INVERSE CORRELATION BETWEEN INDUCED SEISMICITY AND *b*-VALUE, OBSERVED IN THE ZINGRUVAN MINE, SWEDEN

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ABSTRACT
A three-dimensional monitoring seismic network has been in operation in Zinkgruvan mine, south-central Sweden, since November 1996. We make use of 6037 rockbursts, $-2.4 \leq M \leq 2.6$, recorded during a 7-year period and determine *b*-value as a function of time. Calculated *b*-values show large time variations, roughly between 0.6 and 1.8. Almost all statistically significant (99%) drops in *b*-value can be associated with an occurrence of larger shocks ($M \geq 1.6$) in the mine, either as isolated events or as a sequence of several shocks.

KEYWORDS: *b*-value, mining-induced seismicity, rockbursts, forecasting

INTRODUCTION

Monitoring of mine-induced seismicity has improved immensely in a number of countries (e.g. Canada, Czech Republic, Finland, Poland, South Africa, Sweden) during the last two decades with expansion of local seismograph systems into areas of active mining. These systems produce huge, high-quality, data sets which provide the means for complex analyses of the properties of induced tremors in and around the mining volumes. There are no fundamental differences between natural (tectonic) earthquakes and mining-generated shocks (McGarr, 1982) and hence methods and techniques developed to study the behaviour of tectonic events can be employed to learn about the characteristics of micro-tremors generated by underground mining activities.

Zinkgruvan is an ore mine in south-central Sweden. Since the mine installed a seismographic monitoring system in late 1996, more than 6000 mining tremors (rockbursts) have been detected, located and quantified. In a previous paper by Nuannin et al. (2002), hereafter to be referred to as Paper I, 3432 rockbursts from the period between November 9, 1996 and November 14, 2000 have been analysed. We have enjoyed some success when time variations of the *b*-value revealed strong indications that low *b*-values can be associated with subsequent increase of seismicity in the mine.

The main objective of the present study is to perform a similar analysis on extended data volume covering a period from November 1996 to April 2004 and comprising more than 6000 events. We wish to emphasize that evaluation of seismic hazard in the mine is by no means an objective of the present work. The ultimate goal is again to assess the power of varying *b*-value as a precursor of increasing (or decreasing) seismic activity in the mine. The potential of *b*-value variations for prediction of mining induced seismicity were already discussed in the 1970´s (e.g. Rudajev, 1970; Brady, 1977; Gibowicz, 1979). The method employed (also used in Paper I) is known and widely applied e.g. in Canada, Czech Republic, Poland and South Africa (Gibowicz and Lasocki, 2001). Hence, in this respect, the present work does not represent any novelty. However, as a case study, for a particular mine, a successful temporal and spatial forecasting of rockbursts will eventually lead to a reduction of their size and number, i.e. it will increase personnel safety and secure continuity of the production. It is to such an effort this study seeks to make a contribution. The approach is purely empirical based on an analysis of available seismic catalog data. For obvious reasons, we put particular emphasis on possible occurrence of stronger events ($M \geq 1.6$) that could be hazardous for mining.

THE ZINKGRUVAN MINE AND THE SEISMOGRAPHIC NETWORK

Zinkgruvan mine is owned by Lundin Mining AB, a Sweden based company, operated by Zinkgruvan Mining AB. Mining started on a larger scale around the middle of the 19-th century. Currently, the annual mined tonnage amounts to 750 kt of ore.

At present, the deposits are exploited in three underground volumes, Eastern Nygruvan, Western Nygruvan and Burkland. Nygruvan is the largest ore body reaching from the surface down to below 950m. Mining is completed from 650m upward. The deepest working point is 965m below the surface. Today, Nygruvan represents only 20% of the total tonnage mined. In Burkland, mining is completed between 250m and 350m depths. The ore body is also exploited at 450m, 650m and 800m. In 2004, mining started also at the 965m level. Generally speaking, the ore body in Zinkgruvan mine is hosted by leptites. Further out in the hanging wall, there is limestone (marble) with considerably lower compressive strength when compared with that of the leptite. High rock stress and a relatively compact structure have been of major concern in the Nygruvan ore body. We may expect relatively violent rockbursts there. Burkland, which is more fractured should not generate the same magnitudes and/or number of tremors as Nygruvan.

The geology together with the main tectonic features are depicted in Fig. 1. The most distinct fault within the mine volume is the Knalla fault, which delimits the Burkland ore body on the eastern side. The fault is a zone of several thinner and wider (up to 10m) faults together with unfaulted rocks and strikes N-S with a dip of about 75^o to the east. The fault is dry, inflow of water is not a problem in Zinkgruvan. Several minor faults cut the Nygruvan ore body in the NNE-SSW direction (Fig. 1).

In 1996, a digital three-dimensional seismographic network has been installed through a close cooperation with the South African Integrated Seismic System, ISS (Mendecki, 1997). Originally, the system consisted of 6 geophones. Towards the end of 1997 and in summer of 2001, the network was extended to, respectively 8 and 9 sensors which cover well the volume of the mine. Currently, the network consists of 11 geophones. For more technical details concerning the network and the location of sensors, the reader is referred to Paper I. The location procedure, employs a rather simple, homogeneous, isotropic, half-space velocity model. Nevertheless, the location accuracy within the network is high, about 10m (K. Tillman, personal communication). We wish to emphasize that in the present study, the location accuracy is not crucial. To quantify the events, moment magnitude, *M,* defined through the relation of Hanks and Kanamori (1979)

$$M = (2/3)\ \log M_0 - 6.1 \tag{1}$$

is employed, where M_0 is seismic moment in Nm.

THE METHOD

The frequency-magnitude earthquake distribution, FMD, introduced by Ishimoto and Iida (1939) and by Gutenberg and Richter (1954)

$$\log N = a - bM \tag{2}$$

relates the cumulative or incremental number of events, *N*, with magnitude, *M*. We make use of the cumulative distribution, it provides better linear fit since numbers of events are larger i.e. less degraded by statistics of small numbers. It also circumvents the problem of designing a proper incremental interval. The constant *a* describes the seismic activity (log number of events with M=0), it is determined by the event rate and for a certain seismic region depends upon the volume and time-window considered. *b,* which is typically close to 1, is a tectonic parameter describing the relative abundance of large to smaller shocks. It is a parameter controlling the medium capability to release accumulated energy (Kijko, 1997). Relation (2) describes a log-linear behaviour of the FMD and exhibits a scale invariability (self-similarity) which often extends over several orders of magnitude.

Space and temporal variations of the *b*-value have earlier been employed in numerous seismicity studies. After the pioneering works of Mogi (1962), Scholz (1968) and Wyss (1973), they have been extensively used (with varying degree of success) by other workers e.g. to identify volumes of active magma bodies (Wiemer and Benoit, 1996; Wiemer et al., 1998), roots of regional volcanism (Monterroso and Kulhanek, 2003) and to forecast major regional earthquakes (Monterroso, 2003; Nuannin et al., 2005). *b*-value studies related to mining-induced seismicity have been carried out already about 25 years ago e.g. in Brady (1977) or Gibowicz (1979) and more recently in Urbancic (1992), Holub (1995), Mendecki (1997), Feustel (1997) or Guha (2000) among others. A comprehensive summary of achievements during the 1990´s can be found in Gibowicz and Lasocki (2001). In the present work, we accept the explanation of Scholz (1968) and Wyss (1973) who interpret the decrease (increase) of *b* in the form of stress increase (decrease) before an approaching seismic event. We employ the temporal distribution of the *b*-value in the Zinkgruvan mine and examine its possible correlation with the occurrence of stronger rockbursts. Since comparisons are made with results of the previous study, we follow as much as possible the same procedure as that applied in Paper I.

It should be noted that the FMD (2) defines the distribution of magnitudes only. Thus, it may serve as a one-parameter approach to forecast ”large” events. Some authors made attempts to supplement the analysis with observations of other parameters such as event rate (Trifu et al., 1997) or the upper limit of seismic energy (Slavik et al., 1992; Kalenda, 1995). Here, we limit ourselves to a one-parameter approach (see also Paper I) and leave the issue of multi-parameter study for future investigations.

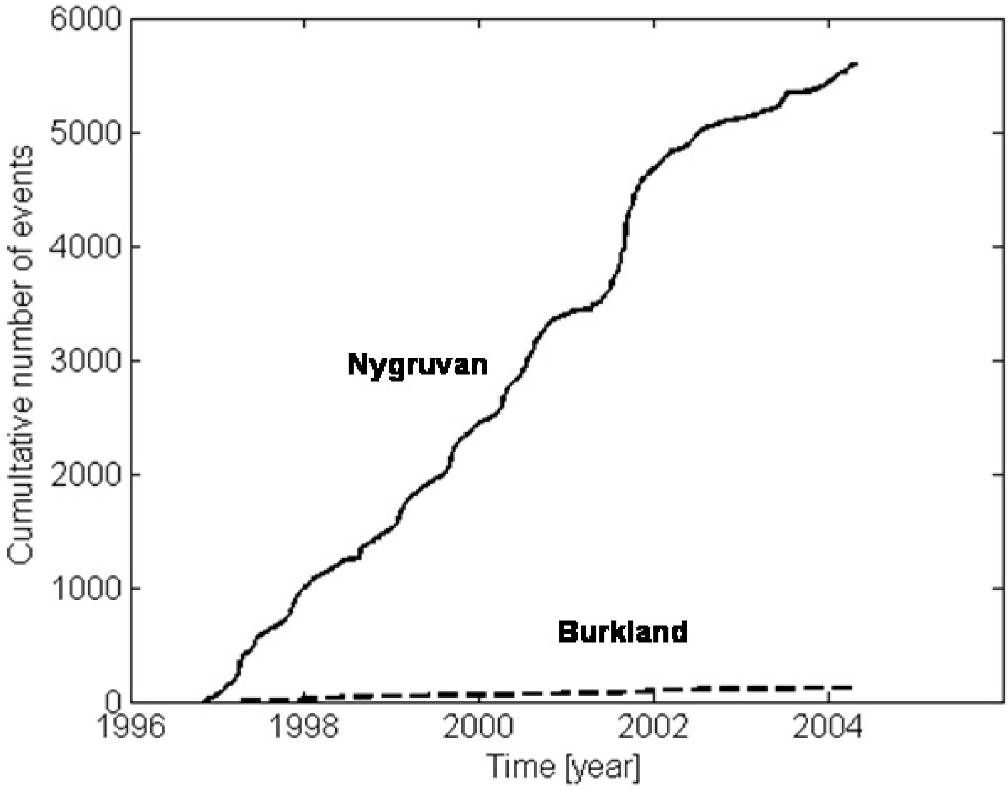

Fig. 3 Cumulative number of rockbursts as a function of time for Burkland and Nygruvan

High quality data, covering a time period of more than seven years, have been collected from the Zinkgruvan network. In the present work, we were able to double the data volume when compared with that used in Paper I. Another difference is the demarcation of mine areas (volumes) to be examined separately. In Paper I, we assumed three regions, the separation being based upon three distinct populations of hypocenters, roughly corresponding to the mining areas of Burkland, western Nygruvan and eastern Nygruvan. However, in the present study, with many more events, we did not find arguments (seismic or tectonic) for similar zonation (cf Fig. 2), nor could we find any hypocenter concentrations along the lesser faults cutting the Nygruvan ore body (Fig. 1). Due to the proximity (several hundred meters at the most; Fig. 2) of Eastern and Western Nygruvan, it is likely that the state of stress in the two fields affects each other. In this case, events from Eastern and Western Nygruvan should be analyzed jointly and consequently, Nygruvan is treated as one unit. The demarcation with respect to Burkland is materialized by the Knalla fault together with the rockbursts distribution (Fig. 2). It was possible to map high-resolution *b*-value variation as a function of time for Nygruvan, however Burkland reveals too low seismicity, with only 183 rockbursts during the period under review, which is not enough for a meaningful analysis.

b-value is calculated in sliding time windows containing a constant number, n, of events. The window moves in time by 10% increments of event counts. A constant number of events in each sample window (rather than a constant window length) is used, as in Paper I, to ensure that a change in the sample size does not effect the analysis, i.e. we establish a time-invariant statistical uncertainty. This approach may suffer from a drawback generated by time intervals with low level seismicity (e.g. due to a pause in mining operations). If this is the case, long time windows will be applied resulting in smoothed *b*-values impractical for any prediction. Cumulative numbers of events as a function of time are displayed in Fig. 3. The curves for Burkland and Nygruvan show no discernible changes in reporting rates, suggesting consistent observation operations during the whole, more than a 7-year period analysed here. An exceptional short jump in the Nygruvan curve in late 2001 is attributed to a rearrangement of production (refilling) routine. The average window length applied to Nygruvan data is 45 days with a standard deviation of 39 days. Thus, we are convinced that the constant n technique is preferable and applicable to the present data. Note that in the

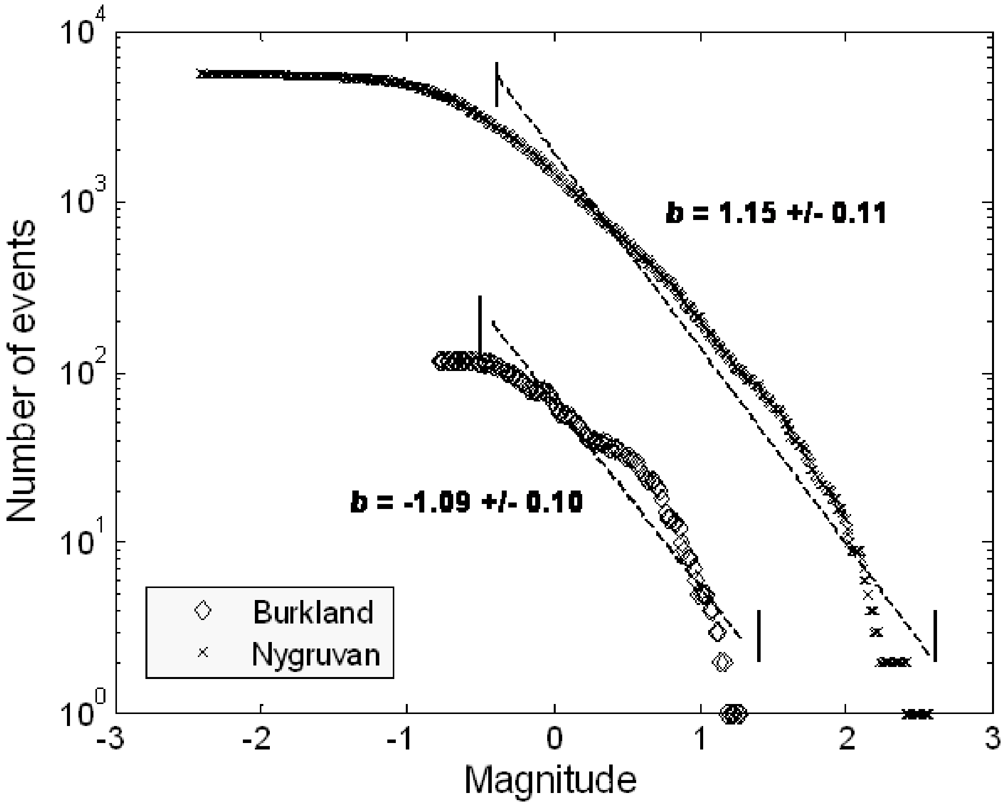

Fig. 4 Frequency-magnitude distributions of rockbusts and deduced overall *b*-values with respective standard deviations for Burkland and Nygruvan. Vertical lines indicate applied threshold magnitudes (-0.5 and -0.4, respectively) and maximum catalog magnitudes

constant-window-length technique, the choice of a proper window length becomes a crucial task. Short windows may not contain enough data, while long windows result in low time resolution and smooth out the investigated anomalies of observed *b*-values.

If we exclude the linear fit by eye, there are practically two methods available to determine the *b*-value, namely the least-squares method and the maximum-likelihood method. Several recent studies (cf e.g Wiemer and Benoit, 1996) compared the two techniques and found good correspondence. Since the former method is used in Paper I, we apply it also in the present study even though the maximum-likelihood method has currently been employed more in various investigations. The choice of the sliding-window length is a compromise between the time resolution and the smoothing effect of broad windows. After a number of tests we used windows with 50 events. The applied time increment of 10% is a result of several tests as well. For FMD calculations, we examined various magnitude intervals ΔM and found only small differences in corresponding threshold magnitudes, M_c. The interval of ΔM=0.1 was applied throughout the present work. By varying M_c, ΔM, n, window increments, time-window length and time periods covered, we confirm that observed changes (anomalies) in b are stable (robust) and not merely consequences of the choice of input parameters.

DATA AND ANALYSIS

During the period of review, i.e. from November 9, 1996 to April 26, 2004, the Zinkgruvan network detected, located and quantified 6037 rockbursts within a moment magnitude range from -2.4 to 2.6. The average rate is between two and three events per day. However, the temporal distribution is highly uneven with rates as high as about 60 events per day (April 4, 1997) or of several hundred shocks per day towards the end of 2001. We deleted all duplexes, events with location accuracy worse than 20m, and all events which were “located” above the surface. Altogether, 325 events were deleted from the original catalog. Locations of the remaining 5712 rockbursts together with the ore bodies are displayed in Fig. 2. The figure reveals two distinct populations of hypocenters, corresponding approximately to mining areas at Burkland and Nygruvan. The demarcation line between the two populations follows roughly the Knalla fault shown in Fig. 1.

In Fig. 4, frequency-magnitude distributions are presented separately for the two regions in the mine and for the whole period under review, i.e. between

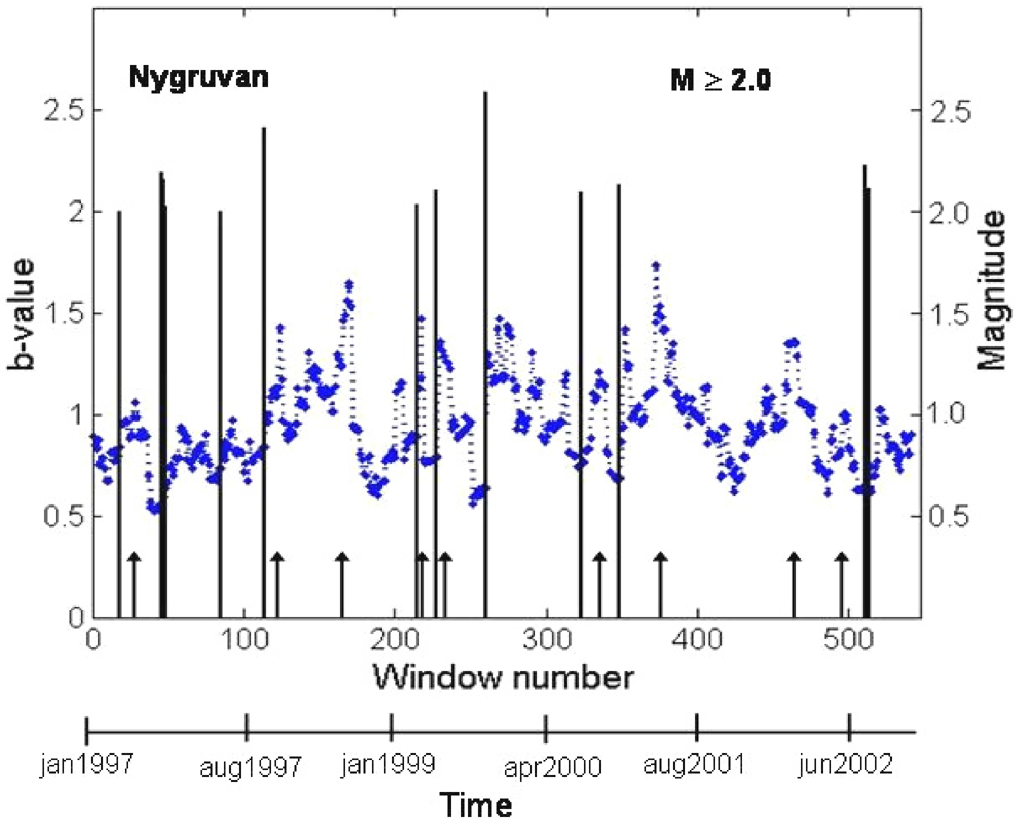

Fig. 5 *b*-value (left scale) as a function of window number or time. Solid, vertical lines represent time of occurrence and magnitude (right scale) of all recorded rockbursts with $M \geq 2$. Arrows indicate beginnings of statistically significant (99%) drops in the *b*-value

November 1996 and April 2004. When examining the temporal variation of *b*, the estimation of the magnitude of completeness, M_c, also called the threshold magnitude is critical (Wiemer and Wyss, 1997). As follows from the figure, M_c values for Burkland, and Nygruvan are -0.5 and -0.4, respectively. Since the respective maximum magnitudes are 1.3 and 2.6, the present analysis comprises data that span over 1.8 and 3.0 magnitude units for the two studied regions and the overall *b*-values are -1.09 and -1.15, respectively.

There are numerous papers referring to the FMD (2). Many of them confirm that the relation (2) holds practically for all magnitude ranges, locations and time periods (Kijko, 1997). In some special cases, observations reveal that rockbursts as well as tectonic (large) earthquakes do not strictly obey the Gutenberg-Richter law (2), especially in the high-magnitude ranges. For example, Kijko et al. (1987) and Trifu et al. (1993) suggest, on the basis of the observed non-similarity, that different mechanisms might be involved in the rockburst generation process, one responsible for the low-energy events and one which generates the high-components of the distribution. Both FMD´s displayed in Fig. 4 show deviations from the log-linear scaling behaviour and in this way support the hypothesis of non-similarity. A thorough examination of this issue extends beyond the scope of the present study. Here, we consider that FMD´s in each particular time window can reasonable well be approximated by a linear least-squares fit.

RESULTS AND DISCUSSION

Prediction, i.e. a simultaneous forecast of time of occurrence, location and magnitude, of individual rockbusts has not been our ambition in the present work. Our efforts have rather been focused on associating observed anomalies (decreases, drops) in *b*-values with lead-time intervals (months rather than days or weeks) of impending higher seismicity in limited volumes of the Zinkgruvan mine.

Figure 5 exhibits the calculated temporal variations of *b* for the Nygruvan region. 2752 events, $M \geq -0.4$, were used in the calculation. The horizontal axis shows time and serial number of the mowing time-window, while the vertical axis displays the

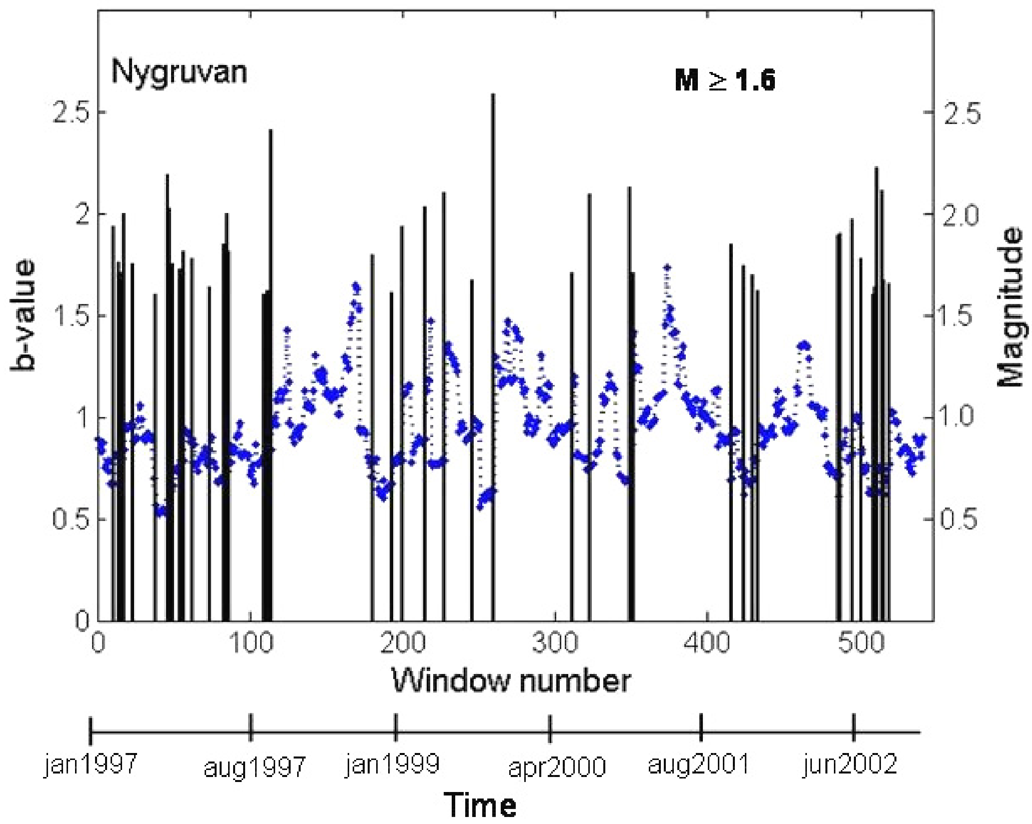

Fig. 6 Same as for Fig. 5, for recorded rockbursts with $M \geq 1.6$

calculated b-value. Note that the time scale is not linear due to a constant number of events in each time window considered. Solid vertical lines identify the time of occurrence and magnitude of larger rockbursts. To facilitate visual scanning only events with $M \geq 2.0$ are displayed. The diagram in Fig. 5 reveals temporal variations in calculated b-values from about 0.6 to about 1.8. Also numerous local maxima and minima are discernible in the diagram. To forecast time periods of increased seismicity and in agreement with the model proposed by Scholz (1968), we search for rapid, statistically significant drops of b-values (i.e. increases of stress). To determine whether or not a drop in b is significant, we applied the F-test. Only drops that were statistically significant at 99% confidence level were considered. In the present analysis, with time windows comprising 50 rockbursts, this means a drop of about 60% or more. During the reviewed time period, there are at least nine such drops, indicated by arrows in Fig. 5. As follows from the figure, in several cases there is a good agreement between a sudden, statistically significant decrease in the $b(t)$ curve and subsequent occurrence of large ($M \geq 2$) rockbursts. However, three large drops of b exhibited in Fig. 5, namely those in 1998, mid 2001 and early 2002 cannot be correlated with any observed rockburst with $M \geq 2$. This absence could be ascribed to the chosen magnitude limit, $M \geq 2$, which probably is too high, disregarding numerous but weaker events. Therefore, we repeated the diagram shown in Fig. 5 with a successively decreasing magnitude limit. As an example, Fig. 6 displays a $b(t)$ plot and all events with $M \geq 1.6$. When compared with Fig. 5, the diagram changes substantially its characteristic. All but one (late 1997) significant drops in b are now followed with one or several shocks with $M \geq 1.6$. Especially spectacular are the changes for rockburst sequences in mid 2001 and in early 2002.

When compared with results achieved in Paper I, we conclude that the present work reveals stronger correlation between sudden decrease in $b(t)$ and successive increase of seismicity. In fact, we could follow this trend in eight cases out of nine (Fig. 6). There are at least two reasons for this improvement. Firstly, doubling the amount of data and the time period under review most likely made the analysis more robust, i.e. less dependent upon the optional parameters entering the computation (ΔM, M_c, n). Secondly, dividing the original event catalog into a number of hypocentral populations (sub-catalogs), without a strong support from local tectonics and mine structure, may cause that also neighbouring production regions contribute to the particular behaviour of *b(t)* in the region studied. This was apparently the case in Paper I, where based on event distribution alone, we divided Nygruvan into two sub-regions which were analyzed separately. The two regions are obviously not isolated areas. A certain degree of interconnection between them certainly exists and complicates the analysis of corresponding *b(t)* diagrams. By deleting the Burkland ore body and by considering Nygruvan as one unit, we circumvent this drawback in the present study.

CONCLUSIONS

The present analysis comprises 6037 rockbursts in Zinkgruvan. The events occurred during a period of 7 years, between November 9, 1996 and April 26, 2004. Results of the present study may be summarized as follows:

- Calculated *b*-values show temporal variations in a broad range from about 0.6 to 1.8.
- In Nygruvan, high correlation is observed between statistically significant (99%) drops in *b(t)* and subsequent event ($M \geq 1.6$) occurrence.
- Most of the associated event occurrence takes place near the bottom points in *b(t)* diagrams.
- Present results seem to be more robust when compared with those presented in Paper I.
- Present findings are encouraging and of value for increasing safety in mines and continuity of production.

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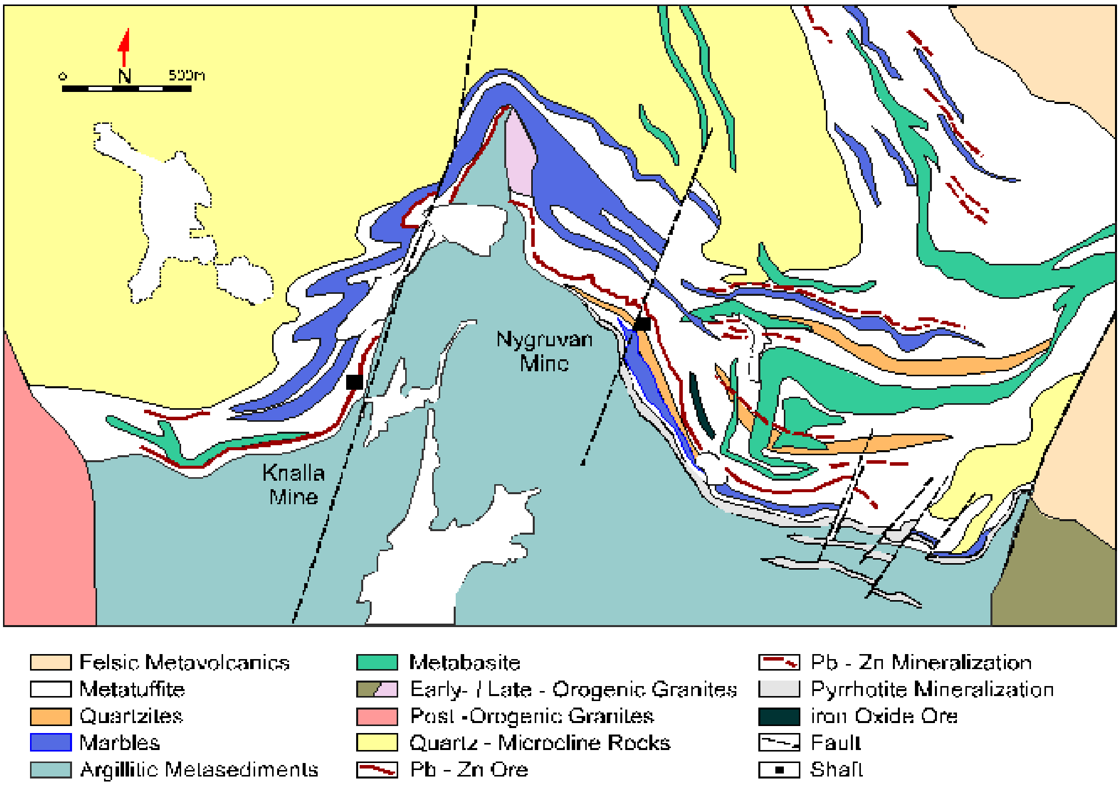

Fig. 1 Geology of the Zinkgruvan mine (reprinted with permission from Hedström et al., 1989)

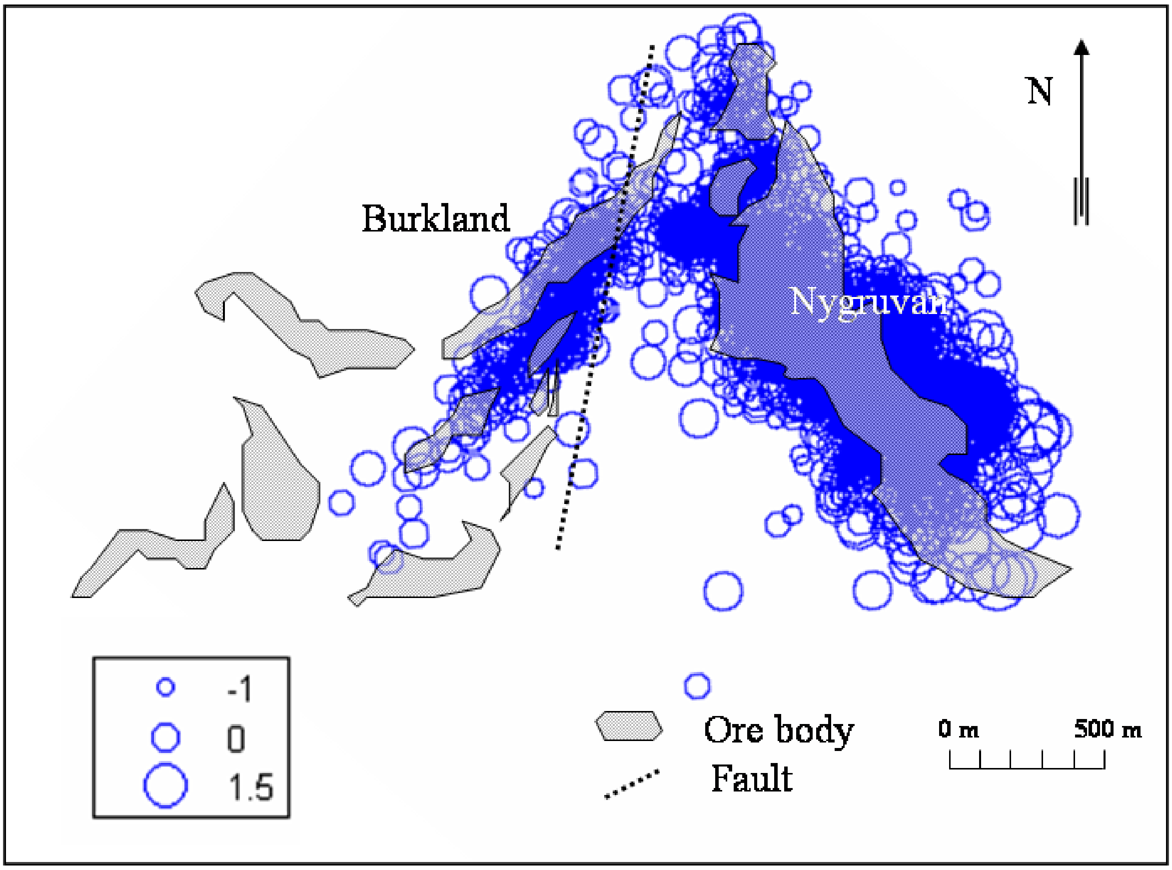

Fig. 2 Epicenters of rockbursts (circles) together with ore bodies (shaded) in Nygruvan and Burkland