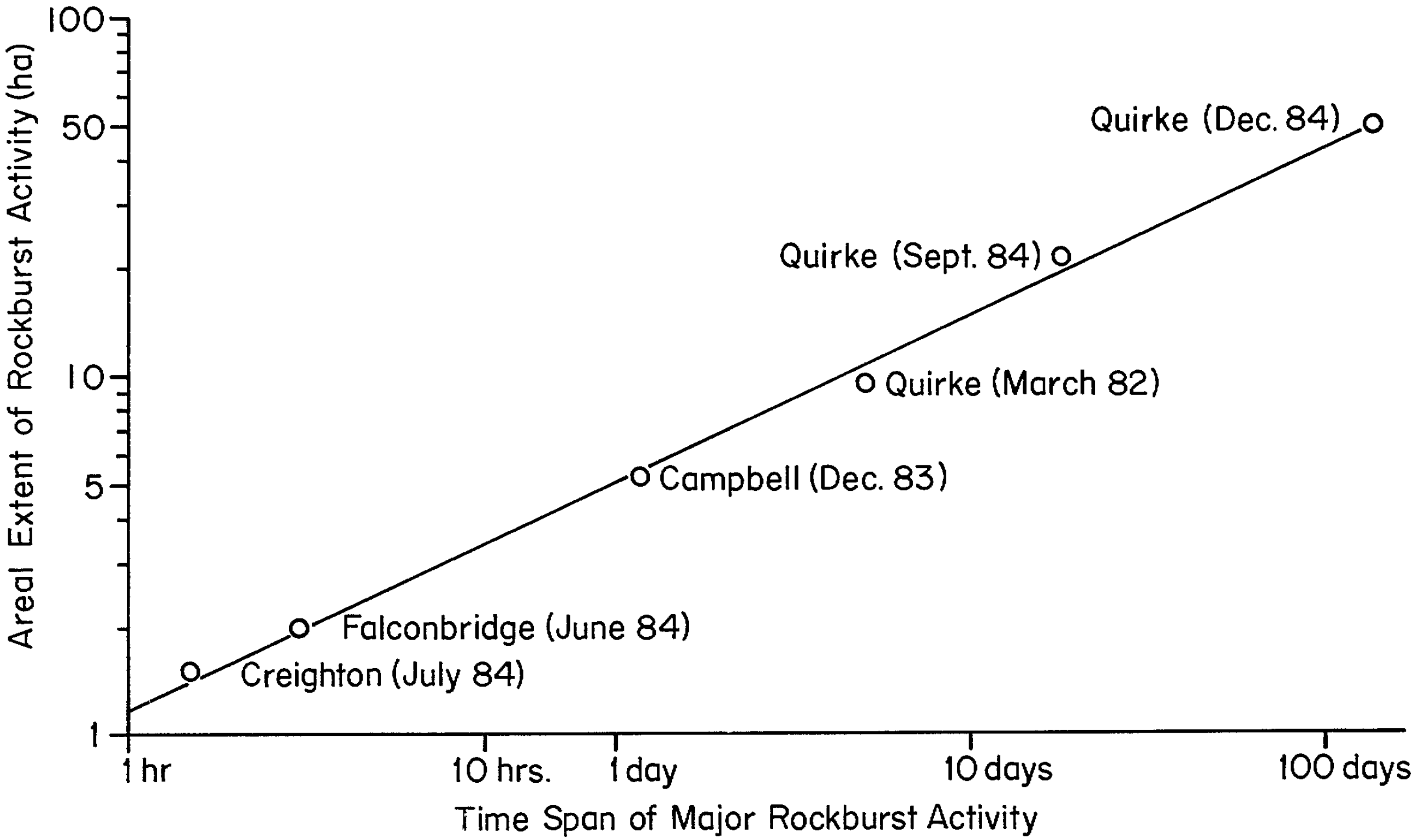

Fig. 11 *-- Relationship between areal extent and time span of major rockburst activity*

Relation entre l'étendue et la durée des principaux coups de toit

REFERENCES

Morrison, R.G.F. "Report on the rockburst situation in Ontario Mines," CIM Bull XLV:225-272; 1942.

Hodgson, E.A. "Dominion Observatory rockburst research 1938-1945," Publ Dom Obs 20(1):248 p.; 1958.

Hodgson, J.H. "A seismic survey in the Canadian Shield based on rockbursts at Kirkland Lake, Ontario," Publ Dom Obs 16(5):110-163; 1953.

Smith, R.B., Winkler, P.L., Anderson, J.G., and Scholz, C.H. "Source mechanisms of microearthquakes associated with underground mines in eastern Utah," Bull Seismol Soc Am 64(4):1295-1318; 1974.

Spottiswoode, S.M. and McGarr, A. "Source parameters of tremors in a deep-level gold mine," Bull Seismol Soc Am 65(1):93-112; 1975.

McGarr, A., Green, R.W.E., and Spottiswoode, S.M. "Strong motion of mine tremors: some implications for near-source ground motion parameters," Bull Seismol Soc Am 71:295-320; 1981.

Gibbowicz, S.J. and Chichowicz, A. "Seismic moment and source size of mining tremors in Upper Silesia, Poland," Acta Geophysica Polen XXV:201-218; 1977.

Westbrook, G.K., Kasznir, N.J., Browitt, C.W.A., and Holdsworth, B.K. "Seismicity induced by coal mining in Stoke-on-Trent (U.K.)," Engin Geol 16:225-241; 1980.

Hinzen, K.G. "Source parameters of mine tremors in the eastern part of the Ruhr-District (West Germany)," J Geophys 51:105-112; 1982.

Shannon, W.G., Schieman, D.R.J., Halliday, R.J., and Munro, P.S. "Canadian Seismograph Operations - 1983," Seismol Series Earth Phys 90:110 p.; 1984.

Smith, W.E.T. and Milne, W.G., "Canadian Earthquakes - 1964," Seismol Series Dom Obs 43:28 p.; 1969.

Nuttli, O.W. "Seismic wave attenuation and magnitude relations for eastern North America," J Geophys Res 78:876-885; 1973.

Richter, C.F. "Elementary seismology," W.H. Freeman and Co. (San Francisco); 1958.

Basham, P.W. and Cajka, M.C. "Contemporary seismicity of northwestern Ontario," Proc 17th Info Meeting on Nuclear Fuel Waste Management Program, Atomic Energy (Canada) Ltd. Tech. Record (in press); 1984.

McGarr, A. "Some applications of seismic source mechanisms to assessing underground hazard," Conf Seismicity in Mines, Johannesburg, South Africa; Sept. 1982.

Hedley, D.G.F., Roxburgh, R.W., and Muppalaneni, S.N. "A case history of rockbursts at Elliot Lake," 2nd Int Conf Stability in Underground Mines, Lexington, Kentucky; Aug. 1984.

Hedley, D.G.F., Neumann, M., Makuch, T., and Blake, W. "Rockbursts at Campbell Red Lake Mine," CIM Rockburst Seminar, Sudbury, Ontario; March 1985.

West, D. "A case history of rockbursts at Falconbridge Mine," CIM Rockburst Seminar, Sudbury, Ontario; March 1985.

Oliver, P.H. "Creighton Mine, July 6, 1984 rockburst," CIM Rockburst Seminar, Sudbury, Ontario; March 1985.